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Beyond Tenure: A Quasi-Experimental Causal Analysis of Community Forest Management on Peatland Biodiversity, Carbon Stocks, and Management Efficacy in Sumatra

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A B S T R A C T

Indonesia's Hutan Desa (HD, Village Forest) program is a cornerstone of global social forestry, yet its causal ecological impacts remain contested. Rigorous, counterfactual-based evidence is urgently needed to validate this policy intervention, particularly in globally critical peat-swamp landscapes. This study employed a quasi-experimental design, using Propensity Score Matching (PSM) to construct a statistically balanced sample of 40 HD (treatment) and 40 non-HD (control) village units in Sumatran peatlands. We analyzed data from 400 1-hectare permanent sample plots (5 plots nested per village). We assessed floral diversity (Shannon-Wiener Index, H'), faunal presence, and ecosystem carbon stocks (Above-Ground, AGB; Soil Organic Carbon, SOC). Causal impacts were quantified using Linear Mixed-Effects Models (LMMs) to account for the nested data structure. We further analyzed the "treatment effect" by modeling dose-response relationships for permit duration and management intensity. After matching, LMMs revealed that HD management has a significant positive causal effect on all ecological outcomes. Floral diversity was significantly higher in HD plots (H' = 2.92) versus control plots (H' = 2.18; $F(1, 78) = 48.21$, $p < 0.001$). Total ecosystem carbon stocks (AGB + SOC in top 100cm) were 36% higher in HD units (255.1 Mg C ha^{-1}) compared to controls (187.3 Mg C ha^{-1}; $F(1, 78) = 53.09$, $p < 0.001$). This was driven by a significant preservation of SOC. Dose-response models further showed that ecological benefits (such as AGB) accumulate significantly with increased permit duration and that higher management intensity is a strong predictor of biodiversity. In conclusion, our findings provide robust, hierarchical evidence that HD management is an effective conservation and climate mitigation strategy. By establishing tenure, enabling active stewardship, and, crucially, protecting peatland hydrology, the HD model delivers verifiable, causal improvements to biodiversity and carbon stocks.

1. Introduction

The global community faces a 'twin crisis' of accelerating biodiversity loss and profound climate change. These crises are inextricably linked, with the degradation of natural ecosystems both driving biodiversity collapse and hampering climate regulation.[1] Tropical forests, which harbor over two-thirds of terrestrial biodiversity and store vast quantities of carbon, are at the epicentre of this challenge. Within the tropics, peat-swamp forests represent a uniquely critical and vulnerable ecosystem. These waterlogged landscapes store a disproportionately large amount of global soil carbon, estimated at over 600 Gt CO_2e, accumulated over millennia.[2]

The island of Sumatra in Indonesia exemplifies this challenge. Sumatran peat-swamp forests have experienced some of the world's most rapid rates of deforestation and degradation, driven primarily by state-led industrial logging concessions, followed by catastrophic conversion to agricultural monocultures (primarily oil palm and pulp/paper plantations).[3] This conversion process, which relies on extensive drainage of the peat, initiates a devastating cascade of irreversible subsidence, massive and persistent carbon emissions from peat oxidation, and a dramatic increase in fire risk. The resulting habitat loss has pushed endemic species such as the Sumatran tiger (*Panthera tigris sumatrae*), orangutan (*Pongo abelii*), and elephant (*Elephas maximus sumatranus*) to the brink of extinction, while the carbon released from drained peatlands positions Indonesia as a leading global greenhouse gas emitter.[4]

In response to this multifaceted crisis, and in alignment with global commitments such as the Paris Agreement and the UN Sustainable Development Goals (SDGs), the Government of Indonesia has initiated ambitious policy reforms. A central pillar of this reform is the *Perhutanan Sosial* (Social Forestry) program. This policy aims to reallocate 12.7 million hectares of the state forest estate to community-based management by 2030. This program represents a fundamental paradigm shift away from a centralized, top-down, and often exclusionary state-led industrial forestry model, moving towards a decentralized, polycentric, and community-centric governance model.[5]

Within the Perhutanan Sosial umbrella, *Hutan Desa* (HD, Village Forest) is a key and rapidly expanding scheme. The HD model grants a 35-year (renewable) forest management right (IUPHKm) to a formally recognized village-level institution, the Lembaga Pengelola Hutan Desa (LPHD, Village Forest Management Body).[6] The theoretical premise of the HD model is rooted in socio-ecological systems (SES) theory. This theory posits that sustainable resource management is most likely to emerge when local resource users (the community) possess clearly defined rights and secure, long-term tenure. This tenure security incentivizes stewardship, allowing communities to adapt management rules to the local ecological context, monitor outcomes, and sanction infractions.[7]

In theory, the HD permit is a transformative intervention. It re-casts the village community from *de facto* encroachers or passive observers into *de jure* stewards of the forest resource. With secure tenure, the LPHD is legally empowered and economically incentivized to protect its forest asset from both external threats (such as illegal logging, corporate encroachment, and fire) and internal pressures (such as agricultural conversion by community members).[8] The potential for long-term income derived from non-timber forest products (NTFPs), ecotourism, and payments for ecosystem services (such as REDD+) is intended to align local economic incentives with global conservation outcomes. This dynamic interplay between the social system (village governance, LPHD capacity, tenure rights, livelihood strategies) and the ecological system (the forest's biodiversity, peatland hydrology, carbon stocks) is the "socio-ecological system in action" that this study investigates.

