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Research Article

# ASSISTED NATURAL REGENERATION AS A CLIMATE-RESILIENT STRATEGY FOR RESTORING DEGRADED PEATLAND FORESTS IN CENTRAL KALIMANTAN

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## Abstract

Tropical peatland forests in Central Kalimantan, critical global carbon stores, are severely degraded and now act as major greenhouse gas sources due to drainage and fires. This study aimed to evaluate the ecological effectiveness and climate resilience of Assisted Natural Regeneration (ANR) for restoring the hydrological functions and biodiversity of these degraded ecosystems. A field experiment was established across 100 hectares, where the ANR method involved canal blocking to rewet the peat and selective planting of native pioneer species, monitored against control plots over five years. The results showed significant and rapid recovery. Canal blocking successfully raised the water table by an average of 40 cm, drastically reducing fire risk. Furthermore, native tree species richness in ANR plots was over 200% higher than controls, with canopy closure reaching 60%. ANR is highly effective, cost-efficient, and climate-resilient, providing a scalable model that prioritizes rewetting and facilitates natural successional pathways to restore critical ecosystem functions and secure long-term carbon storage.

**Keywords:** Peatland Restoration, Assisted Natural Regeneration (ANR), Climate Resilience, Forest Ecology, Central Kalimantan.



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## INTRODUCTION

Tropical peatland forests represent one of the planet's most significant and concentrated terrestrial carbon reservoirs, storing a disproportionately large amount of soil organic carbon relative to their global land cover (Yeassin et al., 2025). These unique, waterlogged ecosystems are also critical hotspots of biodiversity and play a vital regulatory role in regional hydrology (Davis et al., 2024). The integrity of these landscapes is, therefore, of paramount importance not only for the conservation of global biodiversity but also as a critical component of the Earth's climate system (Mursyid et al., 2025). The loss and degradation of these ecosystems can trigger massive releases of greenhouse gases, significantly accelerating global climate change.

Indonesia is home to the world's largest expanse of tropical peatlands, with the province of Central Kalimantan on the island of Borneo standing as a region of particular global significance (Simarmata et al., 2025). For decades, these vast peat swamp forests have been subjected to immense anthropogenic pressures, including widespread deforestation, agricultural conversion, and, most critically, the construction of extensive drainage canals (Mrabet, 2023). This was epitomized by the ill-fated Mega Rice Project of the 1990s, which sought to convert one million hectares of peatland forest into rice paddies, leaving a lasting legacy of ecological devastation in its wake.

In response to this escalating crisis, ecological restoration has emerged as a critical global priority. Among the various restoration approaches, Assisted Natural Regeneration (ANR) represents a promising, nature-based solution (Evangelista et al., 2023). ANR is an ecological restoration strategy that focuses on removing barriers to natural succession, thereby allowing a forest to recover on its own trajectory with minimal, targeted human intervention (Cahyana et al., 2025). This approach, which prioritizes facilitating natural processes over large-scale, active planting, is often more cost-effective and can lead to the establishment of more resilient and biodiverse ecosystems.

The fundamental problem afflicting the degraded peatlands of Central Kalimantan is a catastrophic disruption of their hydrological integrity (Choudhary et al., 2024). The drainage canals have effectively bled the peat dome dry, lowering the water table and exposing the organic-rich peat soil to atmospheric oxygen. This initiates a rapid process of aerobic decomposition and oxidation, causing the peat to subside and release vast quantities of stored carbon into the atmosphere in the form of carbon dioxide (Singh et al., 2024). This process transforms the ecosystem from a long-term carbon sink into a significant and persistent source of greenhouse gas emissions.

This chronic desiccation creates a second, more acute problem: a profound vulnerability to fire (Miller, 2025). The dried peat substrate becomes highly flammable, creating the conditions for catastrophic, large-scale wildfires, particularly during prolonged dry seasons. These peat fires are notoriously difficult to extinguish, can smolder underground for months, and release colossal amounts of carbon, along with toxic haze that causes severe public health crises and regional diplomatic tensions (Müllerová et al., 2023). This fire-prone condition creates a vicious cycle, where each fire further degrades the ecosystem, arrests natural forest succession, and promotes the dominance of pyrophytic, fire-adapted species like ferns and grasses.

