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ECOLOGICAL-ECONOMIC SYSTEM DYNAMICS MODEL OF MANGROVE SILVOFISHERY IN ACTIVE AQUACULTURE PONDS IN MUARA ADANG, EAST KALIMANTAN

MODEL SISTEM DINAMIK EKOLOGI-EKONOMI SILVOFISHERY MANGROVE PADA TAMBAK AKTIF DI MUARA ADANG, KALIMANTAN TIMUR

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ABSTRACT

Mangrove restoration in active aquaculture ponds requires balancing ecological recovery with livelihood sustainability, yet dynamic assessment tools remain limited. This study develops an integrated ecological-economic system dynamics model for a silvofishery landscape in Muara Adang, East Kalimantan, combining mangrove zone dynamics with replanting, pond water quality feedback on fish productivity, four zone-allocation scenarios over 30 years, and a three-layer Total Economic Value (TEV) framework. Environmental modifiers suppressed mangrove growth to 14.7% of the baseline rate, giving low stem densities (1.3–8.4 stems ha^{-1}) and a soil carbon decline from 171 to ~50 ton C ha^{-1} in all scenarios. All scenarios had positive net present value (NPV) at a 5% discount rate, but performance varied across layers. The baseline had the highest tangible NPV (USD 2,359 ha^{-1}), whereas S2 had the highest total NPV (USD 4,990 ha^{-1}) only with ecosystem services. S1 retained 88% of baseline tangible NPV while raising total NPV by 33%. The discount rate, fish productivity, and fish price were most influential. Because the ecological module is simplified, density and carbon trajectories are indicative. The results support the 70:30 silvofishery standard as a balanced baseline, while full restoration requires ecosystem service payments or carbon certification that aren't established.

Keywords: mangrove restoration, silvofishery, blue carbon, system dynamics, total economic value, East Kalimantan.

ABSTRAK

Restorasi mangrove pada tambak aktif memerlukan keseimbangan antara pemulihan ekologi dan keberlanjutan mata pencaharian, namun perangkat penilaian dinamis masih terbatas. Penelitian ini mengembangkan model sistem dinamik ekologi-ekonomi terintegrasi untuk lanskap silvofishery di Muara Adang, Kalimantan Timur, yang menggabungkan dinamika zona mangrove dengan penyulaman, umpan balik kualitas air tambak terhadap produktivitas ikan, empat skenario alokasi zona selama 30 tahun, dan Total Economic Value (TEV) tiga lapis. Modifikator lingkungan menekan pertumbuhan mangrove menjadi 14,7% dari laju dasar, sehingga kerapatan batang rendah (1,3–8,4 batang ha^{-1}) dan karbon tanah turun dari 171 menjadi ~50 ton C ha^{-1} pada semua skenario. Semua skenario menghasilkan Net Present Value (NPV) positif pada diskonto 5% (USD 309–4.990 ha^{-1}), tetapi kinerjanya berbeda antar lapisan. Baseline memiliki NPV tangible tertinggi (USD 2.359 ha^{-1}), sedangkan S2 memiliki NPV total tertinggi (USD 4.990 ha^{-1}) hanya jika jasa ekosistem diperhitungkan. S1 mempertahankan 88% NPV tangible baseline dan menaikkan NPV total sebesar

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33%. Laju diskonto, produktivitas dan harga ikan paling berpengaruh terhadap sensitivitas. Dengan modul ekologi yang disederhanakan, lintasan kerapatan dan karbon bersifat indikatif. Hasil studi mendukung standar silvofishery 70:30 sebagai basis kebijakan yang seimbang, sedangkan restorasi memerlukan mekanisme pembayaran jasa ekosistem ataupun sertifikasi karbon yang belum sepenuhnya terwujud di Muara Adang

Kata kunci: restorasi mangrove, silvofishery, blue carbon, sistem dinamik, total economic value, Kalimantan Timur.

INTRODUCTION

Mangrove ecosystems are among the most carbon-dense forests, storing three to five times as much carbon per unit area as upland forests, with stocks of 800–ter1,200 ton C ha^{-1} (Sitanggang et al., 2025). Indonesia holds about 23.1% of global mangrove cover yet has experienced some of the highest rates of loss, driven mainly by conversion to aquaculture ponds, which account for up to 72.5% of emissions from mangrove degradation (Rahmajati et al., 2026). In East Kalimantan, *Nypa* forest conversion to ponds since the 1980s, compounded by overlapping land-use policies and weak inter-agency coordination, has produced degradation of 47–70% across the Mahakam Delta (Aslan et al., 2021; Ottinger et al., 2026). Most restoration efforts target abandoned or unproductive ponds, but sites such as Muara Adang present a different challenge because most ponds remain economically active. Restoration there cannot disregard ongoing livelihood income, continuous disturbance from aquaculture, and the decisions of current pond operators. However, studies of restoration models for active ponds with degraded mangrove cover remain scarce (Ilman & Anggoro, 2025).

Silvofishery, known in Indonesia as *Wanamina*, combines brackish aquaculture with mangrove conservation in one land-use system. Documented benefits include carbon stocks of 216.9 ton C ha^{-1} in Blanakan, West Java, improved water quality through mangrove biofiltration, and higher fish and shrimp productivity from litterfall nutrients that reduce dependence on artificial feed (Anggoro et al., 2025). These benefits are rarely modeled dynamically or quantified together in one framework, and trade-offs between pond and mangrove zones, including the effect of tree density on pond productivity, remain poorly specified. This study addresses these gaps by developing an integrated ecological-economic evaluation model for silvofishery in active ponds with degraded mangrove cover in East Kalimantan, to support adaptive restoration strategies.

