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Where Intervention Can Still Matter: Anticipatory Management of Indonesian Mangroves under Extreme El Niño

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Abstract

The developing 2026–27 El Niño creates an opportunity to move from retrospective explanation of mangrove damage toward anticipatory management. Its ecological consequences cannot be inferred from climate magnitude alone because regional forcing is mediated by local hydrology, geomorphology and ecosystem condition. Drawing on recent climatic extremes, including links among low water levels, salinization and mangrove deterioration during 2015–16 (Lovelock et al., 2017), this paper identifies five prospective impact vectors: porewater salinization, growth suppression, regeneration failure, canopy deterioration and restricted-stand dieback. These are overlapping manifestations rather than sequential stages toward mortality. We introduce hydroecological buffering to explain how local processes moderate climatic exposure, and actionability to assess whether an identifiable actor can alter the governing mechanism while meaningful outcomes remain preservable. Their intersection distinguishes autonomous resilience, maintained buffering, inherent vulnerability and correctable vulnerability. The framework separates ecological risk from adaptation priority: highly vulnerable systems may offer little management leverage, whereas alterable hydrological or operational constraints may warrant early intervention. Extreme forcing can reveal weaknesses concealed under favourable conditions while narrowing the outcomes management can preserve. The framework supports prospective diagnosis and differentiated management without implying a spatial forecast of mortality.t

1. Introduction: From Forecast Climate Extremes to Anticipatory Mangrove Management

Indonesia's mangrove conservation and restoration programmes are entering an unusual period of climatic risk. By late August 2026, the developing El Niño had strengthened rapidly. Indonesia's Agency for Meteorology, Climatology and Geophysics reported a Niño-3.4 sea-surface-temperature anomaly of +2.99°C on 24 August and characterized the event as a very strong El Niño, while meteorological drought was affecting parts of southern Sumatra and Kalimantan (BMKG, 2026). The World Meteorological Organization projected further intensification through boreal autumn, forecasting an August–October Niño-3.4 anomaly of approximately +2.9°C and a peak around November, alongside probable development of a positive Indian Ocean Dipole (WMO, 2026).

A potentially exceptional climatic event is therefore developing while there remains time to anticipate some of its ecological consequences. Advance warning creates an unusual management opportunity: to move from explaining ecological damage retrospectively toward identifying where intervention may still alter outcomes.

Those outcomes cannot be inferred directly from El Niño magnitude. Mangrove responses to climatic forcing are mediated by rainfall, freshwater discharge, coastal water level, tidal position, elevation, sediment dynamics, geomorphology and hydrological connectivity. Even neighbouring systems may experience the same regional anomaly differently. The relevant question is not simply how strong El Niño becomes, but where its associated forcing encounters coastal systems poorly able to moderate the resulting exposure.

Recent climatic extremes demonstrate why this distinction matters. During the 2015–16 El Niño, severe rainfall deficit contributed to catastrophic Indonesian peat and landscape fires, with fire activity increasing nonlinearly as prolonged dry-season rainfall declined (Field et al., 2016). The same event produced a different warning for mangroves: approximately 8,000 ha of mangrove forest died along the coast of northern Australia following an exceptional combination of low sea level, rainfall deficit, elevated evaporative demand and increasing salinity (Lovelock et al., 2017; Abhik et al., 2021). Mortality was strongly heterogeneous, with freshwater availability, elevation, shoreline position and drainage characteristics differentiating outcomes. In 2019, severe Indonesian drought and peat fire returned without a strong El Niño, under an exceptionally strong positive Indian Ocean Dipole (Lu & Ren, 2020; Yokelson et al., 2022). Different regional climate configurations can therefore converge upon similar proximate stresses, while an extreme El Niño may additionally combine terrestrial drying with adverse coastal water-level conditions.

Mangrove climate-risk scholarship supports this process-based interpretation. Persistence under changing water levels depends partly upon sediment supply and surface-elevation dynamics (Lovelock et al., 2015), while salinity, water limitation and altered inundation can impair coastal woody vegetation before mortality occurs (McDowell et al., 2022). Zhang et al. (2025) detected ENSO-associated variability across more than half of global mangrove area, including reduced leaf area across the western Pacific during El Niño. Climate-smart conservation analysis likewise demonstrates that accounting for spatial variation in mangrove climate resilience can improve conservation prioritization (Dabalà et al., 2026). Collectively, this literature shifts attention from the climatic anomaly toward the conditions through which forcing becomes locally consequential.

This shift also challenges the treatment of forest loss as the principal endpoint of climatic risk. Impairment may begin with porewater salinization and growth suppression, affect recruitment and restoration establishment, progress toward canopy deterioration and, under severe compound exposure, culminate in localized stand dieback. These effects can alter carbon accumulation, regenerative capacity and habitat function while affected areas remain classified as mangrove. Prospective assessment therefore requires attention to ecological function and trajectory, not forest presence alone.

Hydroecological buffering describes the capacity of local physical and ecological processes to moderate the translation of external hydroclimatic forcing into biologically consequential exposure. It emerges from tidal and freshwater connectivity, hydroperiod, elevation, sedimentary and geomorphic setting, disturbance history and developmental stage. Buffering is neither synonymous with ecological integrity nor simply the inverse of degradation; it locates climatic exposure in the relationship between external forcing and the receiving system.

Buffering alone, however, does not establish a management priority. Natural elevation or regional water-level anomalies may lie largely beyond a restoration manager's control, whereas an artificial hydrological restriction or poorly timed planting programme may remain alterable. Ecological vulnerability becomes an anticipatory-management opportunity only where an identifiable actor can change the mechanism governing exposure while meaningful outcomes can still be preserved.

Existing scholarship provides foundations for this distinction but rarely combines them prospectively. Process-based restoration emphasizes diagnosis of the constraints governing ecosystem recovery (Lewis, 2005; Ellison et al., 2020), while hydrogeomorphic research shows how local setting mediates mangrove responses to changing water levels and climatic exposure (Lovelock et al., 2015; Abhik et al., 2021). Climate-smart planning further demonstrates that incorporating spatial differences in resilience can improve conservation allocation (Dabalà et al., 2026). Less attention has been given to how these insights can guide decisions when an extreme event is already foreseeable: where does ecological vulnerability present a meaningful opportunity for anticipatory management, and where does it remain beyond the leverage of the relevant actor?