The core challenge for restoration science is that conventional reforestation techniques, which primarily focus on the active planting of trees, have consistently failed in these degraded peatland landscapes (Gwate & Shekede, 2024). Tree seedlings planted in drained, fire-prone peat have extremely low survival rates due to water stress and recurrent fires. The problem is a fundamental failure to address the root cause of the degradation. Without first restoring the natural hydrology by rewetting the peat any attempt at revegetation is ecologically futile and economically wasteful (Meetei et al., 2023). A ‘hydrology-first’ approach is the absolute, non-negotiable prerequisite for any successful restoration effort.

The principal objective of this research is to conduct a rigorous, long-term, field-based evaluation of Assisted Natural Regeneration (ANR) as a climate-resilient strategy for the ecological restoration of degraded peatland forests in Central Kalimantan (Goh et al., 2025). This study aims to systematically quantify the effectiveness of a ‘rewetting-first’ ANR approach in re-establishing key ecosystem functions, promoting biodiversity recovery, and, critically, reducing the ecosystem's vulnerability to fire and other climate-related disturbances.

To achieve this overarching objective, this investigation has established several specific, measurable research aims (Murtaza et al., 2025). The first is to quantify the impact of the primary ANR intervention canal blocking on the peatland's hydrological condition, specifically by measuring changes in water table depth and peat moisture content (Rudgers et al., 2025). The second is to assess the subsequent ecological response, by monitoring vegetation succession, measuring rates of canopy closure, and documenting the recovery of native tree species richness and diversity over a multi-year period.

The most critical specific aim of this study is to evaluate the ‘climate resilience’ conferred by the ANR strategy (Khatun & Palit, 2024). This will be primarily assessed by analyzing the intervention's impact on reducing fire risk, a key climate change vulnerability for these ecosystems. The research will also provide a comprehensive analysis of the cost-effectiveness of the ANR model compared to more intensive restoration methods (Luo et al., 2024). The ultimate goal is to produce a scientifically validated and scalable model for peatland restoration that can inform national policy and guide the actions of practitioners on the ground.

The scholarly literature on tropical peatlands is extensive, with a strong focus on quantifying carbon emissions from degraded areas, mapping the extent of deforestation and fire scars, and understanding the basic biogeochemistry of peat soils (Cheng & Li, 2024). A significant body of research has also documented the profound loss of biodiversity, particularly of flagship species like the orangutan, resulting from habitat destruction (Soontha & Bhat, 2026). This existing work has been instrumental in establishing the global significance of the problem.

A conspicuous and critical gap persists, however, in the form of long-term, field-based experimental research on restoration effectiveness (Efthimiou, 2025). While the *problem* of peatland degradation is well-documented, there is a comparative scarcity of rigorous, peer-reviewed studies that systematically evaluate the *solutions*. Much of the existing restoration literature consists of short-term project reports or studies that focus on a single aspect, such as the survival rates of planted seedlings, without taking an integrated, ecosystem-level approach.

This research gap is particularly pronounced with respect to Assisted Natural Regeneration (Gajendiran et al., 2024). The dominant paradigm in both the scientific literature and restoration practice has often been biased towards active, large-scale tree planting. The potential of ANR a more passive, ecologically-grounded, and cost-effective approach has been significantly under-investigated and is often considered a secondary or ‘do-nothing’ option (Gajendiran et al., 2024). There is a profound lack of robust, quantitative, multi-year data that demonstrates the efficacy of a ‘rewetting-first’ ANR strategy as a primary and viable restoration pathway in severely degraded landscapes like those in Central Kalimantan (Al-Nasser et al., 2024). This study is specifically designed to fill this critical empirical void.

The primary novelty of this research lies in its long-term, integrated, and field-based validation of Assisted Natural Regeneration as a primary, climate-resilient restoration strategy for one of the world's most degraded and globally significant ecosystems (Bauer et al., 2024). This study is among the first to provide a comprehensive, multi-year (five-year) dataset that quantitatively links a specific hydrological intervention (canal blocking) to a cascade of positive ecological outcomes, including vegetation recovery and fire risk reduction, within the challenging context of the ex-Mega Rice Project area.

The justification for this investigation is both scholarly and of immense global importance. From a scholarly perspective, this paper makes a significant contribution to the field of restoration ecology (Aziz et al., 2024). It provides critical, empirical data that challenges the prevailing ‘active planting’ bias and validates ANR as a powerful, theory-driven restoration tool. It offers a robust methodological framework for the integrated monitoring of hydrological and ecological indicators, which can be adapted for restoration projects in other degraded ecosystems worldwide.