Despite the program's rapid expansion and the optimistic policy narratives surrounding it, a critical knowledge gap persists. Does the Hutan Desa model cause better ecological outcomes? Or, as has been suggested, are HD permits, as a matter of political or administrative convenience, simply being granted to villages that already possess intact, well-managed forests. If the latter is true, the program is merely protecting the protected, rather than actively preventing degradation, and scaling the program will not achieve the desired conservation goals.

The vast majority of existing research on Indonesian social forestry is either qualitative (providing rich, in-depth case study insights but lacking landscape-scale generalizability) or quantitative but correlational (comparing HD and non-HD sites without adequately controlling for pre-existing confounding variables).[9] Simple comparative studies, for example, are highly susceptible to confounding. If HD villages are systematically located further from roads or on steeper slopes than non-HD villages, their lower deforestation rates may be attributable to this biophysical inaccessibility (a covariate) rather than the management regime itself. To provide credible advice to policymakers, justify the massive national and international investment in this program, and understand why it succeeds or fails, it is imperative to move beyond correlation and assess the *causal impact* of the HD intervention. This requires a rigorous, counterfactual-based research design that can isolate the "treatment effect" of the HD permit from the myriad of other biophysical and socio-economic factors that influence forest health.[10]

This study addresses this critical knowledge gap by employing a rigorous multi-stage, quasi-experimental approach. We combine Propensity Score Matching (PSM) to create a statistically robust counterfactual with hierarchical Linear Mixed-Effects Models (LMMs) to quantify the causal ecological efficacy of the Hutan Desa program in Sumatran peat-swamp landscapes. The specific objectives of this research are: (1) To quantify the causal impact (the Average Treatment Effect on the Treated, ATT) of *Hutan Desa* management on terrestrial flora biodiversity, measured by species richness, diversity (Shannon-Wiener Index), and evenness (Pielou's J-Index); (2) To assess the ATT of HD management on ecosystem carbon stocks, by comparing above-ground biomass (AGB) and, critically, soil organic carbon (SOC) in HD and matched control sites; (3) To "open the black box" of the treatment effect by moving beyond a simple binary analysis and modeling dose-response relationships for (a) the duration of the HD permit and (b) the measured intensity of local management; (4) To link these empirical ecological outcomes to Indonesia's progress on UN SDG 15.1 (Life on Land), thereby providing robust, data-driven insights for national and international policy.

The novelty of this study is threefold. First, it applies a quasi-experimental, counterfactual-based design to quantify *simultaneous* biodiversity and carbon impacts, including the often-neglected but dominant peat soil carbon pool. Second, it rectifies a common methodological flaw in field studies by using Linear Mixed-Effects Models to correctly analyze nested plot data, ensuring the statistical validity of our findings. Third, and most significantly, it moves beyond a simple "treatment vs. control" analysis to explore the dose-response mechanisms of *why* the program works, linking outcomes to both permit duration and active management intensity. By isolating the causal effects of the HD management regime, this research provides robust, defensible evidence of the program's socio-ecological efficacy.

2. Methods

This study was conducted in the provinces of Jambi and Riau on the island of Sumatra, Indonesia. These provinces were selected as they represent the epicenter of Indonesia's social forestry expansion, host some of the world's largest and most threatened peat-swamp forest areas, and exhibit high historical rates of deforestation. The study landscape is a complex mosaic of intact and degraded peat-swamp forests, remnant lowland dipterocarp forests, industrial oil palm and pulpwood concessions, and smallholder agriculture. This heterogeneity provides the necessary variation in management regimes, ecological conditions, and socio-economic drivers to construct a robust quasi-experimental study.

To overcome selection bias and construct a valid counterfactual, we employed a quasi-experimental design based on Propensity Score Matching (PSM). This method allows us to construct a statistically valid control group by matching "treatment" units (villages with an HD permit) with "control" units (villages without an HD permit) that share a highly similar set of observable, pre-treatment characteristics. The unit of analysis for the matching procedure was the village (desa); (1) Treatment Group (HD): We created a sampling frame of all villages in Jambi and Riau that had received an official *Hutan Desa* permit between 2010 and 2018 ($N \approx 110$). This timeframe was selected to ensure the "treatment" had been in place for a sufficient duration (minimum 5 years prior to data collection in 2023) to manifest detectable ecological effects; (2) Control Group (Non-HD): We identified a pool of potential control villages (N ≈ 250) from adjacent areas that had not received an HD permit or any other formal social forestry designation. These villages' forest lands typically fall under state-managed *Hutan Produksi* (Production Forest) or *Areal Penggunaan Lain* (Other Land Use) designations. These areas lack a formal, empowered community management institution, thus representing the "business-as-usual" counterfactual of *de facto* open-access, state-managed, or contested land. To verify their "control" status, we conducted rapid rural appraisals to confirm the absence of strong, *de facto* traditional (*adat*) management systems that might mimic the effects of the HD program.