This paper addresses that gap through two linked tasks. First, it identifies five prospective ecological impact vectors: porewater salinization, growth suppression, regeneration failure, canopy deterioration and restricted-stand dieback. These are potentially overlapping manifestations, not mandatory stages toward mortality. Second, it combines hydroecological buffering and actionability to distinguish four management-relevant conditions: autonomous resilience, maintained buffering, inherent vulnerability and correctable vulnerability. The vectors describe what may be happening ecologically; buffering and actionability establish what those observations may mean for management.

Section 2 compares the 2015–16 and 2019 events, specifies the prospective forcing environment, develops the impact vectors and introduces hydroecological buffering. Section 3 adds actionability, develops the four-condition typology and considers how extreme forcing can reveal hidden constraints while narrowing the outcomes intervention can preserve. Section 4 examines implications for diagnosis, restoration practice, monitoring and empirical testing.

The central proposition is that climate anomalies generate regional hazards, but hydroecological buffering determines how those hazards become local ecological exposure. Vulnerability becomes an opportunity for anticipatory management only where an identifiable actor retains leverage over the mechanism producing that exposure and can act before the relevant ecological outcome is fixed.

2. Mangrove Responses to an Extreme El Niño: Historical Evidence and Prospective Impact Vectors

The emerging El Niño has no exact historical analogue for Indonesian mangroves. The most useful evidence comes instead from comparing the very strong 2015–16 El Niño with the severe 2019 positive Indian Ocean Dipole (pIOD). The first demonstrates how extreme El Niño conditions can combine terrestrial drought with anomalous coastal water levels and severe mangrove stress. The second shows that rainfall deficit, declining freshwater availability, peat drying and fire susceptibility can arise under a different climate configuration. Together, these episodes distinguish climatic forcing from the local processes through which ecological impairment occurs.

2.1 The 2015–16 analogue: compound coastal and terrestrial hydroclimatic stress

The 2015–16 El Niño was among the strongest events of the modern observational era (L'Heureux et al., 2017). In Indonesia, severe dry-season rainfall suppression interacted with drainage, degradation and anthropogenic ignition to produce exceptional fire conditions. Fire activity increased sharply when sustained rainfall fell below approximately 4 mm day^{-1} (Field et al., 2016), while Indonesian peat fires emitted an estimated 227 ± 67 Tg C during September–October 2015 (Huijnen et al., 2016). El Niño did not create these landscape vulnerabilities; climatic drying amplified them until thresholds for extensive disturbance were crossed.

The same event exposed a specifically coastal pathway. Along approximately 1,000 km of northern Australian coastline, about 8,000 ha of mangrove forest died during 2015–16. Exceptionally low sea levels coincided with rainfall deficit, elevated evaporative demand and increasing soil salinity; at Mangrove Bay, porewater salinity increased to approximately 30% above mean conditions as canopy condition, vegetation greenness and recruitment declined (Lovelock et al., 2017). Abhik et al. (2021) subsequently showed that sea levels declined earlier and remained anomalously low for longer than during previous very strong El Niño events, overlapping with the season when regional water levels were already naturally low. The ecological significance lay in the compound exposure rather than any single climatic variable.

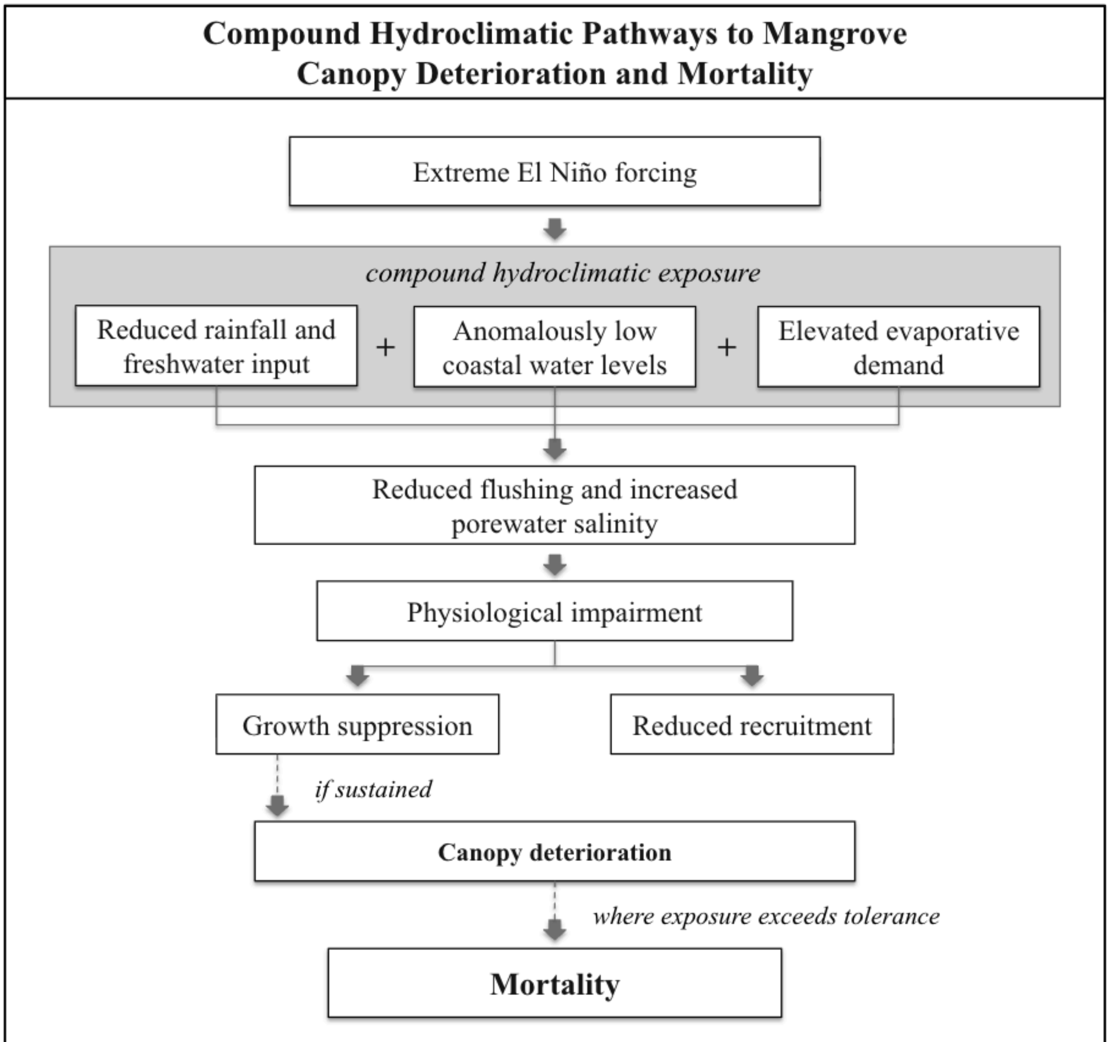

Figure 1. Compound hydroclimatic pathways to mangrove canopy deterioration and mortality. Reduced rainfall and freshwater input, anomalously low coastal water levels and elevated evaporative demand may combine to reduce flushing and increase porewater salinity. Growth and recruitment responses may occur separately, and neither necessarily progresses to canopy deterioration or mortality.