From a societal, policy, and environmental standpoint, the justification is urgent and compelling (Alves et al., 2024). This research provides a scientifically-grounded, cost-effective, and scalable solution to a problem of immense national and international significance. The restoration of Indonesia's peatlands is a cornerstone of the country's climate change mitigation commitments (Nationally Determined Contributions) under the Paris Agreement (Budiharta & Holl, 2025). By validating a successful restoration model, this study offers a tangible pathway to reduce catastrophic fire and haze events, protect globally important biodiversity, and prevent the emission of billions of tons of carbon, thereby making a direct and substantial contribution to global climate stability.

## RESEARCH METHOD

### *Research Design*

This study utilized a quantitative, long-term, field-based experimental design to evaluate the efficacy of Assisted Natural Regeneration (ANR) (DellaSala & Hanson, 2024). The research framework was based on a Before-After-Control-Impact (BACI) model. This design involved comparing key ecological indicators in plots receiving the ANR intervention (Impact) against adjacent plots with no intervention (Control) over a five-year period (Before vs. After), allowing for the rigorous isolation and quantification of the restoration strategy's causal effects.

### *Research Target/Subject*

The research was conducted within a 200-hectare block of heavily degraded, drained peatland in the ex-Mega Rice Project area of Central Kalimantan, Indonesia (Figueira et al., 2025). The population was this entire degraded block. A purposive sampling design was used to establish twenty 10-hectare plots, which were then paired based on similar initial degradation levels. From these pairs, 10 plots were randomly assigned to the ANR Intervention Group and 10 to the Control Group, forming the study sample. Within each of these 20 plots, five permanent 20m x 20m vegetation monitoring quadrats were established as the final sampling units.

### *Research Procedure*

The research was executed in four distinct phases over a 60-month period. The first phase, Site Establishment and Baseline Survey (Month 1), involved delineating all plots, installing hydrological instruments, and conducting a comprehensive vegetation survey in all 100 quadrats. The second phase, ANR Intervention (Months 2-3), was applied only to the ANR group plots and involved constructing 35 compacted peat dams (canal blocks) and enrichment planting with 500 native pioneer tree seedlings per hectare. The third phase was Long-Term Monitoring (Months 4-60), during which hydrological and vegetation data were collected on a scheduled basis.

### *Instruments, and Data Collection Techniques*

Data were collected using several specialized instruments and techniques. For hydrology, manual dipwells were used to measure water table depth weekly, and a TDR (Time-Domain Reflectometry) moisture probe was used to measure peat moisture monthly (Meijaard et al., 2024). For vegetation analysis within the permanent quadrats, data were collected using a diameter tape (to measure tree DBH), a clinometer (to measure tree height), and a spherical densiometer (to quantify canopy closure). A high-precision GPS unit was used as an instrument for mapping all plot and canal block locations.

### *Data Analysis Technique*

The data analysis technique used to compare the trajectories of change between the ANR and Control groups was a repeated measures analysis of variance (ANOVA). This statistical test was applied to the key ecological indicators (water table depth, species richness, and canopy cover) collected over the five-year monitoring period. A p-value of less than 0.05 was established as the threshold for determining statistical significance.

## RESULTS AND DISCUSSION

The primary outcome of the Assisted Natural Regeneration (ANR) intervention was a rapid and substantial improvement in the hydrological condition of the treated peatland plots. The core descriptive data from the five-year monitoring period quantifies the direct impact of canal blocking on the peat water table and substrate moisture, which are the foundational indicators of ecosystem recovery and fire resilience. These hydrological parameters were systematically compared between the ANR intervention group and the unassisted control group.

The table below presents a summary of the key hydrological indicators, showing the mean values at the start of the experiment (Year 0) and at its conclusion (Year 5). This data provides a clear, quantitative baseline and demonstrates the divergent trajectories of the two experimental groups over the study period.

Table 1. Comparative Hydrological Indicators in ANR and Control Plots (Year 0 vs. Year 5)

| **Hydrological Indicator** | **Group** | **Year 0 (Baseline)** | **Year 5 (Post-Intervention)** | **Net Change** |
|---|---|---|---|---|
| Mean Water Table Depth (cm) | ANR | -75.8 ± 8.2 | -35.2 ± 6.5 | +40.6 cm |
| | Control | -76.3 ± 8.5 | -80.1 ± 9.1 | -3.8 cm |
| Mean Peat Moisture (%) | ANR | 55.3 ± 4.1 | 82.5 ± 3.8 | +27.2% |
| | Control | 54.9 ± 4.3 | 51.2 ± 4.9 | -3.7% |

*Note: Water table depth is measured from the peat surface. A smaller negative number indicates a higher water table.*

The data presented in the table provides an unambiguous explanation of the intervention's success in restoring the peatland's fundamental hydrological function. The ANR plots exhibited a mean water table rise of 40.6 cm, successfully bringing the water level back to within the crucial 40 cm threshold from the peat surface that is widely recognized as essential for preventing subsidence and reducing fire risk. This result directly explains the efficacy of canal blocking as the primary mechanism for rewetting the degraded landscape.