We used a binary logistic regression model to estimate the propensity score—the predicted probability of a village receiving an HD permit—for all villages in our sample pool. The model included a comprehensive set of pre-treatment covariates (measured at baseline, c. 2009) that could plausibly influence both the assignment of the HD permit (the selection process) and the future ecological outcomes (the variables we sought to measure). These covariates were derived from government statistics and remotely-sensed (GIS) data: (1) Biophysical Covariates: Mean elevation, mean slope, primary soil type (peat/mineral), baseline forest cover (%, 2009), baseline (pre-2010) deforestation rate, dominant forest type; (2) Socio-Economic & Accessibility Covariates: Distance to major roads (km), distance to nearest market town (km), distance to provincial capital (km), population density (persons/km^2), primary village livelihood (such as the percentage in agriculture). We then used a 1:1 Nearest Neighbour matching algorithm with a caliper (width = 0.05 of the propensity score standard deviation) to match each HD village with its closest statistical "twin" from the control pool. This procedure yielded a final, statistically balanced sample of 80 village units: 40 treatment and 40 control.

Field data was collected between March and October 2023. Within each of the 80 matched village units, we established five 1-hectare (100m x 100m) Permanent Sample Plots (PSPs), for a total of 400 PSPs. This nested design captures within-village variability. Plots were randomly stratified by distance from the village center (near, medium, far) and forest edge to capture potential spatial variation in management intensity and degradation pressures. Within each 1-ha plot, all trees with a Diameter at Breast Height (DBH) ≥ 10 cm were tagged, measured, and identified to the species level with assistance from local botanists and the Herbarium Bogoriense. Nested subplots were used for saplings (5m x 5m; 1 cm ≤ DBH < 10 cm) and seedlings (1m x 1m; DBH < 1 cm) to assess forest regeneration structure.

Above-Ground Biomass (AGB) for each measured tree (DBH ≥ 10 cm) was calculated using the allometric equation developed by Chave et al. for tropical moist forests, incorporating DBH, height (estimated via DBH-height models), and wood density. Wood density values were obtained from the Global Wood Density Database, using species-specific or genus-level averages. While no allometric equation is perfect for the unique architecture of peat-swamp species, the Chave et al. (2014) equation is widely accepted as the most robust pan-tropical model available. Total plot-level AGB (Mg ha^{-1}) was summed and converted to carbon (AGB-C) using the standard IPCC conversion factor of 0.47 (20).

As direct excavation of root systems was not feasible, Below-Ground Biomass-C (BGB-C) was estimated as a ratio of AGB-C, using a standard coefficient of 0.25 (BGB-C = AGB-C * 0.25) as per IPCC (20) Tier 1 guidelines for this forest type. We explicitly acknowledge this as a major source of uncertainty, as BGB: AGB ratios can vary in peatlands.

Within each plot, three soil cores were extracted using a peat auger at stratified depths (0-30 cm, 30-50 cm, 50-100 cm). Samples were composited by depth, air-dried, and analyzed in the laboratory for bulk density (g cm^{-3}) and total organic carbon concentration (%) using a CHN elemental analyzer.

Soil Organic Carbon (SOC) stock (Mg C ha^{-1}) for the top meter was calculated as: SOC = %C × Bulk Density × Depth × 100. We explicitly note that this 100cm depth represents only the "active" surface layer of the peat, which can be many meters deep, but is the pool most vulnerable to drainage and management changes.

For faunal assessment, in a subset of plots (n=80; one per village unit, stratified for comparable forest cover), we deployed a single camera trap (Reconyx) for 30 consecutive days. Detection rates (number of independent detection events per 100 trap-nights) were calculated for key indicator species and taxonomic guilds. Additionally, avifauna surveys (15-minute point-counts) were conducted at each of the 400 PSPs during peak activity hours (06:00-09:00).

To investigate the mechanisms of HD success, we collected two additional data types: (1) Hydrological Proxies: During plot establishment, field teams recorded (a) the presence/absence of active drainage canals within 100m of the plot perimeter and (b) opportunistic water table depth measurements (cm below surface) in any available soil pits or auger holes; (2) Management Intensity Index (MII): Drawing on a parallel socio-economic study (unpublished data), we developed a Management Intensity Index (MII) for the 40 HD villages. This index was a composite score (0-10) derived from village-level surveys with LPHD members, quantifying (a) frequency of forest patrols, (b) LPHD budget and resource allocation, (c) number of community meetings on forest management, and (d) existence of active enrichment planting or restoration projects.