The novelty of this study lies in the combination of four elements that have not been brought together in earlier work: (i) an integrated ecological-economic system dynamics model in place of separate ecological and economic assessments; (ii) a focus on active ponds, where restoration must be reconciled with ongoing aquaculture income, instead of abandoned ponds; (iii) the simulation of four zone-allocation scenarios with an explicit replanting mechanism and a feedback from mangrove density to pond water quality and fish productivity; and (iv) a three-layer Total Economic Valuation that separates tangible market income, conditional stock-based carbon value, and ecosystem service value transferred from other sites.

RESEARCH METHODS

Study Area

The study was conducted in Muara Adang, Paser Regency, East Kalimantan, Indonesia. Three sampling sites from the 2022 field survey were used: Site A (channel zone), Site B (active pond), and Site C (active pond). The total study area was 5.61 ha. The site was characterized by permanent tidal inundation and degraded mangrove cover (Figure 1).



Source: Yayasan Planet Urgensi Indonesia (YPUI) (2022)

Figure 1. Satellite Image of Degraded Mangrove Pond Area in Muara Adang, East Kalimantan

Data Collection

Soil samples from nine points across three sites were analyzed for organic C, total N, P, K, C/N ratio and pH: organic C initializes soil carbon, C/N parameterizes the decomposition modifier and soil pH the growth modifier. Water quality (DO, pH, salinity) was measured at six stations, with zone means presented in Table 1. Pond-zone water quality drives fish productivity through the Water Quality Index (WQI), and mangrove-zone salinity affects the salinity function of the growth modifier.

Table 1. Field Data Summary by Functional Zone

Parameter	Channel/Mangrove Zone (Site A)	Pond Zone (Site B + C)
DO (mg L^{-1})	7.06	7.96
pH (water)	6.44	7.14
Salinity (ppt)	24.7	17.0
Computed WQI	0.5156	0.9148
Organic C (%, soil)	3.80	3.93
C/N ratio (soil)	23.5	23.1
Soil pH	5.66	6.47
Initial C_soil (ton C ha^{-1})	171.00	176.85
Maximum density	681 stems ha^{-1}	681 stems ha^{-1}

Bulk density (BD) was not measured in Muara Adang, so 0.90 g cm^{-3} was adopted from Ningrum et al. (2024), who reported 0.74–1.15 g cm^{-3} for degraded mangrove soils in Kutai Kartanegara, East Kalimantan. Initial soil carbon was computed over a 50 cm depth, also following Ningrum et al. (2024).

Model Framework

An integrated ecological-economic system dynamics model was developed in Python 3 using scipy.integrate.solve_ivp (RK45; relative tolerance 10^{-8}, absolute tolerance 10^{-6}, maximum step 0.1 yr and 0.05 yr during replanting, and a 30-year simulation horizon), following the stock-and-flow methodology of Forrester et al. (1976). The model partitions each hectare into a pond zone (f_pond) and a mangrove zone (f_mng = 1 − f_pond), with ecological states per hectare of the mangrove zone and economic outputs scaled to the total area, as illustrated in Figure 2.

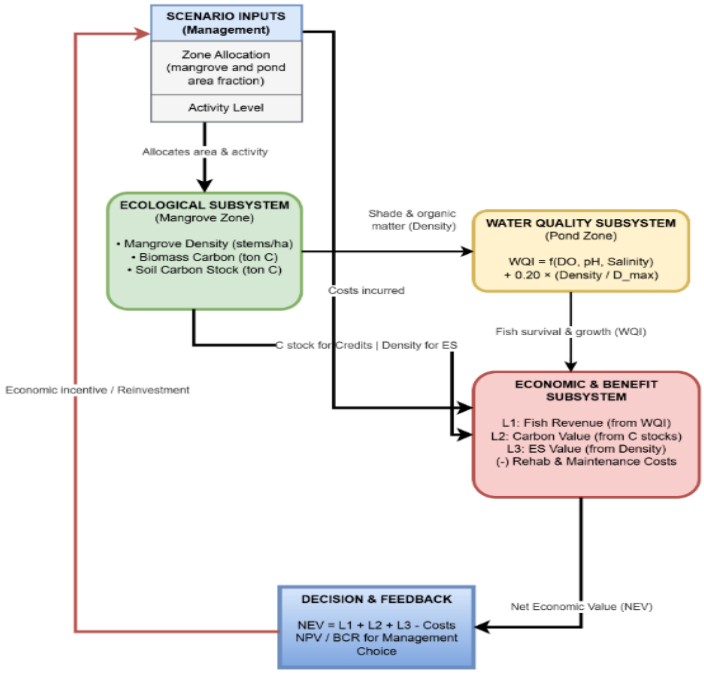

Figure 2. Model Framework of Ecological-Economic System Dynamics of Mangrove Silvofishery in Muara Adang, East Kalimantan

Scenario Design

Four scenarios represent the range of plausible management trajectories (Table 2). All share identical initial conditions and field-derived environmental parameters, but differ in zone allocation, activity level, initial stem density (lower in S0), and planting input.