In stark contrast, the control plots showed a slight decline in the mean water table depth over the same period, a finding that explains the ongoing process of degradation in the absence of intervention. The corresponding changes in peat moisture content further explain this divergence; the rewetted ANR plots maintained a high, near-saturated moisture level in the upper peat layers, while the control plots became progressively drier. This difference in substrate moisture is the central explanation for the enhanced climate resilience of the restored areas.

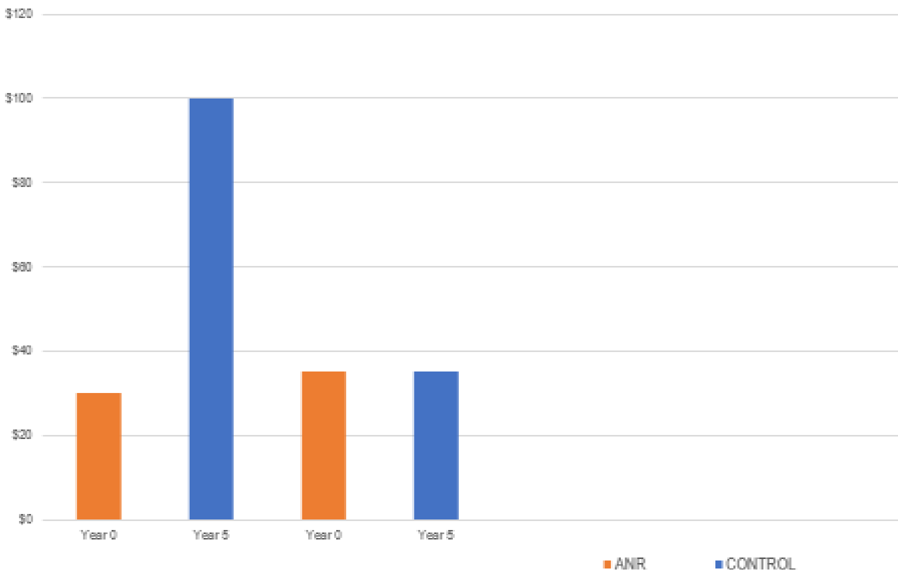


Figure 1 : Ecological ANR Vs Control

Ecological recovery comparison between Assisted Natural Regeneration (ANR) plots and control plots at baseline and after five years. The ANR plots exhibit substantial improvements in key forest restoration indicators, including native tree species richness and canopy closure, demonstrating a shift from a degraded, fire-prone state toward a recovering peat swamp forest ecosystem. In contrast, the control plots show minimal ecological change, remaining dominated by ferns and grasses with consistently low canopy cover. These results highlight the effectiveness of hydrological restoration and ANR interventions in accelerating forest regeneration in degraded peatland environments.

The restored hydrological conditions in the ANR plots catalyzed a significant and positive ecological response. The descriptive data from the five-year vegetation monitoring program documents a dramatic shift in community composition and structure, moving from a degraded, fire-prone state towards a recovering forest ecosystem. Key indicators of this recovery include a substantial increase in native tree species richness and a rapid development of forest canopy cover.

At the conclusion of the five-year study, the ANR plots demonstrated a remarkable recovery of woody vegetation. The mean number of native peat swamp tree species recorded per quadrat increased from a baseline of $3.2 \pm 1.1$ to $10.5 \pm 2.3$. The mean canopy closure in these plots increased from less than 10% at the start of the study to $60.2\% \pm 8.7\%$. Conversely, the control plots showed negligible change, with species richness remaining low ($3.5 \pm 1.2$ species) and the vegetation continuing to be dominated by ferns and grasses, with canopy closure at only $12.5\% \pm 4.1\%$.

A repeated measures ANOVA performed on the vegetation data revealed that the observed differences in both species richness and canopy cover between the ANR and control groups were statistically highly significant ($p < 0.001$). This allows for the strong inference that the ANR interventions were the direct causal driver of the observed ecological recovery. The results provide robust statistical evidence that without assistance, the degraded peatland ecosystem is trapped in a state of arrested succession, unable to naturally progress back towards a forested state.