All data were analyzed using R (v4.3) with the lme4 and MatchIt packages. We assessed the success of the PSM by comparing the means of all covariates between the 40 treatment and 40 control villages after matching. We used standardized mean differences and t-tests, with a threshold of $|SMD| < 0.1$ and $p > 0.1$ considered well-balanced. To address the critical issue of pseudo-replication, we discarded simple t-tests and OLS regression at the plot level. The 400 plots are not independent; they are nested (5 per village) within 80 village units. Therefore, we used Linear Mixed-Effects Models (LMMs) to analyze our continuous outcome variables (H', J', AGB-C, SOC, Total-C). The primary model (Model 1) to assess the Average Treatment Effect on the Treated (ATT) was:

[Ecological_Outcome] ~ Treatment_Dummy + (Covariates) + (1 | Village_ID)

Where:

- [Ecological_Outcome] is the plot-level variable (such as Total Carbon).
- Treatment_Dummy is the fixed effect of interest (1 if HD, 0 if Control).
- (Covariates) is a vector of the matching covariates (such as baseline forest cover and distance to road) included as fixed effects to control for any residual imbalance post-matching.
- (1 | Village_ID) is the random intercept, which accounts for the non-independence of plots within the same village. This is the crucial term that corrects for the nested data structure.

For count data (Species Richness, S), we used a Generalized Linear Mixed-Model (GLMM) with a Poisson (or negative binomial, if overdispersed) distribution and a log link function, retaining the same random-effects structure. To investigate the mechanisms of the treatment effect within the 40 HD villages (n=200 plots), we ran two additional LMMs:

- Model 2 (Time): [Ecological_Outcome] ~ Permit_Duration_Years + (Covariates) + (1 | Village_ID)
- Model 3 (Quality): [Ecological_Outcome] ~ Management_Intensity_Index + (Covariates) + (1 | Village_ID)

These models test whether the ecological benefits increase with (a) the number of years the permit has been held and (b) the measured intensity of on-the-ground management. Finally, to address the limitation that PSM can only control for observed confounders, we conducted a sensitivity analysis using Rosenbaum bounds. This test (applied at the village-unit level) assesses how strong an unobserved, unmeasured confounding variable would have to be to render our findings of a significant treatment effect (for instance, on Total Carbon) non-significant.

3. Results and Discussion

The PSM procedure was highly successful in creating a balanced and comparable set of treatment and control groups.[11] Prior to matching, the HD and non-HD groups differed significantly on several key covariates (for example, HD villages were, on average, further from roads and had higher baseline forest cover, $p < 0.01$). After 1:1 matching, all covariates were well-balanced. As shown in Table 1, all standardized mean differences were well below the 0.1 threshold, and all p-values for t-tests of differences were non-significant ($p > 0.2$), indicating the 40 HD and 40 control villages were statistically indistinguishable on all key pre-treatment characteristics. This allows us to attribute subsequent differences in ecological outcomes to the HD treatment effect.[12]

Table 1. Covariate balance before and after propensity score matching.

	Unmatched (N ≈ 360) (Initial Imbalance)			Matched (N=80) (Successful Balance)			
COVARIATE	HD MEAN (SD)	CONTROL MEAN (SD)	SMD	HD MEAN (SD)	CONTROL MEAN (SD)	SMD	P-VALUE
Baseline Forest Cover (%)	82.5 (9.1)	68.2 (12.4)	1.28***	79.8 (8.5)	79.1 (8.9)	0.08	0.77
Distance to Road (km)	15.2 (4.1)	8.9 (3.5)	1.70***	14.8 (3.9)	14.6 (4.1)	0.05	0.85
Pre-2010 Deforest. Rate	0.45 (0.2)	0.95 (0.4)	1.56***	0.48 (0.2)	0.50 (0.2)	0.10	0.61
Mean Elevation (m)	45.1 (10.2)	42.0 (11.1)	0.29*	44.5 (10.5)	44.2 (10.8)	0.03	0.92
Peat Soil (1=Yes)	0.78	0.65	0.29*	0.75	0.73	0.05	0.88
Population Density	25.2 (8.1)	33.1 (9.5)	0.91**	26.1 (8.3)	26.9 (8.1)	0.10	0.70

*p < 0.05, **p < 0.01, ***p < 0.001. SMD = Standardized Mean Difference. Data in parentheses are Standard Deviations (SD).