Table 2. Scenario Definitions

Scenario	Pond fraction (f_pond)	Mangrove fraction (f_mng)	Activity factor	Description
S0 - Baseline	0.90	0.10	0.90	No intervention; natural regeneration only
S1 - Silvofishery	0.70	0.30	0.30	Active pond and mangrove planting (Muthoh et al., 2022)
S2 - Full Restoration	0.10	0.90	0.05	Mangrove rehabilitation priority; minimal aquaculture
S3 - Hybrid	0.50	0.50	0.15	Balanced eco-silvofishery; equal zone allocation

S0 (Baseline) is the no-management counterfactual. S1 (Silvofishery) follows the standard 70:30 configuration (Muthoh et al., 2022). S2 (Full Restoration) bounds the scenario space on the ecological side. S3 (Hybrid) applies a 50:50 allocation consistent with eco-silvofishery designs

reported by Basyuni et al. (2022). S1, S2 and S3 receive a replanting program (see Model Structure) with planting density caps of 1,100, 10,000 and 2,500 stems ha^{-1} of mangrove zone, respectively. These caps are assumptions of this study, with the S1 value set from *Wanamina* planting practice (Basyuni et al., 2022). S0 receives no planting.

Model Structure

Ecological Subsystem

The ecological subsystem tracks four state variables in the mangrove zone: aboveground biomass carbon (C_biomass), litter (C_litter), soil organic carbon (C_soil) and stem density. Initial values are identical across scenarios except density. C_soil is 171.0 ton C ha^{-1}, computed from primary data (Site A), whereas C_biomass (10.0 ton C ha^{-1}), C_litter (1.0 ton C ha^{-1}) and density (20 stems ha^{-1} in S0, 50 in S1 to S3) are assumed remnant-stand values that were not measured. The initial pond-zone WQI is 0.9148, computed from Site B and C measurements.

The four state variables are governed by the following ODEs:

$$dC_biomass/dt = r_growth \cdot C_biomass \cdot f_sal \cdot f_inund \cdot f_pH - r_litter \cdot C_biomass \quad (1)$$

$$dC_litter/dt = r_litter \cdot C_biomass - r_decomp \cdot C_litter \cdot h_CN \cdot f_inund \cdot (1 + 0.15 \cdot act) \quad (2)$$

$$dC_soil/dt = r_decomp \cdot C_litter \cdot h_CN \cdot f_inund - r_resp \cdot C_soil \cdot f_inund - r_tide \cdot C_soil \quad (3)$$

$$dDensity/dt = r_recruit \cdot Density \cdot f_sal \cdot f_inund \cdot f_pH \cdot (1 - Density/D_max) - r_mort \cdot Density \cdot (1 + 0.30 \cdot act) \quad (4)$$

Here, *act* is the scenario activity factor; *D_max* is maximum density; *r_tide* is the tidal carbon export rate. f_pH is added to growth (Eq. 1) and recruitment (Eq. 4), applying the soil pH modifier derived from primary soil data. The activity coefficients 0.15 (decomposition) and 0.30 (mortality) represent moderate increases in decomposition and mortality, respectively, due to human disturbance (pond maintenance, water manipulation, and selective thinning).

Mangrove Establishment and Replanting

Initial stocks are not zero. All scenarios start from a degraded remnant stand (see Ecological Subsystem), and S1 to S3 receive planting input through a quarterly replanting (sulaman) program during the first three years (12 events), the only external source of stems and biomass carbon. Between events the stocks follow Eqs. (1) to (4). At event k, the number of stems replanted (N_k) and the state updates are:

$$N_k = min[\, max(0, D_start - D_before), max(0, D_plant - D_before) \,] \quad (4a)$$

$$D_after = D_before + N_k \quad (4b)$$

$$C_biomass, after = C_biomass, before + N_k \cdot c_stem \quad (4c)$$

$$Cost_after = Cost_before + N_k \cdot c_seed \cdot f_mng \quad (4d)$$

Here, D_start and D_before are density at the start and end of the interval before correction, and D_after is density after it. The first term in Eq. (4a) is the net density loss over the interval and the second is the gap to the planting cap D_plant (1,100, 10,000 and 2,500 stems ha^{-1} for S1, S2 and S3; zero for S0), so replanting replaces losses but never exceeds the cap. Biomass per seedling (c_stem = 2.3 × 10^{-5} ton C) is estimated for a seedling of about 50 g dry mass and 47% carbon with the allometry of Komiyama et al. (2008), and seedling cost (c_seed) is an assumed USD 0.05. After year 3 density follows natural recruitment and mortality only. Because simulated losses are small

relative to the caps, the caps never bind: replanting replaced about 10 to 11 stems ha^{-1} in each scenario at a cost below USD 0.5 ha^{-1}, and the model does not simulate planting at full density.

Environmental Modifier Functions

Four dimensionless environmental modifier functions, bounded between 0 and 1, translate field-measured conditions into rate multipliers. The salinity modifier (f_sal) follows a Gaussian optimum function representing a unimodal biological response to salinity (Yuan et al., 2020), with γ and sal_opt given in Table 3:

$$f_sal = exp(-\gamma \cdot (sal - sal_opt)^2) \quad (5)$$

The inundation modifier (f_inund) is a linear suppressor representing growth, decomposition, and respiration suppression under waterlogged conditions:

$$f_inund = max(0, 1 - h / h_ref) \quad (6)$$

where h = 0.41 m (mean) and h_ref = 0.82 m (maximum), giving f_inund = 0.500 in Muara Adang. The soil pH modifier (f_pH) follows a monomolecular saturating function reflecting acid-sulfate phytotoxicity below pH 4.0 (Pezeshki, 2001), with pH_ref given in Table 3:

$$f_pH = 1 - exp(-0.5 \cdot (pH - pH_ref)) \quad (7)$$

The C/N modifier (h_CN) is a hyperbolic inhibition of litter decomposition with half-saturation CN_half = 30 (Swift et al., 1979):

$$h_CN = 1 / (1 + (C/N) / CN_half) \quad (8)$$

The three mangrove-zone modifiers act multiplicatively on growth (f_sal × f_inund × f_pH = 0.521 × 0.500 × 0.564 = 0.147), meaning vegetation growth operates at approximately 14.7% of the base rate under current site conditions.