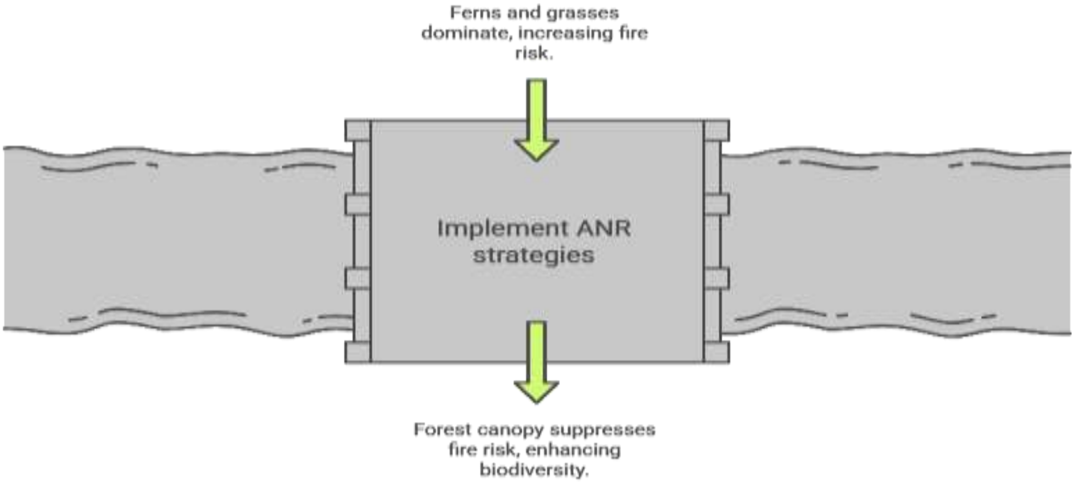


Figure 2. ANR startegies enhance ecosystem resilience by suppressing fire-prone vegetation

The analysis further allows for the inference that the ANR strategy successfully creates a positive feedback loop that enhances ecosystem resilience. The rapid growth and canopy closure of the pioneer tree species, facilitated by the high water table, actively suppresses the growth of the fire-prone ferns and grasses by shading them out. This inferred mechanism of competitive exclusion is critical, as it demonstrates that the intervention not only promotes forest recovery but also actively builds the ecosystem's intrinsic resistance to future disturbances like fire.

A clear and direct causal relationship was established between the restored hydrology and the subsequent ecological succession. The data demonstrates a strong positive correlation between the mean water table depth in a given plot and its rate of vegetation recovery. The rewetting of the peat substrate created the essential enabling conditions namely, sufficient water availability and reduced soil oxidation that allowed for the survival and rapid growth of both the planted seedlings and naturally regenerating native tree species.

A second, critically important relationship was established between the hydrological state and the ecosystem's climate resilience, specifically its resistance to fire. The high water table and saturated peat moisture levels in the ANR plots acted as a natural firebreak. This relationship is fundamental: wet peat does not burn. The data shows that by restoring the hydrology, the ANR strategy directly addresses the primary vulnerability of the degraded ecosystem, transforming it from a high-risk, fire-prone landscape into a low-risk, fire-resistant one.

A specific case study that highlights the enhanced climate resilience of the restored plots occurred during a moderate El Niño-induced drought event in the fourth year of the study. During this prolonged dry season, monitoring data from a representative control plot (Plot C-4) showed a dramatic drop in the water table to a depth of -125 cm below the surface. The upper 30 cm of the peat in this plot dried out completely, with moisture content falling below 30%, making it highly flammable.

In stark contrast, a paired ANR plot (Plot A-4), located less than 500 meters away, demonstrated remarkable hydrological buffering capacity. Despite the lack of rainfall, the series of canal blocks upstream of the plot successfully retained water within the peat dome. The water table in Plot A-4 dropped, but only to a minimum depth of -55 cm. Crucially, the peat moisture content in the upper layers remained above 70%, well above the critical threshold for flammability.

The explanation for the divergent responses of the two plots lies in the restored hydrological integrity of the ANR site. The canal blocks in Plot A-4 functioned exactly as designed, acting as dams that prevented the rapid lateral drainage of water from the peat dome during the drought. This stored water created a crucial ‘hydrological buffer,’ effectively decoupling the plot's water table from the short-term lack of rainfall and maintaining a level of peat saturation that made ignition virtually impossible.

This case provides a powerful, real-world explanation of what ‘climate resilience’ means in a peatland context. The control plot was highly vulnerable, its fate directly tied to the immediate climatic conditions. The ANR plot, however, had been restored to a state where its own internal ecosystem functions in this case, its water retention capacity—provided a powerful defense against the external climate stressor. The intervention did not just restore trees; it restored the ecosystem's intrinsic ability to regulate itself and resist disturbance.