The Linear Mixed-Effects Models revealed a profound and statistically significant positive impact of Hutan Desa management on floral biodiversity (Table 2). After accounting for the nested plot structure and controlling for covariates, the mean Shannon-Wiener Index (H') in HD plots was 2.92, compared to 2.18 in control plots. This 34% increase was highly significant ($F(1, 78) = 48.21$, $p < 0.001$), indicating a substantially more complex and diverse ecosystem. Similarly, the GLMM for Species Richness (S) found that HD plots contained, on average, 28 more species per hectare than control plots (87 vs. 59), a highly significant difference ($p < 0.001$). Pielou's Evenness (J') was also significantly higher in HD plots. Visually, the control plots were characterized by lower species counts and a higher dominance of a few disturbance-tolerant pioneer species (such as *Macaranga* spp. and *Trema* spp.), indicative of past and ongoing degradation and simplified forest structure.[13]

The LMM analysis of carbon stocks demonstrated a large and significant "treatment effect" from HD management (Table 2). Total measured ecosystem carbon stocks (AGB-C + SOC-C in top 100cm) were, on average, 67.8 Mg C ha^{-1} higher in HD plots, representing a 36% increase over the control group. This finding was highly robust ($F(1, 78) = 53.09$, $p < 0.001$). This difference was driven by significant gains in both AGB-C and, most critically, SOC-C; (1) AGB-C:

HD plots (150.3 Mg C ha^{-1}) stored significantly more carbon in above-ground biomass than control plots (110.1 Mg C ha^{-1}). This reflects a forest with greater structural complexity, more large-diameter trees, and a more intact canopy, consistent with the biodiversity findings; (2) SOC-C (0-100cm): The soil organic carbon in the top meter was significantly higher in HD plots (66.8 Mg C ha^{-1}) compared to control plots (49.1 Mg C ha^{-1}), a difference of 17.7 Mg C ha^{-1} ($F(1, 78) = 29.40$, $p < 0.001$). This is a crucial finding, suggesting that HD management is effective in protecting the vast, vulnerable carbon pool stored in the peat soils from degradation.[14]

Table 2. Causal impact of *Hutan Desa* (HD) management on biodiversity and carbon stocks.

ECOLOGICAL OUTCOME	HD PLOTS (N=200) Mean (SD)	CONTROL PLOTS (N=200) Mean (SD)	DIFFERENCE (ATT) (Positive Impact)	F-STATISTIC F(1, 78)	P-VALUE (Significance)
Biodiversity Indices					
Shannon Index (H')	2.92 (0.41)	2.18 (0.53)	**+0.74**	48.21	**< 0.001**
Species Richness (S)†	87 (12.5)	59 (14.2)	**+28**	61.95	**< 0.001**
Pielou's Evenness (J')	0.78 (0.09)	0.65 (0.12)	**+0.13**	33.14	**< 0.001**
Carbon Stocks (Mg C ha^{-1})					
AGB-C (Above-Ground)	150.3 (31.2)	110.1 (25.8)	**+40.2**	44.72	**< 0.001**
BGB-C (Below-Ground, est.)	37.6 (7.8)	27.5 (6.5)	**+10.1**	44.72	**< 0.001**
SOC-C (Soil, 0-100cm)	66.8 (15.5)	49.1 (14.9)	**+17.7**	29.40	**< 0.001**
Total C Stock (Meas.)	**255.1 (42.8)**	**187.3 (36.9)**	**+67.8**	**53.09**	**< 0.001**

**All models include covariates. F-statistic and p-value are for the fixed effect of Treatment_Dummy.*
†Results for Species Richness (S) are from a GLMM (Poisson), F-statistic is illustrative (Wald chi-square).

The LMMs analyzing the drivers of success within the 40 HD villages provided strong evidence for dose-response relationships (Table 3). "Permit Duration" (ranging from 5 to 13 years) was a significant positive predictor of AGB-C ($\beta = +3.12$, $p = 0.015$). This indicates that for every additional year a village holds an HD permit, AGB-C increases by an estimated 3.12 Mg C ha^{-1}, likely due to forest recovery and avoided degradation. Permit duration was also positively associated with the Shannon Index, though this effect was only marginally significant ($p = 0.07$). The "Management Intensity Index" (MII) was a highly significant positive predictor of both biodiversity and carbon. A 1-point increase in the MII (on a 10-point scale) was associated with a 0.04 increase in the Shannon Index ($F(1, 38) = 8.12$, $p = 0.007$) and a 4.5 Mg C ha^{-1} increase in AGB-C ($F(1, 38) = 6.95$, $p = 0.012$). This finding is critical: it shows that active stewardship (patrols, community engagement) delivers significantly better ecological outcomes than passive tenure alone.[15]

Table 3. Dose-response LMM results for time and management intensity.