Mortality was strongly heterogeneous. Freshwater availability moderated salinity effects, while elevation, shoreline position and drainage characteristics differentiated severely affected stands from those that survived (Lovelock et al., 2017; Abhik et al., 2021). Salinity increases the osmotic cost of water uptake and salt regulation, while water limitation can impair photosynthesis and hydraulic function before mortality becomes evident (McDowell et al., 2022). Mangroves can therefore experience severe physiological water stress despite occupying an intertidal environment.

The Australian event appears to represent an extreme expression of broader climatic sensitivity rather than an isolated anomaly. Zhang et al. (2025) detected significant ENSO-associated growth variability across more than half of global mangrove area, including a general reduction in leaf area across the western Pacific during El Niño. Short-term sea-level fluctuations emerged as an important explanatory mechanism. The 2015–16 record therefore establishes the possibility that terrestrial drying and adverse coastal water-level anomalies can operate simultaneously, while local conditions determine where regional forcing becomes severe ecological stress.

2.2 The 2019 comparator: convergent exposure under different climatic forcing

Indonesia again experienced exceptional drought and fire in 2019, when approximately 1.65 million ha of forest and land burned (KLHK, 2020). Yet the large-scale climate configuration differed markedly from 2015. Direct peat-fire measurements were collected approximately ENSO-neutral conditions, while an exceptionally strong positive IOD developed in the Indian Ocean (Yokelson et al., 2022). Lu and Ren (2020) identified the 2019 pIOD as the strongest since 1982 on record, and linked it to severe rainfall suppression over Indonesia.

In South Sumatra, declining peat groundwater was significantly associated with increasing hotspot occurrence, with Irfan et al. (2024) identifying groundwater level as an important control on fire susceptibility. The proximal pathway was straightforward: rainfall deficit led to groundwater drawdown, peat desiccation and increased fire susceptibility. Once peat became sufficiently dry to burn, Yokelson et al. (2022) found closely comparable methane emission factors during the 2015 and 2019 fires. Climate mode helped determine how the landscape reached a hazardous hydrological state; it did not uniquely determine the subsequent disturbance process.

The comparison separates two categories of concern. General hydroclimatic-deficit mechanisms—reduced rainfall, freshwater deficit, groundwater decline and fire susceptibility—can arise under different climate configurations. Extreme El Niño conditions may additionally combine severe terrestrial drying with adverse western Pacific coastal water levels. This does not imply widespread Indonesian mangrove dieback; it identifies compound terrestrial–marine exposure as a mechanism warranting prospective attention.

2.3 Prospective hydroclimatic forcing under a strong 2026–27 El Niño

The developing event creates a prospective forcing environment rather than a predetermined ecological outcome. Forecasts indicate the possibility of severe precipitation deficit across parts of Indonesia, potentially accompanied by a positive IOD and substantial spatial variation in drought intensity (BMKG, 2026; WMO, 2026). Reduced precipitation may diminish direct freshwater inputs to mangroves and riverine or catchment discharge, particularly where dry conditions persist across adjoining watersheds.

Rainfall deficit may also interact with changes in coastal water level. During 2015–16, unusually early and persistent low sea levels compounded seasonally low water conditions along northern Australia, while freshwater availability and hydrogeomorphic position differentiated local exposure (Lovelock et al., 2017; Abhik et al., 2021). Global analysis subsequently associated ENSO-related short-term sea-level fluctuations with coherent changes in mangrove leaf area, including reductions across much of the western Pacific during El Niño (Zhang et al., 2025). These findings justify monitoring coastal water-level behaviour during the developing event, without implying that the earlier anomaly will recur with the same timing, location or magnitude.

Elevated atmospheric demand may intensify exposure. When high evaporative demand coincides with reduced freshwater dilution and less frequent tidal inundation, salts may concentrate within intertidal soils. Increasing salinity can then constrain water uptake, photosynthesis and hydraulic function even where mangroves remain physically surrounded by water (McDowell et al., 2022).

The prospective forcing package can be summarized as:

precipitation deficit + reduced freshwater discharge + potential coastal water-level depression + elevated evaporative demand

These factors need not coincide everywhere or with equal magnitude. Their significance lies in where terrestrial and marine forcing combine to push local conditions beyond their normal range. The formulation identifies a prospective forcing environment, not a prediction of ecological impact.

2.4 Five prospective ecological impact vectors

Historical evidence cannot support a quantitative forecast of Indonesian mangrove mortality during the developing event. It can, however, identify mechanisms through which ecological impairment could plausibly emerge. We distinguish five prospective impact vectors.

PS — Porewater salinization. Reduced rainfall and freshwater discharge can decrease dilution, while reduced tidal inundation or restricted flushing can increase salt accumulation. The 2015–16 observations provide direct evidence of increasing porewater salinity under combined low rainfall and anomalously low sea level (Lovelock et al., 2017). Risk should therefore increase where freshwater influence is weak, mangroves occupy naturally exposed tidal positions or artificial restrictions limit exchange.

GS — Growth suppression. Physiological impairment can precede structural damage. Salinity and water limitation can reduce photosynthesis and hydraulic function (McDowell et al., 2022), while Zhang et al. (2025)

detected widespread El Niño-associated reductions in mangrove leaf area across the western Pacific. Growth suppression may therefore be geographically extensive while remaining largely invisible to conventional forest-cover monitoring.

RF — Regeneration failure. This vector encompasses failure of natural recruitment and failure of young restoration cohorts to establish or persist. Propagule establishment, juvenile survival and planted cohorts are sensitive to salinity, hydroperiod, tidal elevation and hydrological connectivity. Recruitment declined during the 2015–16 Australian event (Lovelock et al., 2017), while restoration scholarship demonstrates the importance of hydrological setting, site selection and developmental stage to establishment success (Lewis, 2005; Primavera & Esteban, 2008; Su et al., 2021). Climatic stress may therefore expose vulnerabilities embedded in restoration design, with different consequences for mature forest, naturally regenerating sites and seedling-dominated restoration.