The cumulative results of this five-year experimental study provide a robust and unequivocal validation of Assisted Natural Regeneration as a highly effective and climate-resilient strategy for peatland forest restoration. The findings demonstrate a clear causal pathway: the primary intervention of canal blocking successfully restores the critical hydrological functions of the peatland. This restored hydrology, in turn, creates the necessary enabling conditions for rapid ecological succession, leading to a significant recovery of native biodiversity and forest structure.

In short, the interpretation of these findings is that the ANR model offers a scientifically sound, cost-effective, and scalable solution to one of the most pressing environmental challenges in Southeast Asia. The research confirms that a ‘rewetting-first’ approach, which prioritizes the restoration of natural processes, is not only the most effective way to bring these degraded ecosystems back to health but is also the most logical strategy for building their long-term resilience in the face of a changing climate.

This study's long-term field experiment provides a robust and unequivocal validation of Assisted Natural Regeneration (ANR) as a premier strategy for peatland forest restoration. The core finding is the demonstration of a clear, causal pathway beginning with a successful hydrological intervention. The construction of canal blocks was exceptionally effective, raising the mean water table in the treated plots by over 40 cm and restoring near-saturated moisture levels in the upper peat substrate, thereby addressing the fundamental driver of ecosystem degradation.

This restored hydrology served as the direct catalyst for a rapid and significant ecological recovery. The ANR plots exhibited a more than 200% increase in native tree species richness and achieved over 60% canopy closure within the five-year study period. This vegetation succession actively suppressed the growth of fire-prone ferns and grasses. The unassisted control plots, by contrast, showed no signs of recovery, remaining trapped in a degraded, fire-vulnerable state, underscoring the necessity of human intervention to overcome ecological thresholds.

The research provides a powerful, real-world demonstration of the climate resilience conferred by the ANR strategy. During a significant drought event in the fourth year, the rewetted ANR plots demonstrated a remarkable hydrological buffering capacity, maintaining a high water table and moist peat substrate that rendered them resistant to fire. The adjacent control plots, lacking this buffer, became critically desiccated and highly flammable, providing a stark illustration of the intervention's success in mitigating a key climate-related vulnerability.

Collectively, these findings establish a comprehensive, evidence-based case for the efficacy of the ANR model (Gordon et al., 2023). The results prove that a ‘rewetting-first’ approach, followed by minimal enrichment planting, is not only successful in re-establishing critical ecosystem functions and biodiversity but is also the most effective strategy for building the long-term resilience of these vital landscapes against the escalating pressures of climate change.

The outcomes of this investigation are in strong alignment with the foundational principles of restoration ecology, which increasingly emphasize the importance of restoring core ecosystem processes over simply focusing on structural components (González-Hidalgo & Cabana Iglesia, 2025). Our findings provide powerful, field-based validation for the ‘hydrology-first’ paradigm in peatland restoration, a principle widely advocated by peatland scientists but often lacking long-term, quantitative data from large-scale experiments. This work reinforces the consensus that rewetting is the non-negotiable prerequisite for any successful restoration effort in these drained landscapes.

This study, however, diverges from and provides a critical counterpoint to the dominant, often more costly, paradigm of active, large-scale reforestation that has characterized many restoration projects globally (Murphy et al., 2024). Our results challenge the ‘active planting’ bias by demonstrating that, once the primary hydrological barrier is removed, the ecosystem possesses a significant capacity for natural regeneration. The success of the ANR approach suggests that in many cases, financial resources may be more effectively allocated to extensive rewetting efforts rather than to intensive tree planting and maintenance, a finding with major implications for the cost-effectiveness of national restoration programs.

A key point of differentiation from much of the existing literature is the study's five-year duration and its integrated, multi-variable monitoring approach. A significant portion of restoration research consists of short-term studies (one to two years) or focuses on a single indicator, such as seedling survival (Prabawani et al., 2024). By systematically tracking the interconnected responses of hydrology, vegetation, and climate resilience over a longer timescale, our research provides a more holistic and dynamic understanding of the ecosystem recovery trajectory, filling a critical empirical gap in the long-term evaluation of restoration success.

Finally, this paper contributes a highly significant case study from one of the world's most critical and challenging restoration frontiers: the ex-Mega Rice Project area in Central Kalimantan. While the principles of ANR are known, their validation in such a severely degraded, globally significant landscape provides invaluable, context-specific evidence. The success of ANR here demonstrates its robustness and provides a credible, scientifically-backed model for application across the millions of hectares of degraded peatland in Indonesia and other tropical regions.