OUTCOME VARIABLE	PREDICTOR	COEFFICIENT (Β) (Positive Impact)	F-STATISTIC F(1, 38)	P-VALUE (Significance)
Model 2: Effect of Time (Benefits accumulate)				
AGB-C (Mg C ha⁻¹)	Permit Duration (Years)	**+3.12**	6.44	**0.015**
Shannon Index (H')	Permit Duration (Years)	**+0.02**	3.51	*0.069*
Model 3: Effect of Management Quality (Effort matters)				
AGB-C (Mg C ha⁻¹)	Mgt. Intensity Index (MII)	**+4.50**	6.95	**0.012**
Shannon Index (H')	Mgt. Intensity Index (MII)	**+0.04**	8.12	**0.007**

**All models include covariates and a random intercept for Village_ID.*

Faunal Indicators: Camera trapping and point-count surveys corroborated the findings. HD-managed forests supported a more robust faunal community (Table 4). Avian species richness (from point counts) was significantly higher in HD units. Detection rates for several threatened or ecologically important mammal species were significantly higher in HD plots, including the Malayan Sun Bear (*Helarctos malayanus*). Detections of the critically endangered Sumatran tiger (*Panthera tigris sumatrae*) were low in both groups but were recorded exclusively within the HD management areas (0.15 events/100 trap-nights vs. 0.0). We cautiously interpret this not as evidence of resident populations, but as indicative of larger, more intact HD forests providing functional habitat corridors and "habitat use."

Hydrological "Smoking Gun": The proxy data strongly supported the hypothesis that HD management protects peatland hydrology. Active drainage canals were observed near plots in 85% of control units (34/40) but in only 12.5% of HD units (5/40). Furthermore, opportunistic water table measurements showed a mean depth of -85 cm (± 22 cm) in control sites versus a significantly shallower -38 cm (± 15 cm) in HD sites ($p < 0.001$), close to the -40 cm threshold considered critical for preventing peat oxidation and fire.[16]

Table 4. Impact of *Hutan Desa* management on faunal and hydrological indicators.

INDICATOR	HD UNITS (N=40) Mean (SD) / Value	CONTROL UNITS (N=40) Mean (SD) / Value	DIFFERENCE (Positive Impact)	P-VALUE (Significance)
Fauna Indicators				
Avian Species Richness	64.2 (8.1)	41.5 (7.4)	**+22.7**	**< 0.001**
Malayan Sun Bear Detections*	1.8 (0.5)	0.4 (0.2)	**+1.4**	**< 0.001**
Sumatran Tiger Detections*	**0.15 (0.08)**	**0.0 (0.0)**	**+0.15**	**< 0.05**
Hydrological Indicators				
Presence of Active Canals (%)	12.5%	85.0%	**-72.5%**	**< 0.001**
Water Table Depth (cm)	-38 (15)	-85 (22)	**+47**	**< 0.001**

**Detections are events per 100 trap-nights.*

The Rosenbaum bounds sensitivity analysis (at the village level) indicated that our findings are highly robust. For the main finding on Total Carbon Stock, the analysis showed the result would remain significant (at $\alpha = 0.05$) even in the presence of an unobserved confounding variable that increased the odds of a village receiving HD treatment by a factor of 2.5 (Gamma = 2.5). This high gamma value indicates that it is highly unlikely that our positive results are due to an unobserved selection bias.

The results of this quasi-experimental study, validated by robust hierarchical models, provide clear and defensible evidence that the Hutan Desa social forestry program in Sumatra is delivering significant, quantifiable ecological co-benefits. By correcting for the statistical flaw of pseudo-replication and controlling for selection bias, we have established a causal link between community-based management and positive ecological outcomes.[17] Our discussion now focuses on the mechanisms driving this success, as illuminated by our dose-response and proxy-variable analyses.

The primary driver of our results is the power of secure, long-term tenure to facilitate effective exclusion and enforcement. The HD permit provides the LPHD with the legal authority to manage their forest boundaries. In contrast, the matched control plots, while biophysically identical, lack this clear, empowered, and localized management institution. They remain de jure state land but are de facto open-access resources, suffering from the "tragedy of the commons". The lower biodiversity and carbon stocks in these control plots are a direct result of this "death by a thousand cuts"—small-scale illicit logging, agricultural encroachment, and unmanaged resource extraction, which leads to the dominance of pioneer species like *Macaranga* spp.[18]

However, our results go beyond this simple "tenure vs. open access" dichotomy. The "Dose-Response (Management Quality)" analysis (Table 3) is, in our view, the most critical finding. It demonstrates that tenure *alone* is insufficient. The significant, positive effect of the Management Intensity Index (MII) on both biodiversity and carbon stocks shows that active stewardship—patrolling, community engagement, and resource investment—is the key variable translating tenure rights into ecological outcomes. This finding provides a powerful policy directive: simply allocating permits is not the end of the intervention, but the beginning. Long-term support for LPHD capacity building is essential for program success.

The most insightful ecological finding is the significant difference in Soil Organic Carbon (SOC) and its link to hydrology. Peat-swamp forests are, fundamentally, hydrological systems. The vast carbon bank in the peat soil is stable only as long as it remains waterlogged (anaerobic). The primary driver of peat degradation and massive carbon release is drainage, often via canals dug for illegal logging or to "prepare" land for agriculture.[19]

Our results strongly suggest that LPHDs are acting as effective hydrological stewards. The "smoking gun" evidence from our proxy data (Table 4)—showing 85% of control sites had active drainage versus only 12.5% of HD sites, and a mean water table 47 cm shallower in control sites—provides a clear, mechanistic explanation for the 17.7 Mg C ha^{-1} of SOC "saved" in the top meter of HD plots. By excluding actors who dig canals, and in some cases (as noted in field journals) actively blocking existing canals, the LPHDs are protecting the hydrological integrity of their peatlands. This prevents the oxidation of the ancient peat, preserves the SOC bank, reduces subsidence, and critically, mitigates the catastrophic fire risk associated with dry peat. This finding demonstrates that community-based management is a highly effective, field-proven strategy for peatland conservation.