CD — Canopy deterioration. Sustained physiological stress can progress from reduced productivity toward defoliation, thinning, branch mortality and declining crown condition. Such deterioration accompanied increasing salinity during the 2015–16 event (Lovelock et al., 2017), consistent with pathways through which sustained coastal environmental stress can progress toward woody-plant mortality (McDowell et al., 2022). Canopy deterioration indicates that stress is no longer confined to suppressed function.

SD — Restricted-stand dieback. Severe compound exposure can produce stand-scale mortality, but historical evidence suggests that such effects should be spatially concentrated rather than uniform. In northern Australia, the distribution and severity of dieback varied with elevation, shoreline position, freshwater influence and drainage characteristics (Abhik et al., 2021). For Indonesia, the defensible prospective hypothesis is therefore elevated dieback risk in poorly buffered stands where severe salinity, prolonged low-water exposure or artificial hydrological restriction coincide.

These vectors are neither mutually exclusive nor mandatory stages in a fixed progression. They may overlap, occur simultaneously, affect developmental stages differently and vary spatially within the same landscape. Salinization may suppress growth without producing structural damage; regeneration may fail while mature forest remains intact; and canopy deterioration need not progress to stand-scale mortality. The vectors describe ecological manifestations to be investigated, not a deterministic ladder toward dieback.

Peat and edge fire remain relevant as external disturbance pathways at mangrove–terrestrial boundaries, particularly where rainfall deficit and declining groundwater increase fire susceptibility (Field et al., 2016; Irfan et al., 2024). Fire is excluded from the five vectors because it arises principally from landscape drying, combustible substrates and ignition rather than as an internal mangrove response.

The five-vector formulation also broadens the relevant endpoint beyond categorical forest loss. Mangrove carbon accumulation depends upon root production and sediment processes as well as standing biomass; Arnaud et al. (2023) estimated mean root production at approximately 770 ± 202 g dry biomass m^{-2} yr^{-1} and identified precipitation and hydrogeomorphic setting among its controls. Climatic stress can therefore suppress accumulation without immediately reversing existing carbon stocks. Regeneration failure may similarly delay the recovery of ecosystem functions, particularly in young restoration cohorts (Su et al., 2021). Mangrove condition can influence fisheries production (Carrasquilla-Henao & Juanes, 2017), but carbon, fisheries and livelihood effects are context-dependent consequences of ecological impairment rather than additional ecological vectors.

The vectors clarify what may become ecologically manifest. They do not establish where manifestation will be strongest or which observations indicate a management opportunity.

2.5 From impact vectors to differential exposure: hydroecological buffering

Hydroecological buffering describes the capacity of local physical and ecological processes to moderate the translation of external hydroclimatic forcing into biologically consequential exposure. Mangrove establishment and development are strongly conditioned by salinity, flooding and other site-specific variables (Krauss et al., 2008), while persistence under changing water levels depends partly upon sediment availability and surface-elevation dynamics (Lovelock et al., 2015). During the 2015–16 dieback, freshwater influence, elevation and drainage position differentiated outcomes under shared regional forcing (Lovelock et al., 2017; Abhik et al., 2021). Buffering synthesizes these relationships through tidal and freshwater connectivity, hydroperiod, elevation, sedimentary and geomorphic setting, disturbance history and developmental stage.

The causal relationship can be expressed as:

regional hydroclimatic forcing → hydroecological buffering → local exposure → impact-vector expression

Low buffering does not necessarily indicate degradation. A naturally high-intertidal mangrove may be weakly buffered because of its geomorphic position, while a former aquaculture pond may be weakly buffered because residual infrastructure restricts tidal exchange. Similar impacts can therefore arise from mechanisms that differ substantially in their susceptibility to intervention.

Buffering explains where and why exposure may intensify, but not what management should do. That requires determining whether an identifiable actor can alter the governing mechanism while intervention can still improve ecological outcome. Section 3 introduces actionability and combines it with buffering to distinguish conditions requiring protection, maintenance, restraint or targeted correction.

3. From Ecological Exposure to Anticipatory Management

Hydroecological buffering explains why climatic forcing produces different local exposure, but it does not determine whether intervention is appropriate. Similar impacts may arise from intrinsic hydrogeomorphic conditions or alterable constraints. Moving from ecological exposure to anticipatory management therefore requires a second dimension: actionability.

3.1 Hydroecological buffering and actionability

Actionability describes whether an identifiable actor can alter the mechanism governing site condition while intervention can still materially improve ecological outcome. It contains two connected questions: can the causal mechanism be changed, and can changing it now preserve the outcome at risk?

This distinction has an established basis in conservation decision science. Ecological importance and threat magnitude are insufficient grounds for intervention priority when considered independently of management feasibility. Joseph et al. (2009) showed that management cost and probability of success can materially alter the allocation of limited conservation resources, while Priority Threat Management evaluates strategies through expected biodiversity benefit, feasibility and cost (Carwardine et al., 2019). Identifying a substantial ecological risk does not establish that intervention is possible, timely or likely to succeed.

Regional rainfall deficit and climate-driven coastal water-level anomalies are largely exogenous to mangrove managers. Geomorphic elevation may also be effectively fixed at the timescale of an unfolding event. A blocked culvert, residual bund, poorly timed planting programme or project-controlled restriction to tidal exchange is different: part of the pathway translating climatic forcing into exposure may be susceptible to management.

Technical feasibility is nevertheless insufficient. An artificial restriction may remain physically removable after a restoration cohort has died, but its removal can no longer prevent the loss of that cohort. Changing a planting schedule may prevent additional exposure while doing little for seedlings that have already crossed a mortality threshold. Adaptive-pathways research similarly identifies conditions beyond which a management action no longer achieves its objective (Haasnoot et al., 2013). Actionability therefore declines when the ecological outcome motivating intervention is no longer alterable, even if the underlying mechanism remains tractable.

Actionability is also actor-dependent. A mechanism beyond the authority of a restoration project may remain alterable by communities, infrastructure authorities or government agencies. It must therefore be assessed relative to a specified actor as well as a mechanism, outcome and period.

Hydroecological buffering describes the condition of the receiving system; actionability describes available management leverage over the mechanisms governing that condition. Combining them produces four ideal-typical conditions.