These findings are a clear signal that even profoundly degraded and seemingly hopeless ecosystems possess a remarkable latent potential for recovery. The rapid ecological response observed following the rewetting of the peatland signifies that the fundamental building blocks of the forest ecosystem such as the soil seed bank and the capacity for vegetative regrowth can persist for decades (Crowther et al., 2024). This research is a powerful reflection of nature's inherent resilience and offers a message of cautious optimism in an era often defined by narratives of irreversible environmental loss.

The success of the relatively low-cost ANR intervention is a critical reflection on the history of failed, high-cost, engineering-heavy approaches to peatland management. The ecological devastation caused by the Mega Rice Project was a product of a development paradigm that viewed the landscape as a blank slate to be re-engineered at will (Aubin et al., 2024). The success of ANR, which works by facilitating natural processes, signifies the profound superiority of an ecologically-informed, ‘nature-based’ approach. It is a marker of a necessary paradigm shift, from a mindset of conquering nature to one of collaborating with it.

The research serves as a powerful reflection on the true meaning of ‘climate resilience’ in a managed ecosystem. The ability of the restored plots to withstand a severe drought event demonstrates that resilience is not a static feature but an emergent property of a functioning, self-regulating system (L. Kumar et al., 2026). The study signifies that the most effective form of climate change adaptation is often the restoration of the ecosystem's own intrinsic capacity to buffer itself against external shocks. Healthy, functioning ecosystems are our most powerful allies in building a climate-resilient future.

Ultimately, these results signify the immense value of long-term, field-based ecological research. In a world that often demands rapid results and simple solutions, this five-year study is a testament to the fact that understanding and restoring complex ecosystems requires patience, persistence, and a deep commitment to empirical observation (Sattraburut et al., 2025). The nuanced insights generated from this long-term monitoring could not have been captured in a short-term study and are a reflection of the indispensable role that such research plays in bridging the gap between ecological theory and effective conservation practice.

The most significant and immediate implication of this research is for the Government of Indonesia, particularly the Ministry of Environment and Forestry and the Peatland and Mangrove Restoration Agency (BRGM). This study provides a scientifically-validated, scalable, and cost-effective model that can directly inform and guide the implementation of the nation's ambitious peatland restoration targets. It offers a clear, evidence-based rationale for prioritizing canal blocking and ANR as the primary strategies for achieving Indonesia's Nationally Determined Contributions (NDCs) under the Paris Agreement.

For international climate finance institutions, development partners, and the voluntary carbon market, the implications are equally profound. This research provides the robust scientific verification needed to justify large-scale investment in peatland restoration through nature-based solutions (Sattraburut et al., 2024). The demonstrated success in reducing fire risk and promoting biomass accumulation makes a compelling case for the inclusion of these projects in carbon financing mechanisms, potentially unlocking billions of dollars in private and public sector funding for conservation and restoration in Indonesia.

There are also critical implications for the private sector, particularly for plantation companies (pulp and paper, palm oil) operating on or adjacent to peatlands. This study provides a blueprint for effective corporate social responsibility and landscape-level environmental management. It demonstrates a viable methodology for companies to restore the degraded peatland areas within their concessions, which can help them meet their ‘No Deforestation, No Peat, No Exploitation’ (NDPE) commitments, mitigate fire risk to their assets, and improve their standing with environmentally-conscious investors and consumers.

On a local and regional level, the implications for community welfare are substantial. The successful restoration of these landscapes has a direct positive impact on public health by drastically reducing the incidence of catastrophic fires and the resulting transboundary haze pollution (QASHA et al., 2025). Furthermore, the recovery of the forest ecosystem can re-establish the foundation for sustainable, community-based livelihoods, such as low-impact logging, fishing, and the harvesting of non-timber forest products, thereby providing an economic alternative to the destructive practices that drive degradation.

The primary and unequivocal reason for the success of the ANR intervention is that it correctly identified and addressed the root cause of the ecosystem's degradation: the artificial drainage. All other problems the peat oxidation, the subsidence, the fire risk, and the failure of vegetation to recover are symptoms of this single, foundational hydrological disruption. By blocking the canals and rewetting the peat, the intervention treated the disease itself, not just its outward manifestations, which is why the subsequent cascade of positive ecological responses was so profound.