Water Quality Index (WQI) and Pond Zone Dynamics

A composite WQI for the pond zone averages three sub-indices from pond-zone field data (Table 1): I_DO (linear; Boyd, 1998), I_pH (Gaussian, optimum 7.5; Nadi et al., 2025) and I_sal (Gaussian, optimum 15 ppt; Kodikara et al., 2017):

$$WQI = (1/3) \cdot I_DO + (1/3) \cdot I_pH + (1/3) \cdot I_sal \quad (9)$$

WQI in the pond zone evolves dynamically toward a target value:

$$dWQI_pond/dt = (WQI_target - WQI_pond) / \tau_WQI \quad (10)$$

$$WQI_target = clip(WQI_field + \omega \cdot (Density/D_max) \cdot f_mng - 0.15 \cdot act, 0.05, 1.0) \quad (11)$$

where WQI_field is the pond-zone WQI from field data (Table 1), τ_WQI = 2 years is the multi-annual equilibration time of semi-closed brackish ponds (Novida et al., 2025), and ω = 0.20 is the maximum WQI improvement per unit density relative to carrying capacity (Rebolledo Monsalve & Verduga, 2023). The target is clipped to [0.05, 1.0] to avoid implausible values.

Economic Subsystem and TEV Framework

The economic subsystem applies a Total Economic Value (TEV) framework (Juniyanti et al., 2026), disaggregating cumulative benefits into three layers by valuation type (Table 5): L1 tangible market income and rehabilitation cost, L2 conditional stock-based carbon value, and L3 intangible

ecosystem service value via benefit transfer. Four cumulative stock variables are tracked per hectare of total area through the following ODEs:

$$dVal_carbon/dt = (C_biomass + C_soil) \cdot f_mng \cdot 3.667 \cdot p_C \cdot \varepsilon \cdot p_cert \quad (12)$$

$$dIncome_SF/dt = F_max \cdot WQI_pond \cdot d_eff \cdot p_F \cdot 1000 \cdot f_pond \cdot (1 - c_op) \quad (13)$$

$$dVal_ES/dt = (v_CP + v_WQ + v_bio) \cdot (Density/D_max) \cdot f_mng \quad (14)$$

$$dCost/dt = c_rehab \cdot c_op \cdot R_pond \cdot max(0, (0.9 - act)/0.9) \ (plus\ seedling\ cost\ at\ replanting\ events, Eq.4d) \quad (15)$$

The factor 3.667 = 44/12 (CO_2 to C mass ratio). The term p_cert = 0.50 discounts carbon value by the probability of Verified Carbon Standard (VCS) certification, which has not been established in Muara Adang, and ε = 0.70 is the share of the stock eligible for credits under the VCS blue carbon methodology. The pond productivity multiplier d_eff = 0.3 + 0.7 (Density/D_max) lies between 0.3 and 1.0 and is a structural assumption of this study. The operating cost ratio c_op = 0.32 is the share of gross pond revenue spent on operation (Nuriyawan & Erwansa, 2022). F_max = 0.66 ton ha^{-1} pond yr^{-1} is the maximum production of the Yayasan Mangrove Lestari demonstration plot (Nuriyawan & Erwansa, 2022), and p_C = USD 3.27 per ton CO_2 is the IDXCarbon average price (Martino & Naomi, 2025). In Eq. (15), R_pond = F_max · WQI_pond · d_eff · p_F · 1000 · f_pond is gross pond revenue (USD ha^{-1} yr^{-1}; 1000 converts tons to kg), and c_rehab = 0.10 is the rehabilitation and maintenance share of operating cost, applied with the intensity term max (0, (0.9 − act)/0.9), which sets rehabilitation cost to zero for S0. The model has no separate rehabilitation and maintenance phase: the same c_rehab applies over the horizon, and the only phase-specific cost is the seedling cost of Eq. (4d). Values and sources are in Table 3.

Val_carbon in Eq. (12) is neither sequestration nor credits issued. It prices the standing carbon stock (biomass plus soil) of the mangrove zone each year after the certification discounts and accumulates the annual values, so it equals a scenario coefficient times the time-integrated stock. For S1 the coefficient is 0.30 × 3.667 × 3.27 × 0.70 × 0.50 = 1.259 USD per ton C yr^{-1} and the integrated stock is about 3,014 ton C ha^{-1}yr , giving USD 3,795 ha^{-1} (S0, S2 and S3: 1,267, 11,379 and 6,323). Because the stock declines from about 181 to 50 ton C ha^{-1} in every scenario, Val_carbon is almost proportional to the mangrove fraction and is not an additionality-based credit.