3.2 A The Adaptation Leverage Matrix

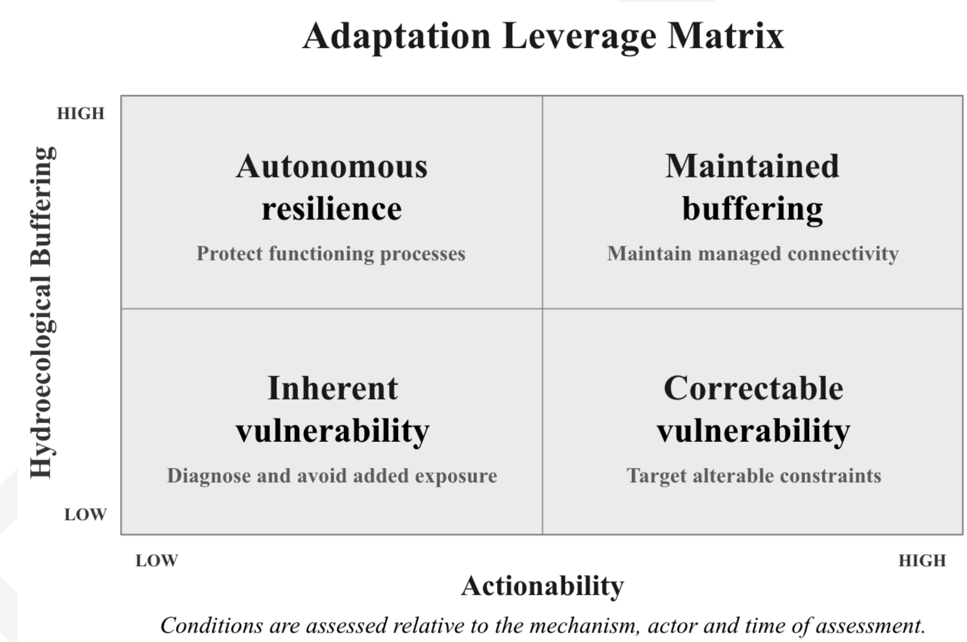

Figure 2. Adaptation Leverage Matrix. High buffering combined with low actionability represents autonomous resilience; high buffering combined with high actionability represents maintained buffering; low buffering combined with low actionability represents inherent vulnerability; and low buffering combined with high actionability represents correctable vulnerability. The conditions are ideal types whose application depends upon the site, causal mechanism, relevant actor and period of assessment.

The five vectors and the four typological conditions perform different functions. The vectors describe ecological manifestations; buffering and actionability describe the management-relevant conditions in which those manifestations occur. Porewater salinization, growth suppression or regeneration failure could occur in any quadrant if external forcing were sufficiently strong. Their presence does not assign a site automatically to a particular condition.

The matrix is relative rather than absolute. Buffering is assessed against a specified forcing environment, while actionability is assessed relative to an identifiable actor, outcome and period. A system that buffers ordinary seasonal variability may become weakly buffered under compound freshwater and coastal water-level anomalies. A mechanism actionable during advance warning may cease to offer meaningful leverage as impacts accumulate. The quadrants therefore describe conditions at a particular time, not permanent classifications of entire landscapes.

Low buffering identifies susceptibility, but only high actionability indicates substantial management leverage over the mechanisms producing exposure. Conversely, high buffering may reflect either largely autonomous ecological processes or processes that remain effective partly because they have been restored or maintained.

3.3 Four conditions and their management postures

Inherent vulnerability: low buffering × low actionability. Inherent vulnerability describes settings in which climatic forcing translates strongly into local exposure, but the dominant mechanism is not realistically alterable by the relevant actor within the available period. Examples include naturally high-intertidal or back-mangrove positions, weakly freshwater-influenced forests and geomorphic settings in which prolonged low-water or hypersaline exposure follows principally from elevation and landscape position.

Low buffering in these settings need not indicate degradation or management failure. As the northern Australian dieback demonstrated, differences in exposure can arise from freshwater influence, elevation, shoreline position and drainage characteristics under broadly shared climatic forcing (Abhik et al., 2021). Where these conditions reflect natural hydrogeomorphic setting rather than artificial restriction, vulnerability may be substantial without being locally correctable.

The appropriate posture is restraint informed by diagnosis. Managers can avoid additional obstruction, drainage or disturbance and reconsider whether restoration or carbon-performance expectations are appropriate. The actionable decision may concern programme design or site selection rather than alteration of the ecosystem itself. Severe vulnerability does not create an obligation to engineer a naturally exposed setting.

Correctable vulnerability: low buffering × high actionability. Correctable vulnerability presents the strongest immediate case for anticipatory intervention. Buffering is weak, but the mechanism producing or amplifying exposure is at least partly alterable before the ecological outcome is fixed.

Former aquaculture landscapes provide a clear example. Residual bunds or inadequate connections may restrict tidal exchange after land use has ceased. Rainfall may partially compensate during ordinary conditions, but the restrictions become more consequential when rainfall and coastal water levels decline. Roads or culverts may create comparable constraints, while operational decisions can expose restoration cohorts through unsuitable elevation, hydroperiod or deployment timing.

Process-based restoration has long emphasized diagnosing the physical conditions preventing natural recovery before defaulting to planting (Lewis, 2005). Primavera and Esteban (2008) documented how inappropriate site and species selection contributed to rehabilitation failure, while Ellison et al. (2020) frame restoration as adaptive management in which evidence about hydrology and ecological response changes implementation. The relevant intervention is the one that alters the causal pathway, not necessarily the most visible engineering activity.

The central test is whether an ecologically plausible and managerially attainable better-buffered condition exists. Depending upon the diagnosis, management might correct a project-controlled restriction, change restoration deployment or protect surviving cohorts and natural regeneration. If vulnerability arises principally from natural geomorphic position or regional forcing, the site does not become correctable merely because an intervention can be imagined.

Maintained buffering: high buffering × high actionability. Maintained buffering describes systems in which exposure is presently moderated effectively, but management retains influence over the supporting processes. Examples include rehabilitated aquaculture landscapes with restored tidal exchange, maintained culverts or channels, and restoration programmes responsive to hydrological conditions.

High actionability does not imply that a new intervention is required. The priority is to preserve existing buffering through preventative maintenance and operational flexibility. Functioning connections should be protected, necessary infrastructure maintained and restoration work adjusted before exposing additional cohorts.

