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Financial Distress in Nature-Based Carbon Markets: A System Dynamics Model of Corporate Liquidity Under Climate Shocks and Revenue Deferral

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A B S T R A C T
Indonesia's carbon market framework reconstitutes peatland conservation as a financially tradable activity through SPE-GRK carbon credits, but its institutional architecture contains structural vulnerabilities such as mandatory Measurement, Reporting, and Verification (MRV) cycle imposed by SRN-PPI creating a temporal mismatch between ongoing operational expenditures and realized carbon revenues. This study develops an integrated System Dynamics model that simultaneously captures financial, ecological, and institutional subsystems to quantify Minimum Cash Threshold (MCT) that peatland restoration companies must maintain to survive MRV waiting period under El Niño climate shocks. Five simulation scenarios reveal that under extreme El Niño conditions, an insolvency trap feedback loop is activated around Month 4, triggering canal maintenance cessation, WTD collapse, and permanent removal of SPE-GRK (ecological collapse), with financial co-payments that cannot be detected by static cost-benefit analysis. Required MCT increases from 68.97 billion rupiah to 172.42 billion rupiah under extreme El Niño conditions, with increases exceeding standard initial reserve. Policy simulations show that accelerating MRV to 12 months alone is insufficient to prevent collapse under S2-equivalent conditions. These findings extend Financial Distress Theory to domain of delayed revenues from nature-based carbon projects.

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INTRODUCTION

Indonesia's tropical peatlands are one of most important ecological assets in global carbon system. Covering approximately 13.4 million hectares, or about 36% of world's tropical peatland area, these ecosystems store approximately 57.4 GtC accumulated over thousands of years (Page & Hooijer, 2016; Anda et al., 2021). Peatland degradation has irreversible consequences, not only for Indonesia's Nationally Determined Contribution (NDC) targets under Paris Agreement, but also for global climate stabilization. 2015 El Niño event illustrated this material vulnerability, a single year of drought triggered peatland fires that released approximately 1.75 GtCO2e, with daily emissions exceeding average daily output of United States economy, resulting in economic losses of approximately USD 28 billion (Field et al., 2016; Harris et al., 2015; Kiely et al., 2021).

In response, Indonesian government operationalized *Nilai Ekonomi Karbon* (NEK) framework through *Peraturan Presiden* No. 98/2021 and established domestic exchange IDXCarbon. This framework allows restoration entities to generate *Sertifikat Pengurangan Emisi Gas Rumah Kaca* (SPE-GRK), which can be monetized at a base average price of IDR 62,533 per tCO2e by 2023 (IEEFA, 2025). In its institutional design, this framework rationally aligns financial incentives with ecological outcomes. However, its financial architecture contains a critical structural vulnerability that has not received sufficient academic attention, carbon revenues are institutionally deferred by mandatory Measurement, Reporting, and Verification (MRV) cycle managed through *Sistem Registri Nasional Pengendalian Perubahan Iklim* (SRN-PPI), which creates an administrative delay of 12–24 months between on-the-ground ecological activities and issuance of tradable credits (Rahmawati & Pratama, 2023). During this period, restoration companies must fund ongoing operational expenses, including canal maintenance, fire patrols, and emergency response, entirely from existing cash reserves, with no offsetting revenue. This temporal asymmetry between realized costs and revenue receipts is what this study defines as illusion of liquidity in peatland carbon market.

A systematic review of existing studies shows that this illusion of liquidity remains structurally unexplored. Predominant peatland economics research uses static Cost-Benefit Analysis (CBA) to evaluate project feasibility (Rahmawati & Pratama, 2023; Santoso et al., 2022), treating long-term carbon revenues as a proxy for financial sustainability without modeling temporal gap between cost expenditures and revenue realization. Veen et al. (2025) show that delays in MRV are financially significant for CDR projects, but use static DCF analysis that fails to model co-evolutionary ecological-financial feedback loops. Sheikh et al. (2025) address barriers to private financing for nature-based solutions at investor level, not at operational cash flow level. Zhang et al. (2024) apply System Dynamics to carbon market pricing mechanisms but not to corporate level. Result is that assumption that carbon credits earned on ground are automatically converted into corporate cash inflows is institutionally untenable within SRN-PPI framework, but no previous study has dynamically modeled this constraint.

This literature gap has significant material consequences. When El Niño climate shocks simultaneously increase operational expenditures by 40–300% above baseline (Spracklen et al., 2021; Lestari et al., 2024) while carbon revenues remain locked in administrative channels, restoration companies face a complex liquidity crisis that static models cannot detect. A mutually reinforcing feedback mechanism operates whereby declining water table depth (WTD) increases maintenance costs in real time, while carbon revenues that would offset these costs remain delayed. If companies reduce canal maintenance budgets in response, infrastructure deteriorates, WTD declines further, IPCC Tier 2 emissions increase exponentially, SPE-GHG volumes decline, and future revenues are irreversibly eroded. This co-evolutionary collapse represents a critical issue at intersection of biophysical dynamics, corporate finance, and institutional design.