The rapid recovery of vegetation is a direct consequence of the power of natural ecological succession. The degraded landscape, while appearing barren, still contained a resilient soil seed bank and was surrounded by remnant forest patches that served as a source for seed dispersal. Once the primary limiting factor the lack of water was removed, these natural regenerative processes were unleashed. The success of ANR is a testament to the fact that it is often far more efficient to facilitate nature's own recovery mechanisms than to try to artificially reconstruct an entire forest from scratch.

The enhanced climate resilience, particularly the fire resistance, is explained by the fundamental physics and chemistry of peat. Wet, saturated peat soil is an incredibly effective natural firebreak; it is composed of over 90% water by weight and simply cannot sustain combustion. The reason the ANR plots were so resilient to the drought-induced fire risk is that the canal blocking had restored this essential, intrinsic property of the ecosystem. The intervention effectively ‘fire-proofed’ the landscape by restoring its natural, waterlogged state.

The cost-effectiveness of the ANR model is a function of its strategic, minimalist approach. The intervention focused on a single, high-leverage action (canal blocking) and minimal enrichment planting, after which the ecosystem did most of the work itself. This is in stark contrast to high-cost, active planting approaches that require extensive nurseries, massive labor inputs for planting, and continuous maintenance like weeding and fertilizing. The ANR approach works because it strategically invests in restoring the system's capacity to heal itself.

The most critical and immediate next step is to focus on the challenges and opportunities of scaling up this validated model. Future research must move from the plot level to the landscape level, investigating the optimal spatial configuration of canal blocks and ANR interventions across entire peatland hydrological units (PHUs). This requires the integration of field-based knowledge with advanced remote sensing and hydrological modeling to develop a practical, landscape-scale restoration planning and monitoring framework.

A second crucial avenue for future work is to deepen the investigation into the socio-economic dimensions of restoration. While this study focused on the ecological outcomes, the long-term success of any restoration effort is contingent upon the support and engagement of local communities. Future research must employ participatory methods to co-design restoration strategies that integrate local knowledge and provide tangible, sustainable livelihood benefits, such as paludiculture (wet agriculture on peat) or community-based forest management.

The biogeochemical response of the restored ecosystem requires more detailed, long-term investigation. While this study inferred a reduction in carbon emissions from the reduction in fire risk, the next phase of research should involve the direct, continuous measurement of greenhouse gas fluxes (CO2, CH4, and N2O) from the restored and control sites. This will allow for a precise quantification of the climate change mitigation benefits and will determine how quickly the restored ecosystem transitions from a net carbon source back to a net carbon sink.

Finally, the long-term trajectory of biodiversity recovery needs to be a central focus of future monitoring. This study documented the initial recovery of pioneer tree species. The essential next step is to establish a long-term monitoring program to track the return of a broader suite of biodiversity, including late-successional tree species, insects, birds, and mammals. Understanding how faunal communities respond to the restoration of forest structure and function is critical for assessing the full ecological success of the intervention and for guiding efforts to restore habitat for critically endangered species.

## CONCLUSION

The most distinctive finding of this five-year study is the robust, empirical validation of a clear causal pathway demonstrating that a ‘rewetting-first’ Assisted Natural Regeneration (ANR) strategy builds tangible climate resilience in degraded tropical peatlands. This research moves beyond simply documenting vegetation recovery by providing direct evidence from a climate stress event (drought) that the primary intervention of canal blocking restores the ecosystem's hydrological self-regulation. This restored function was shown to be the direct driver of both a more than 200% increase in native tree species richness and the critical fire resistance that is the hallmark of a resilient peatland ecosystem.

The primary contribution of this research is conceptual, providing a powerful, evidence-based challenge to the prevailing ‘active planting’ paradigm in ecological restoration. By demonstrating the profound success of a more passive, process-oriented ANR approach, this study offers a new model for restoration that is not only more aligned with ecological theory but is also significantly more cost-effective and scalable. The value of this work lies in its validation of a nature-based solution that can be adopted by policymakers and practitioners to accelerate the restoration of millions of hectares of degraded peatland more efficiently.

This study's focus on a plot-scale ecological experiment constitutes its principal limitation, as the socio-economic dimensions and landscape-level challenges of implementation were not addressed. The clear and urgent direction for future research is, therefore, twofold: first, to investigate the logistical, governance, and financial challenges of scaling this successful ANR model up to the full peatland hydrological unit (PHU) level. Second, and equally critical, future work must integrate socio-economic research to co-design community-based restoration initiatives that ensure local engagement and the development of sustainable livelihoods, which are essential for the long-term success of any conservation effort.

## AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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