Autonomous resilience: high buffering × low actionability. Autonomous resilience describes systems in which local processes substantially moderate climatic forcing but do so largely independently of project-level management. Mature creek- and river-fringe forests with strong tidal and freshwater connection, naturally regenerating accretionary surfaces and extensive functioning channel networks may approximate this condition.

Low actionability is not a deficiency here. It reflects the predominantly natural or landscape-scale character of the processes supporting resilience. The appropriate posture is protection and restraint: conserve connectivity, mature vegetation, propagule sources and space for geomorphic adjustment rather than assuming that resilience requires active intervention. These systems can also provide reference conditions against which responses elsewhere are interpreted.

The matrix therefore associates four conditions with four broad postures: protect autonomous processes, maintain management-supported buffering, exercise restraint where vulnerability is intrinsic, and correct alterable constraints where weak buffering is avoidably amplified.

3.4 El Niño as a stress test and the narrowing adaptation window

The Adaptation Leverage Matrix provides a snapshot of management-relevant conditions. An extreme El Niño can stress-test that condition by reducing climatic inputs that conceal marginal hydrology during ordinary years. Rainfall and normal coastal water levels may partially compensate for restricted exchange, marginal tidal elevation or excessive dependence on freshwater. A former aquaculture pond may appear functional while rainfall limits salinity accumulation; a planting block may establish during favourable wet years; and a culvert may appear adequate until reduced water levels narrow the period of effective exchange.

Impact-vector expression can reveal these dependencies. Spatial concentration of porewater salinization may identify inadequate flushing. Growth suppression may expose physiological stress before structural damage appears. Regeneration failure may show that conditions have moved beyond the establishment range of propagules or planted cohorts, while canopy deterioration and restricted-stand dieback may identify sites where exposure has become severe enough to affect ecosystem structure.

The diagnostic value of these observations lies in comparing their distribution with hydrological, geomorphic and management conditions. Salinization may reflect regional forcing, natural tidal position, artificial restriction or their interaction. Regeneration failure may arise from climatic exposure, restoration design, propagule limitation or antecedent degradation. El Niño does not redefine the matrix; it reveals how sites perform when favourable climatic conditions no longer compensate for underlying constraints.

Emerging evidence may change both diagnosis and response. Salinization concentrated behind an embankment may reveal a correctable connection problem, while broadly distributed increases across contrasting sites may indicate regional forcing with little immediate local leverage. Restoration mortality initially attributed to generalized drought may prove concentrated at unsuitable elevations, redirecting management from hydrological engineering toward planting decisions. Information becomes actionable when it distinguishes mechanisms and changes what an actor should do.

The range of alterable outcomes also changes as the event progresses. Early diagnosis may allow a restriction to be corrected, planting suspended or surviving cohorts protected. Later, the same intervention may remain technically feasible but no longer preserve the function or cohort that justified it. Loss of one outcome does not eliminate every management option: a failed cohort may no longer be recoverable, while future exposure can still be avoided and natural regeneration protected. Nevertheless, accumulating damage narrows the scope of anticipatory action.

Severe structural deterioration may also weaken future buffering by altering vegetation, sediment retention and subsequent establishment. This possibility is conditional and should not be inferred from early physiological or demographic responses alone.

The practical assessment sequence is therefore:

What impact vector is emerging?
→ What mechanism is producing or amplifying exposure?
→ Can an identifiable actor alter that mechanism?
→ Can action still improve the ecological outcome?
→ What is at stake if the opportunity is missed?

Ecological value, carbon stocks and accumulation, restoration investment, fisheries and livelihood functions, and the difficulty of recovery can guide allocation among actionable opportunities. Consequence does not make an intractable mechanism actionable, but it helps determine how urgently available leverage should be used.

The purpose of early intervention is not simply to repair climatic damage, but to act where extreme forcing encounters an alterable weakness before the relevant ecological outcome can no longer be preserved.

4. Discussion: Learning and Acting Before Outcomes Are Fixed

The contribution of this analysis is not a new mangrove-restoration technique. It lies in asking how knowledge derived largely from retrospective studies can guide management when an extreme climatic event is foreseeable but its ecological outcomes remain unresolved. Advance warning permits managers to investigate where known mechanisms may become consequential and which vulnerabilities remain open to intervention. This requires moving beyond climatic indices as proxies for ecological outcomes and beyond vulnerability as a sufficient basis for management priority.

4.1 From retrospective attribution to prospective diagnosis

The historical episodes examined in Section 2 are most useful prospectively as sources of causal mechanisms, not predictions of repeated outcomes. They show how different climate configurations can generate severe hydrological stress, while local hydrogeomorphic conditions determine where that stress becomes ecologically consequential. Their transferable lesson is diagnostic: regional climatic forcing identifies reasons for concern, but local mechanisms determine what should be investigated and whether management can alter the outcome.

The present analysis applies those mechanisms prospectively. The impact vectors identify ecological manifestations to investigate, buffering directs attention to the local conditions mediating their expression, and actionability asks whether an actor can alter the mechanism before the relevant outcome is fixed. This is more limited than forecasting mortality, which would require spatially resolved climatic, hydrological, geomorphic and ecological information not presently available at national scale. Prospective diagnosis instead organizes uncertainty around causal questions capable of changing a decision.

4.2 Applications to restoration and coastal management

Application begins by determining whether exposure reflects natural tidal position, limited freshwater influence, artificial hydrological restriction, restoration design or some combination. Porewater salinization or regeneration failure may indicate weak buffering, but neither establishes whether the underlying weakness is intrinsic or correctable.

Process-based restoration emphasizes identifying the physical constraints preventing recovery before planting or engineering is prescribed (Lewis, 2005). Adaptive approaches likewise treat evidence about hydrology and ecological response as a basis for changing implementation (Ellison et al., 2020). Visible impairment therefore justifies investigation; intervention requires evidence that a specified action can alter its cause.

This distinction avoids prioritizing either the most visibly stressed sites, where management may lack leverage, or activities that are easy to implement but ecologically inconsequential. The relevant target is the intersection of consequence and attainable improvement.

Developmental state affects both. Regeneration failure beneath mature forest may reduce recruitment while established vegetation and propagule sources remain intact; equivalent exposure in seedling-dominated restoration may threaten most of the developing ecosystem. Restoration outcomes vary with age, method and environmental setting (Su et al., 2021), while Indonesian opportunities are constrained by biogeomorphology, previous land use and land status (Sasmito et al., 2023). Young restoration may also be more actionable because managers retain control over planting schedules, site selection and project infrastructure.