Economic performance is reported as Net Present Value (NPV) across three TEV layers discounted at a rate (ρ) of 5% per year:

L1: Tangible only (direct market cash flows):

$$NPV_L1 = (Income_SF - Cost_cumul) \cdot exp(-\rho \cdot t) \quad (16)$$

L2: Conditional tangible (with stock-based carbon value at p_cert = 0.50):

$$NPV_L2 = (Income_SF + Val_carbon - Cost_cumul) \cdot exp(-\rho \cdot t) \quad (17)$$

L3: Full TEV (with ecosystem services via benefit transfer):

$$NPV_L3 = (Income_SF + Val_carbon + Val_ES - Cost_cumul) \cdot exp(-\rho \cdot t) \quad (18)$$

NPV in Eqs. (16) to (18) is computed from cumulative values, so at t = 30 yr all flows are discounted by one factor, exp (−0.05 × 30) = 0.223. This terminal convention understates present value because

early flows are discounted too heavily. Discounting annual flows individually gives NPV of USD 5,563, 6,321 and 6,513 ha^{-1} for S0 (Layers 1 to 3), 4,949, 7,219 and 9,170 for S1, 730, 7,537 and 13,619 for S2, and 3,600, 7,382 and 10,709 for S3. The Layer 1 and 3 orderings are unchanged, but at Layer 2 the order becomes S2 > S3 > S1 > S0, so the Layer 2 ranking depends on the convention. The terminal convention is reported for continuity, and it also makes the NPV curves in Figure 4 peak near year 15, not an economic loss but an artifact. Benefit–Cost Ratio (BCR) is reported as the ratio of total discounted benefits to total discounted costs, where BCR > 1 indicates economic viability (Heo & Heo, 2022):

$$BCR = PV(Income_SF + Val_carbon + Val_ES) \,/\, PV(Cost_cumul) \quad (19)$$

Income_SF is cumulative silvofishery net revenue, Val_carbon the cumulative stock-based carbon value (Eq. 12), Val_ES the cumulative ecosystem service value and Cost_cumul the cumulative rehabilitation expenditure including seedlings.

Model parameters are in Table 3 (Parameterization). Ecological rates follow Southeast Asian mangrove studies, environmental modifiers come from physiology and Muara Adang field data, and economic parameters come from the Muara Badak Ulu silvofishery (Nuriyawan & Erwansa, 2022), carbon market prices and benefit transfer.

Table 3. Model Parameters, Values, and Sources

Parameter	Symbol	Value	Source
Ecological rates			
Biomass growth rate	r_growth	0.20 yr^{-1}	Komiyama et al., 2008
Litterfall rate	r_litter	0.15 yr^{-1}	Athasyah et al., 2023
Decomposition rate	r_decomp	0.30 yr^{-1}	Alongi, 2020; Murdiyarso et al., 2015; Selviani et al., 2024
Soil respiration rate	r_resp	0.05 yr^{-1}	Alongi, 2020
Stem recruitment rate	r_recruit	0.25 yr^{-1}	Sadono et al., 2020
Stem mortality rate (base)	r_mort	0.10 yr^{-1}	Putz & Chan, 1986
Environmental modifier parameters			
Salinity optimum	sal_opt	15 ppt	Kodikara et al., 2017
Salinity width parameter	γ	0.00693 ppt^{-2}	Basyuni et al., 2018
Inundation reference depth	h_ref	0.82 m	Field data
Tidal carbon export rate	r_tide	0.02 yr^{-1}	Back-calculated from global DOC export range (Sullivan et al., 2025)
C/N half-saturation constant	CN_half	30	Alongi, 2020
Soil pH	pH_ref	4.0	Pezeshki, 2001; Richards, 1959
Economic parameters			
Carbon price	p_C	USD 3.27/ton CO_2	Martino et al., 2025
Carbon certification fraction	ε	0.70	VCS blue carbon standard
VCS certification probability	p_cert	0.50	Assumption: no active certification in Muara Adang
Maximum fish production	F_max	0.66 ton ha^{-1} yr^{-1} (pond area)	YML silvofishery demonstration plot, Muara Badak Ulu (Nuriyawan & Erwansa, 2022)

Parameter	Symbol	Value	Source
Fish price	p_F	USD 3.60/kg	YML silvofishery demonstration plot (Nuriyawan & Erwansa, 2022)
Coastal protection value	v_CP	USD 6,429 ha^{-1} yr^{-1} (mangrove area)	Juniyanti et al., 2026
Water quality regulatory value	v_WQ	USD 2,800 ha^{-1} yr^{-1} (mangrove area)	Caballero et al., 2025
Biodiversity value	v_bio	USD 139 ha^{-1} yr^{-1} (mangrove area)	Juniyanti et al., 2026
Discount rate	ρ	5% yr^{-1}	Standard CBA practice
Pond productivity multiplier	d_eff	0.3 + 0.7 (Density/D_max), range 0.3–1.0	Structural assumption (this study)
Operating cost ratio	c_op	0.32 (dimensionless)	Nuriyawan & Erwansa, 2022
Rehabilitation and maintenance cost share	c_rehab	0.10 of operating cost (dimensionless), times intensity term (0.9 − act)/0.9	Nuriyawan & Erwansa, 2022
Replanting parameters			
Replanting interval	Δt_rep	0.25 yr (quarterly)	Assumption
Replanting duration	T_rep	3 yr	Assumption
Planting density cap (S0 / S1 / S2 / S3)	D_plant	0 / 1,100 / 10,000 / 2,500 stems ha^{-1}	Assumption: S1 after Basyuni et al., 2022
Seedling cost	c_seed	USD 0.05 per seedling	Assumed nursery price
Biomass carbon per seedling	c_stem	2.3×10^{-5} ton C per stem	Estimated with allometry of Komiyama et al., 2008

Assumption of constant economic parameters. F_max, p_F, p_C, c_op, c_rehab and the ecosystem service values are held constant for 30 years in constant USD because they come from a single demonstration plot, one market average and benefit transfer, so no defensible trend can be estimated. This implies fish productivity is sustained for 30 years without disease, soil degradation or market shocks, which is optimistic. Because fish productivity and price are the main market drivers (SI = +0.58), a permanent 50% reduction in either lowers S1 total NPV from USD 3,608 to 2,565 ha^{-1} (−29%; Table 5).