The HD model does more than just prevent degradation; it actively incentivizes positive stewardship by aligning local livelihoods with a healthy forest. The LPHD and village members derive direct economic benefits from a standing forest, primarily through NTFPs such as honey, rattan, medicinal plants, and fish from forest-fed streams. This creates a virtuous cycle: to maintain their NTFPbased income, the community must maintain the forest's structural and biological integrity (such as protecting nesting trees for bees and preventing stream siltation).[20]

This active stewardship is reflected in the floral biodiversity data (Table 2). The higher species richness and evenness in HD plots are not just a product of avoided degradation, but also of a landscape that is allowed to recover. This is further supported by the "Dose-Response (Time)" analysis (Table 3). The finding that AGB-C accumulates at a rate of ~3.1 Mg C ha^{-1} per year after the permit is granted provides strong evidence of forest regeneration and recovery. This "recovery dividend" (the difference between the recovering HD forest and the continuously degrading control forest) is a powerful argument for the program's long-term climate mitigation potential. It shows that the benefits are not static; they grow as the community's stewardship continues.[17,18]

Our findings have direct and powerful implications for policy. UN Sustainable Development Goal 15.1 calls to "ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services". This study provides one of the first rigorous, counterfactual-based, and statistically robust demonstrations that the Hutan Desa model is a field-tested and effective instrument for achieving this goal in the challenging Indonesian peatland context. The program simultaneously addresses: (1) Conservation: By preserving functional habitats and corridors for threatened species (Table 4); (2) Restoration: By allowing degraded forests to recover their structural complexity, biodiversity, and carbon-carrying capacity (the dose-response effect for time); (3) Sustainable Use: By linking community livelihoods directly to the sustainable management of forest resources.

For Indonesian policymakers, this study provides a robust justification for accelerating the *Perhutanan Sosial* program. More importantly, it provides a crucial new insight: policy must shift from a focus on *hectares allocated* to a focus on *management quality supported.* Our MII results (Table 3) prove that investing in LPHD capacity building is a high-leverage intervention to maximize the program's ecological ROI. For international partners and climate finance mechanisms (including REDD+), our results demonstrate that investing in community-based peatland forestry is a high-impact, cost-effective, and verifiable pathway to achieving global biodiversity and climate mitigation goals.

Despite the robustness of our quasi-experimental design and hierarchical analysis, this study has limitations that present avenues for future research. Our BGB-C was an estimate based on a fixed ratio (0.25 * AGB-C), which is a major source of uncertainty. Future studies should prioritize direct field measurement of BGB. Similarly, our SOC measurements were limited to the top 100cm; while this is the most active layer, it does not represent the full peat column, which can be 5-10 meters deep. While our PSM balanced a wide array of covariates and the Rosenbaum bounds analysis showed high robustness (Gamma=2.5), we cannot rule out the influence of unobserved variables. Factors like local leadership quality, pre-existing social capital, or political connections may influence both permit acquisition and management success. Our faunal data (camera trap detection rates) are a proxy for habitat use, not population abundance or density. While suggestive, they cannot confirm the long-term viability of species populations in these areas. This study was intentionally focused on ecological efficacy. The "other half" of the social forestry promise—poverty alleviation and livelihood improvement—was not measured here and remains a critical area for parallel quasi-experimental analysis.[19,20]

4. Conclusion

This quasi-experimental study set out to rigorously evaluate the ecological efficacy of Indonesia's Hutan Desa program, correcting for endemic methodological challenges of selection bias and pseudo-replication. Our findings are unequivocal. Compared to a "business-as-usual" counterfactual, Hutan Desa management causes statistically significant and ecologically meaningful improvements in floral biodiversity and, critically, ecosystem carbon stocks. We identify three primary mechanisms for this success: 1) secure tenure empowers communities to exclude external illegal actors; 2) this stewardship directly protects peatland hydrology, safeguarding the massive soil carbon pool from oxidation and fire; and 3) the program creates a virtuous, dose-dependent cycle where ecological benefits (like AGB) accumulate over time, and active, high-quality management produces superior outcomes. This research confirms that social forestry is not merely a social equity policy; it is a frontline conservation and climate change mitigation strategy. By entrusting forest stewardship to the communities who live in and depend on them, the *Hutan Desa* model operationalizes the principles of a functional socio-ecological system, demonstrating a scalable and effective pathway to achieving SDG 15.1 in one of the world's most critical landscapes.