Actionability must be assessed at the appropriate institutional scale. Projects may control restoration operations and local infrastructure; communities may influence waterways, ignition and natural regeneration; and government agencies may control land use and drainage networks. A mechanism inaccessible to one actor may remain actionable to another, provided authority and responsibility are identified before the intervention window closes.

4.3 Monitoring as prospective learning

The developing event creates an opportunity to evaluate relationships specified before the principal ecological outcome is known. Strong tests would compare sites experiencing similar regional forcing but differing in hydrological connectivity, freshwater influence, tidal position, developmental state or the availability of corrective action.

Monitoring should follow the causal structure:

climatic forcing → local hydroecological state → impact-vector expression → causal diagnosis → management decision → ecological outcome

Relevant observations include local hydrology, salinity, vegetation condition, recruitment or restoration survival, geomorphic setting and hydrological infrastructure. Intervention timing, responsible actor and intended outcome must also be recorded if management effectiveness is to be evaluated.

Monitoring becomes management-relevant when it distinguishes causal explanations or changes a decision. Salinity observations are more useful when related to rainfall, tidal exposure or a suspected restriction; seedling-survival observations become actionable when they indicate that continued deployment under the same conditions is unlikely to succeed. Spatial contrasts may reveal mechanisms that a single time series cannot.

Observation is not itself adaptation. Where no feasible intervention exists, it may support attribution and future site selection. Where a mechanism is actionable, monitoring should be linked to conditions that trigger a specified response. The event can thus improve present decisions while strengthening evidence for future extremes. Failure of the hypothesized relationships should prompt revision of the framework.

4.4 Limits and testable propositions

The analysis has five principal limitations.

First, the 2015–16 northern Australian dieback provides mechanistic evidence, not an Indonesian mortality function. Ecological and hydrogeomorphic conditions differ among coastlines, while regional climate indices cannot determine exposure at individual sites. The historical analogue and prospective forcing package identify conditions requiring observation, not a spatial prediction of impact.

Second, hydroecological buffering is an integrating concept rather than a validated universal index. Its components are measurable, but their relative importance will vary among settings, developmental stages and hazards. Actionability is likewise relational: it depends upon the mechanism, actor, authority, timing and outcome under consideration. Neither should be treated as a permanent site classification.

Third, attribution will remain difficult. Observed impairment may reflect climatic forcing, antecedent hydrological alteration, restoration design or interacting disturbances. Conversely, the absence of mapped forest loss does not establish the absence of functional impairment.

Fourth, the proposition that structural deterioration can weaken future buffering remains hypothetical. Vegetation loss may alter sediment and hydrological processes, but its magnitude and timing will vary. Early vector expression should not be interpreted as evidence that buffering itself has deteriorated.

Finally, intervention can create maladaptation. Hydrological modification may alter inundation, erosion or sedimentation, while poorly designed water-control measures and emergency planting can create new ecological problems. Anticipatory intervention must therefore follow causal diagnosis.

Within these limits, the framework generates four testable propositions:

1. Under comparable forcing, sites with weaker buffering should exhibit stronger expression of one or more impact vectors.
2. Among weakly buffered sites, those where artificial hydrological constraints amplify exposure should offer greater scope for intervention than those governed by intrinsic hydrogeomorphology.
3. Early impact-vector expression should improve causal diagnosis, while advanced structural deterioration should reduce the outcomes still alterable through intervention.
4. Equivalent exposure should produce stronger consequences in young restoration than in mature forest, particularly where restoration hydrology or site selection is already marginal.

These propositions are conditional; their failure should lead to revision of the framework rather than retrospective expansion of what counts as support.

4.5 Implications beyond the present event

Beyond the present El Niño, distinguishing hydroecological buffering from actionability can inform restoration planning before extreme conditions expose unsuitable assumptions. Separating intrinsic limitations from constraints created by infrastructure or implementation can improve site selection and focus monitoring on causes that management may be able to alter.

Climate-smart planning recognizes spatial differences in mangrove resilience (Dabalà et al., 2026). By asking why a system is vulnerable, which actor retains leverage over the relevant mechanism and whether intervention can still improve the outcome, the present analysis extends that perspective from long-term spatial prioritization toward event-scale management. Although other hazards will activate different ecological pathways, the distinction between exposure and actionable vulnerability remains applicable.

5. Conclusion: Anticipating Where Intervention Can Still Matter

The developing El Niño should not be interpreted as a uniform threat to Indonesian mangroves. Regional forcing becomes local ecological exposure through differences in hydroecological buffering, while the five impact vectors enable that exposure to be recognized before categorical forest loss occurs.

Vulnerability alone does not determine adaptation priority. Actionability identifies whether an actor can alter the mechanism producing exposure while meaningful outcomes remain preservable. Management should therefore protect autonomous processes, maintain existing buffering, exercise restraint where vulnerability is intrinsic and target constraints that remain correctable.

Extreme forcing can reveal weaknesses concealed under favourable conditions, but accumulating damage narrows the scope for effective intervention. The value of climate foresight lies not in predicting precisely where mangroves will fail, but in recognizing where failure may still be prevented or reduced.

References

Abhik, S., Hope, P., Hendon, H. H., Hutley, L. B., Johnson, S., Drosdowsky, W., Brown, J. R., & Duke, N. C. (2021). Influence of the 2015–2016 El Niño on the record-breaking mangrove dieback along northern Australia coast. *Scientific Reports, 11*, 20411. https://doi.org/10.1038/s41598-021-99313-w

Arnaud, M., Krause, S., Norby, R. J., Dang, T. H., Acil, N., Kettridge, N., Gauci, V., & Ullah, S. (2023). Global mangrove root production, its controls and roles in the blue carbon budget of mangroves. *Global Change Biology, 29*(12), 3256–3270. https://doi.org/10.1111/gcb.16701

Badan Meteorologi, Klimatologi, dan Geofisika. (2026, August 24). *Analisis dinamika atmosfer Dasarian II Agustus 2026*.