RESULTS AND DISCUSSION

Ecological Trajectories

Environmental modifiers from field data reduced effective mangrove growth and recruitment to 14.7% of base rates (f_sal × f_inund × f_pH = 0.521 × 0.500 × 0.564), with salinity at 24.7 ppt, inundation at 0.41 m and soil pH at 5.66 each contributing (Kodikara et al., 2017; Pezeshki, 2001), consistent with constraints on mangrove establishment in active pond landscapes (Tarunamulia et al., 2024). Replanting held density at the initial 50 stems ha^{-1} in S1 to S3 for the first three years

(Figure 3a). After planting stopped, mortality exceeded recruitment and density fell to 1.32–8.41 stems ha^{-1} at year 30; replanting raised year-30 density by only 1.3 to 1.5 stems ha^{-1} relative to runs without it (S1: 6.88 versus 5.54). Biomass carbon fell from 10.0 to 0.27 ton C ha^{-1} in all scenarios (Figure 3c), because growth in Eq. (1) depends on the biomass stock and not on stem density, and soil carbon fell from the measured 171.0 to 49.9–50.0 ton C ha^{-1} with differences among scenarios below 0.1 ton C ha^{-1} (Figure 3b). Zone allocation therefore has negligible influence on carbon dynamics at current density. Fish production tracked pond fraction (0.019–0.140 ton ha^{-1} yr^{-1}; Figure 3e), and the mangrove–WQI–fishery feedback stayed dormant (SI = +0.001; Figure 3d) because terminal density under S1 (1.0% of D_max) gives a WQI bonus below 0.001.

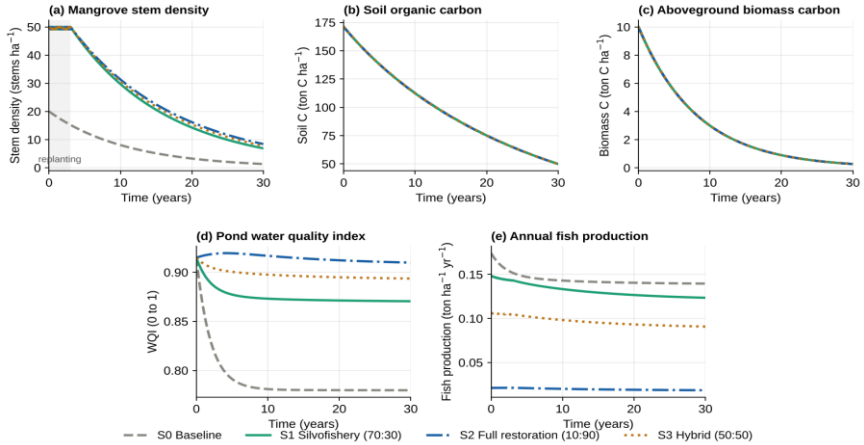

Figure 3. Ecological Trajectories: (a) Stem Density, with the Shaded Period Showing Replanting (D_max = 681 stems ha^{-1}), (b) Soil Carbon, (c) Aboveground Biomass Carbon, (d) Pond WQI, and (e) Fish Production

Economic Viability and TEV Layer Analysis

All four scenarios returned positive NPV in all three TEV layers (Table 4), so positive returns are not unique to S1, but the ranking changes with the layer. At Layer 1, S0 was highest (USD 2,359 ha^{-1}), followed by S1 (2,086), S3 (1,520) and S2 (309). At Layer 2, S1 (2,933) and S3 (2,931) were practically identical, ahead of S2 (2,848) and S0 (2,642); the USD 2 gap is far below input uncertainty. At Layer 3, S2 was highest (4,990), followed by S3 (4,094), S1 (3,608) and S0 (2,705). S1 retained 88% of the baseline tangible NPV while raising total NPV by 33%, consistent with the *Wanamina* standard (70:30) of the Ministry of Marine Affairs and Fisheries. Rehabilitation cost was low (USD 303 ha^{-1} for S1; seedlings under USD 1) because it is 10% of operating cost from Muara Badak Ulu observations (Nuriyawan & Erwansa, 2022) rather than built from fixed-cost items.

S2 (Full Restoration, 10:90) ranks first only when non-market values are recognized. Its Layer 1 NPV (USD 309 ha^{-1}) is the lowest because only 10% of the area is in production; stock-based carbon value (Layer 2, p_cert = 0.50) raises it to USD 2,848 ha^{-1}, still below S1 and S3 at the base carbon price, and ecosystem services (Layer 3) raise it to USD 4,990 ha^{-1} (Juniyanti et al., 2026; Caballero et al., 2025). Because Eq. (14) multiplies a benefit-transfer value by the density ratio and mangrove fraction, the S2 advantage comes from its 90% mangrove area and not from faster recovery, as density differs little among S1 to S3 (6.9–8.4 stems ha^{-1}). Restoration priority therefore cannot be justified on

market grounds alone, and the site has no carbon certification or payment mechanism. S3 (Hybrid, 50:50) lies between S1 and S2 in every layer except Layer 2 (BCR_total 66.93). S0 generated the highest cumulative silvofishery income (USD 10,572 ha^{-1}) but with declining WQI and negligible mangrove density, an unsustainable trajectory. The high BCR values (22.34–346.17) reflect a low cost base that is a fixed share of pond operating cost (see Limitations). Trajectories are shown in Figure 4.