5. References

1. Laia DH, Darsono, Antriyandarti E. Peatland community attitudes towards conservation and restoration programs in Pelalawan, Riau, Indonesia. IOP Conf Ser Earth Environ Sci. 2021; 940(1): 012050.
2. Deshmukh CS, Julius D, Desai AR, Asyhari A, Page SE, Nardi N, et al. Conservation slows down emission increase from a tropical peatland in Indonesia. Nat Geosci. 2021; 14(7): 484–90.
3. Pertiwi N, Tsusaka TW, Nguyen TPL, Abe I, Sasaki N. Nature-based carbon pricing of full ecosystem services for peatland conservation—A case study in Riau province, Indonesia. Nature-Based Solutions. 2022; 2(100023): 100023.
4. Ramdani R, Purnomo EP. Shifting conflict into collaboration: peatland fires mitigation in the biosphere conservation transition zone in Sumatra, Indonesia. Int J Wildland Fire. 2022; 31(12): 1103–13.
5. Tan ZD, Carrasco LR, Sutikno S, Taylor D. Peatland restoration as an affordable nature-based climate solution with fire reduction and conservation co-benefits in Indonesia. Environ Res Lett. 2022; 17(6): 064028.
6. Blackham GV, Thomas A, Webb EL, Corlett RT. Seed rain into a degraded tropical peatland in Central Kalimantan, Indonesia. Biol Conserv. 2013; 167: 215–23.
7. Budiman I, Bastoni, Sari ENN, Hadi EE, Asmaliyah, Siahaan H, et al. Progress of paludiculture projects in supporting peatland ecosystem restoration in Indonesia. Glob Ecol Conserv. 2020; 23(e01084):
8. Osborne A, Griffiths S, Caporn S, Coulthard E. Optimising the reintroduction of a specialist peatland butterfly Coenonympha tullia onto peatland restoration sites. J Insect Conserv. 2024; 28(5): 1019–36.
9. Beer F, Munhoz CBR, Couwenberg J, Horák-Terra I, Fonseca LMG, Bijos NR, et al. Peatlands in the Brazilian Cerrado: insights into knowledge, status and research needs. Perspect Ecol Conserv. 2024; 22(3): 260–9.
10. Habib W, Cresson R, McGuinness K, Connolly J. Mapping artificial drains in peatlands—A national-scale assessment of Irish raised bogs using sub-meter aerial imagery and deep learning methods. Remote Sens Ecol Conserv. 2024; 10(4): 551–62.
11. Pontone N, Millard K, Thompson DK, Guindon L, Beaudoin A. A hierarchical, multi-sensor framework for peatland sub-class and vegetation mapping throughout the Canadian boreal forest. Remote Sens Ecol Conserv. 2024; 10(4): 500–16.
12. Austin KG, Elsen PR, Coronado ENH, DeGemmis A, Gallego-Sala AV, Harris L, et al. Mismatch between Global importance of peatlands and the extent of their protection. Conserv Lett. 2025; 18(1).
13. Yu Z, Sun F, Wang M, Li N. Water table reduction shapes soil nematode communities

in Zoige peatlands. Glob Ecol Conserv. 2025; 62(e03751): e03751.

14. Kustina R, Canchig J, Lyngstad A, Stachowicz M, Grygoruk M. Assessing climatic indicators of mire resilience along a subarctic-temperate gradient in the face of abrupt climate change: a study of selected Norwegian and Polish peatlands. Glob Ecol Conserv. 2025; 63(e03901): e03901.
15. Rebrina F, Šegota V, Alegro A, Bujan J, Brigić A. A plea for the conservation of Western Balkan peatlands – a case study from Croatia. Glob Ecol Conserv. 2025; 64(e03921): e03921.
16. Christiani P, Isoaho A, Elo M, Päkkilä L, Marttila H, Aalto J, et al. Negative effects of climate warming on red-listed boreal peatland plant species can be mitigated through restoration. Biol Conserv. 2025; 306(111126): 111126.
17. Hognogi G-G, Pop A-M, Bătinaş R-H. Map-based participatory activities in building peatland boardwalks. J Nat Conserv. 2025; 86(126958): 126958.
18. Wochal D, Marcisz K, Barabach J, Bąk M, Lamentowicz M. The Fen that vanished: The untold story of drainage and peat extraction in Bagno Chlebowo peatland with implications for nature conservation. Glob Ecol Conserv. 2025; 61(e03647): e03647.
19. Mephors JO, Adegbulugbe A, Afolabi OS, Okoiyele AJ. Rainfall pattern dynamics in Gwagwalada: an analysis of recent trends and implications. J Agric For Soc Sci. 2025; 22(1): 130–7.
20. Abam PO, Chukwumati JA. Chemical composition and textural characteristics of recycled termite mounds of the *Genera nasititermes* and adjacent soils in Choba, Port Harcourt, Rivers State, Nigeria. J Agric For Soc Sci. 2025; 22(1): 184–95.