Carrasquilla-Henao, M., & Juanes, F. (2017). Mangroves enhance local fisheries catches: A global meta-analysis. *Fish and Fisheries, 18*(1), 79–93. https://doi.org/10.1111/faf.12168

Carwardine, J., Martin, T. G., Firn, J., Ponce Reyes, R., Nicol, S., Reeson, A., Grantham, H. S., Stratford, D., Kehoe, L., & Chadès, I. (2019). Priority Threat Management for biodiversity conservation: A handbook. *Journal of Applied Ecology, 56*(2), 481–490. https://doi.org/10.1111/1365-2664.13268

Dabalà, A., Brown, C. J., Van der Stocken, T., Buelow, C. A., Schoeman, D. S., Dunn, D. C., Lovelock, C. E., Dahdouh-Guebas, F., Flower, J., Neubert, S., Buenafe, K. C. V., Everett, J. D., Esturas, K. J. T., & Richardson, A. J. (2026). Safeguarding climate-resilient mangroves requires only a moderate increase in the global protected area. *Nature Communications, 17*, 2063. https://doi.org/10.1038/s41467-026-68877-4

Ellison, A. M., Felson, A. J., & Friess, D. A. (2020). Mangrove rehabilitation and restoration as experimental adaptive management. *Frontiers in Marine Science, 7*, 327. https://doi.org/10.3389/fmars.2020.00327

Field, R. D., van der Werf, G. R., Fanin, T., Fetzer, E. J., Fuller, R., Jethva, H., Levy, R., Livesey, N. J., Luo, M., Torres, O., & Worden, H. M. (2016). Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. *Proceedings of the National Academy of Sciences, 113*(33), 9204–9209. https://doi.org/10.1073/pnas.1524888113

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change, 23*(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Huijnen, V., Wooster, M. J., Kaiser, J. W., Gaveau, D. L. A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B., & van Weele, M. (2016). Fire carbon emissions over maritime Southeast Asia in 2015 largest since 1997. *Scientific Reports, 6*, 26886. https://doi.org/10.1038/srep26886

Irfan, M., Koriyanti, E., Saleh, K., Hadi, Safrina, S., Awaludin, Sulaiman, A., Akhsan, H., Suhadi, Suwignyo, R. A., Choi, E., & Iskandar, I. (2024). Dynamics of peatland fires in South Sumatra in 2019: Role of groundwater levels. *Land, 13*(3), 373. https://doi.org/10.3390/land13030373

Joseph, L. N., Maloney, R. F., & Possingham, H. P. (2009). Optimal allocation of resources among threatened species: A project prioritization protocol. *Conservation Biology, 23*(2), 328–338. https://doi.org/10.1111/j.1523-1739.2008.01124.x

Kementerian Lingkungan Hidup dan Kehutanan. (2020). *Rekapitulasi luas kebakaran hutan dan lahan per provinsi di Indonesia*. Direktorat Pengendalian Kebakaran Hutan dan Lahan.

Krauss, K. W., Lovelock, C. E., McKee, K. L., López-Hoffman, L., Ewe, S. M. L., & Sousa, W. P. (2008). Environmental drivers in mangrove establishment and early development: A review. *Aquatic Botany, 89*(2), 105–127. https://doi.org/10.1016/j.aquabot.2007.12.014

L'Heureux, M. L., Takahashi, K., Watkins, A. B., Barnston, A. G., Becker, E. J., Di Liberto, T. E., Gamble, F., Gottschalck, J., Halpert, M. S., Huang, B., Mosquera-Vásquez, K., & Wittenberg, A. T. (2017). Observing and predicting the 2015/16 El Niño. *Bulletin of the American Meteorological Society, 98*(7), 1363–1382. https://doi.org/10.1175/BAMS-D-16-0009.1

Lewis, R. R., III. (2005). Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering, 24*(4), 403–418. https://doi.org/10.1016/j.ecoleng.2004.10.003

Lovelock, C. E., Cahoon, D. R., Friess, D. A., Guntenspergen, G. R., Krauss, K. W., Reef, R., Rogers, K., Saunders, M. L., Sidik, F., Swales, A., Saintilan, N., Thuyen, L. X., & Triet, T. (2015). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature, 526*, 559–563. https://doi.org/10.1038/nature15538

Lovelock, C. E., Feller, I. C., Reef, R., Hickey, S., & Ball, M. C. (2017). Mangrove dieback during fluctuating sea levels. *Scientific Reports, 7*, 1680. https://doi.org/10.1038/s41598-017-01927-6

Lu, B., & Ren, H.-L. (2020). What caused the extreme Indian Ocean Dipole event in 2019? *Geophysical Research Letters, 47*, e2020GL087768. https://doi.org/10.1029/2020GL087768

McDowell, N. G., Ball, M. C., Bond-Lamberty, B., Kirwan, M. L., Krauss, K. W., Megonigal, J. P., Mencuccini, M., Ward, N. D., Weintraub, M. N., & Bailey, V. L. (2022). Processes and mechanisms of coastal woody-plant mortality. *Global Change Biology, 28*(20), 5881–5900. https://doi.org/10.1111/gcb.16297

Primavera, J. H., & Esteban, J. M. A. (2008). A review of mangrove rehabilitation in the Philippines: Successes, failures and future prospects. *Wetlands Ecology and Management, 16*(5), 345–358. https://doi.org/10.1007/s11273-008-9101-y

Sasmito, S. D., Basyuni, M., Kridalaksana, A., Saragi-Sasmito, M. F., Lovelock, C. E., & Murdiyarso, D. (2023). Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves. *Nature Ecology & Evolution, 7*(1), 62–70. https://doi.org/10.1038/s41559-022-01926-5

Su, J., Friess, D. A., & Gasparatos, A. (2021). A meta-analysis of the ecological and economic outcomes of mangrove restoration. *Nature Communications, 12*, 5050. https://doi.org/10.1038/s41467-021-25349-1

World Meteorological Organization. (2026, July 31). *Global Seasonal Climate Update for August–September–October 2026*.

Yokelson, R. J., Saharjo, B. H., Stockwell, C. E., Putra, E. I., Jayarathne, T., Akbar, A., Albar, I., Blake, D. R., Graham, L. L. B., Kurniawan, A., Meinardi, S., Ningrum, D., Nurhayati, A. D., Saad, A., Sakuntaladewi, N., Setianto, E., Simpson, I. J., Stone, E. A., Sutikno, S., Thomas, A., Ryan, K. C., & Cochrane, M. A. (2022). Tropical peat fire emissions: 2019 field measurements in Sumatra and Borneo and synthesis with previous studies. *Atmospheric Chemistry and Physics, 22*, 10173–10194. https://doi.org/10.5194/acp-22-10173-2022

Zhang, Z., Luo, X., Friess, D. A., & Li, Y. (2025). Global mangrove growth variability driven by climatic oscillation-induced sea-level fluctuations. *Nature Geoscience, 18*, 488–494. https://doi.org/10.1038/s41561-025-01701-8