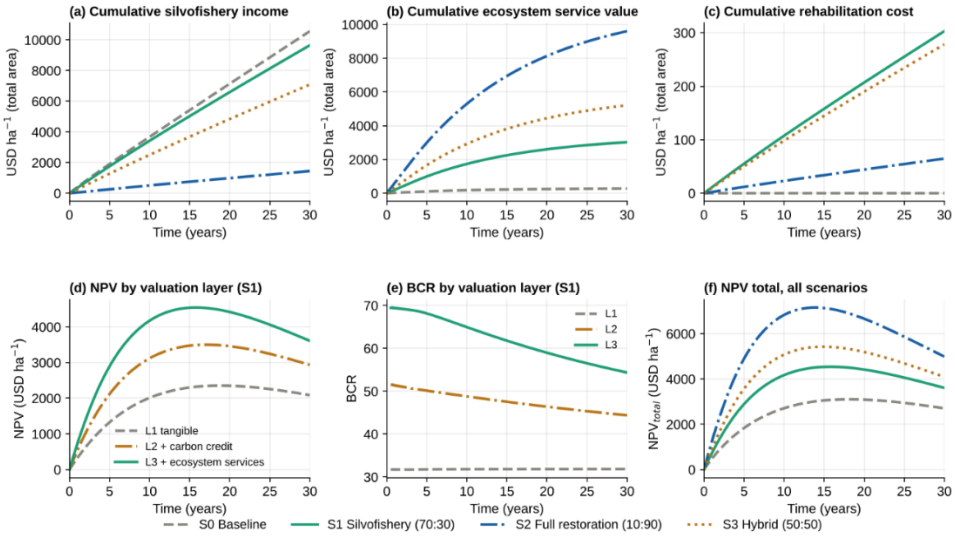

Figure 4. (a) Cumulative Silvofishery Income, (b) Ecosystem Service Value, (c) Rehabilitation Cost, (d) NPV, (e) BCR by Valuation Layer for S1, and (f) NPV_L3 (total) for All Scenarios

Sensitivity Analysis and Model Limitations

A one-at-a-time analysis on S1 (NPV Layer 3, year 30) varied thirteen parameters by ±20%; SI = [(NPV_high − NPV_low) / (2 × NPV_base)] / 0.20, and |SI| ≥ 0.5 was classed as highly sensitive. The discount rate had the largest index (−1.52), which follows from terminal discounting (the elasticity of exp(−ρT) is −ρT = −1.5 by construction), followed by fish productivity and price (+0.58). No ecological parameter exceeded 0.5. Stem mortality (−0.19) was the largest, followed by carbon price (+0.23), soil pH (+0.14), coastal protection (+0.13), and recruitment and water quality (+0.06). Validation used three directional criteria (S2 has the highest carbon value, S0 the highest silvofishery income, densities stay below 681 stems ha^{-1}) and literature benchmarks. Ranking stability over wider ranges is in Table 5.

Several assumptions limit the results. First, bulk density (0.90 g cm^{-3}) and depth (50 cm) come from Ningrum et al. (2024), and initial biomass carbon, litter, and stem density are assumed, not measured. Second, ω and the activity coefficients on decomposition (0.15) and mortality (0.30) are uncalibrated structural assumptions, although ω has negligible influence (SI = +0.001). Third, Val_carbon prices standing stock and not additional sequestration; stocks decline in every scenario, so an additionality-based credit would be much lower. Fourth, terminal discounting makes the Layer 2 ranking convention-dependent. Fifth, rehabilitation cost is a share of pond operating cost, so it is lowest in S2, and full-density planting, fencing, and monitoring costs are not represented. Sixth, the ecological module is not stage-structured: recruitment (about 0.037 yr^{-1} after the environmental modifiers) is below mortality (at least 0.10 yr^{-1}) and biomass growth does not depend on stem density, so the simulated decline in density and carbon is a structural outcome and the ecological

trajectories should be read as indicative, not predictive. The Layer 1 and 3 rankings were stable across Table 5. Table 4 summarizes year-30 metrics. No scenario leads in every layer: S0 leads on tangible NPV, S1 and S3 are tied under conditional carbon value, and S2 leads on total NPV.

Table 4. Summary of Key Metrics at Year 30 Across Four Scenarios

Metric	S0 Baseline	S1 Silvofishery	S2 Restoration	S3 Hybrid
Zone allocation				
Pond fraction (%)	90	70	10	50
Mangrove fraction (%)	10	30	90	50
Ecological subsystem (year 30)				
Stem density (stems ha^{-1}, mangrove zone)	1.32	6.88	8.41	7.76
C_soil (ton C ha^{-1}, mangrove zone)	50.02	49.96	49.92	49.94
WQI pond zone	0.780	0.870	0.910	0.894
Fish production (ton ha^{-1} yr^{-1}, total area)	0.140	0.123	0.019	0.091
Layer 1: Tangible (direct market cash flows, year 30)				
Cumulative silvofishery income (USD ha^{-1})	10,572	9,653	1,448	7,091
Rehabilitation cost (USD ha^{-1})	0	303	65	278
NPV_L1 (tangible; (USD ha^{-1}, discounted 5%)	**2,359**	**2,086**	**309**	**1,520**
BCR_L1	**n/a**	**31.86**	**22.34**	**25.48**
(+ stock-based carbon value, p_cert = 0.50)				
Val_carbon cumulative ((USD ha^{-1})	1,267	3,795	11,379	6,323
NPV_L2 (conditional tangible; (USD ha^{-1}, discounted 5%)	**2,642**	**2,933**	**2,848**	**2,931**
BCR_L2	**n/a**	**44.38**	**197.96**	**48.19**
Layer 3: Intangible (+ ecosystem services, benefit transfer)				
Val_ES cumulative (USD ha^{-1})	283	3,024	9,603	5,213
NPV_L3 (total; (USD ha^{-1}, discounted 5%)	**2,705**	**3,608**	**4,990**	**4,094**
BCR_total	**n/a**	**54.36**	**346.17**	**66.93**

Robustness of The Scenario Ranking

Table 5 tests ranking stability over stress ranges defined by the authors (±50% for fish productivity, fish price, and carbon price; 0.5 to 5 times the rehabilitation share; 0 to 1 for certification probability; 3% to 10% discount rate), since no multi-year local data exist to set realistic ranges.

Table 5. Range Tests of Key Parameters

Parameter and Tested Range	S1 Total NPV at Lowest / Highest Value (USD ha^{-1})	Highest NPV_L1	Highest NPV_L2	Highest NPV_L3
Fish productivity (F_max) or fish price (p_F), 0.5 to 1.5 times base (0.33–0.99 ton ha^{-1} yr^{-1}; USD 1.80–5.40 kg^{-1})	2,565 / 4,651	S0 throughout	S2 at 0.5–0.75 times; S1 at 1.0–1.5 times	S2 throughout
Carbon price (p_C), 0.5 to 1.5 times base (USD 1.64–4.91 per ton CO_2)	3,185 / 4,031	S0 (unaffected)	S1 up to base price; S2 above USD 3.44	S2 throughout
Carbon price, wide stress range (USD 1–20 per ton CO_2)	3,020 / 7,941	S0 (unaffected)	S0 at USD 1; S1 near USD 3; S2 from USD 5	S2 throughout
Rehabilitation cost share (c_rehab), 0.5 to 5 times base (0.05–0.50)	3,642 / 3,338	S0 throughout	S1 at 0.5 and 1 times; S3 at 2 times; S2 at 5 times	S2 throughout
Certification probability (p_cert), 0 to 1	2,761 / 4,455	S0 throughout	S0 at 0; S1 at 0.25–0.50; S2 at 1	S1 at 0; S2 from 0.25
Discount rate (ρ), 3% to 10%	6,574 / 805	S0 throughout	S1 (S3 within USD 5)	S2 throughout

S0 had the highest tangible NPV across every range. S2 had the highest total NPV across every range except zero certification probability, where S1 led (USD 2,761 ha^{-1}). The Layer 2 leader changed with assumptions: S1 and S3 differ by USD 2 ha^{-1} at base values, and S2 overtakes both above about USD 3.4 per ton CO_2, only 5% above the base price, so Layer 2 does not support a ranking. A 50% fall in fish productivity or price lowered S1 total NPV by 29% (to USD 2,565 ha^{-1}) without changing the Layer 1 or 3 ranking.

Policy Implications

The layered ranking is the central policy finding. S0 gives the highest tangible NPV but leaves negligible mangrove recovery (1.32 stems ha^{-1} at year 30). S1 and S3 are practically tied when carbon markets are accessible, but payments for ecosystem services (PES) are absent (USD 2,933 and 2,931 ha^{-1}), and S2 leads in the full-TEV only if non-market values are formally accounted for, which makes full restoration a public good needing climate finance, PES, or regulation, none of which exist at the site. S1 is the robust compromise: positive NPV in all layers (USD 2,086–3,608 ha^{-1}), 88% of baseline tangible NPV, alignment with the *Wanamina* standard, and no need for certification or subsidy. The high BCR values (22.34–346.17) are partly illusory because rehabilitation cost is only 10% of operating cost (USD 65–303 ha^{-1} over 30 years) and is lowest in S2; fixed-cost inputs (full-density planting, fencing, monitoring) would lower them substantially.

CONCLUSION AND SUGGESTION

Conclusion

Scenario S1 (Silvofishery, 70:30) is recommended as a balanced default. It returns positive NPV in all TEV layers without external subsidy, retains 88% of the baseline tangible NPV and raises total NPV by 33%, although it does not lead any single layer. Positive returns are not unique to S1, since all four scenarios were positive. The persistent 14.7% growth suppression indicates that site amelioration is a prerequisite for meaningful ecological recovery and for activating the mangrove–fishery feedback, and a system dynamics model with a soil amelioration module is the next step. Realizing carbon and ecosystem service values depends on formal mechanisms such as VCS certification or PES, which are not yet established in Muara Adang.

Suggestion

Future work could extend with a stage-structured mangrove module and a soil amelioration component that represents how interventions improve site conditions, how long the effects last, and what they cost. Such a model could show how much improvement is needed before recovery begins, whether the added fish and ecosystem service value justifies the cost, and which intervention is most cost-effective. This is a hypothesis for further study and not a result of the present analysis.

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