Theoretical foundation for this study rests on two complementary frameworks. Financial Distress Theory, specifically Myers' (1977) underinvestment theory, provides a foundation for corporate finance, where firms approaching a liquidity threshold rationally reduce productive investments even with positive long-term net present value (NPV). This study extends Myers' framework to nature-based carbon projects, where indirect costs of financial distress manifest as irreversible ecological collapse or dimensions not present in conventional FDT literature (Warner, 1977; Weiss, 1990). Feedback Systems Theory (Forrester, 1961) provides a structural basis for understanding why long administrative delays in feedback loops generate systemic instability under exogenous shocks. Ecological Economics (Daly & Farley, 2004) provides boundary conditions that require financial subsystem to be modeled as dependent on biophysical constraints.

This study aims to dynamically model interactions between peatland biophysical dynamics (IPCC Tier 2 emission factors), corporate cash flow constraints (Financial Distress Theory), and institutional time delays of SRN-PPI using System Dynamics methodology. Novelty of this study is that it formally integrates biophysical emissions science, carbon market financial modeling, and bureaucratic process analysis into a single dynamically interacting stress testing framework; it extends underinvestment problem of Financial Distress Theory to nature-based carbon projects where financial distress results in irrecoverable ecological costs; and it is first to quantify Minimum Cash Threshold (MCT) which is minimum working capital that peatland restoration companies must maintain to prevent ecological infrastructure degradation during MRV lead time period. This study is guided by two research questions:

1. How does structure of feedback loop between WTD biophysical dynamics, El Niño-driven operational cost burdens, and MRV time delays affect financial viability of peatland restoration companies?
2. What is minimum cash reserve threshold that restoration companies must secure to prevent ecological infrastructure degradation under extreme climate scenarios?

LITERATURE REVIEW

This literature review examines scholarly sources published primarily in last decade (2017–2025) that address three thematic domains: financial distress in a carbon regulatory environment, System Dynamics modeling in carbon market analysis, and empirical peatland restoration economics in Indonesia.

Financial Distress in Carbon Regulatory Environments

Nguyen and Phan (2020) provide a causal foundation by utilizing Australia's Kyoto Protocol ratification as a quasi-natural experiment, showing that high-carbon emitting firms experience a significantly increased risk of financial distress as measured by modified Altman Z-score, with effect amplified for financially constrained firms by setting financial constraints as a multiplier of carbon regulatory pressure. Lambertides and Tsouknidis (2024) strengthen this relationship in European context, showing through a Merton option-based default model that EU-ETS Phase III mandatory auctions produce a statistically significant increase in market-implied bankruptcy probability. Ding et al. (2023) extend empirical scope to China's regulatory environment, documenting that higher corporate carbon emissions are associated with an increased risk of financial distress, which is exacerbated among firms with weaker operational capacity. Adamolekun (2024) establishes a bidirectional relationship between ecological degradation and corporate financial health across 7,949 firms across 70 countries. Caldecott and Dericks (2017) introduced concept of minimum solvency threshold which is minimum financial condition of a firm below which regulatory pressures result in socially detrimental firm failure as a direct theoretical precursor of MCT in this study.

A critical debate in this theme concerns direction of financial distress mechanism due to carbon. Existing literature universally examines financial distress from perspective of carbon regulatory costs. However, no research has examined financial distress arising from revenue side of carbon market, particularly delay in institutionally generated revenues through mandatory administrative verification cycles.

System Dynamics Modeling in Carbon Markets

Zhang et al. (2024) and Chi et al. (2022) represent dominant stream applying System Dynamics to carbon market mechanisms at market or sector level. Zhang et al. built a model with explicit time delays to simulate dynamic interactions between carbon trading markets, green certificate markets, and electricity pricing, finding that integration produces nonlinear price equilibria through endogenous feedback loops inaccessible to static equilibrium analysis. Purnomo et al. (2020) extended application of SD to Indonesian peatland policy, constructing a 30-year simulation showing that policy interventions targeting one feedback loop often produce compensatory responses in other, a direct demonstration of Forrester's counterintuitive system behavior insight. Veen et al. (2025) confirmed that delays in MRV are financially material by showing that digital MRV can shorten break-even timeframe of CDR projects, although their static NPV approach limits ability to model mutually reinforcing feedback loops.

Peatland Restoration Economics in Indonesia

Jalilov et al. (2025) documented that peatland restoration yields substantial economic benefits, but existing assessments fail to comprehensively capture trade-offs and opportunity costs. Harrison et al. (2020) found restoration concessions to be financially unviable without commodity integration due to high costs and low carbon prices, with empirical evidence of financial distress among restoration entities. Sari et al. (2021) estimated that Indonesia's 2.49 million hectare restoration mandate requires USD 4.6 billion through blended financing and green bonds, establishing a baseline for macro-level financing gap. Applegate et al. (2022) identified eight agroforestry models that provide sustainable livelihoods while supporting peatland hydrological rehabilitation. A critical debate concerns whether financial viability can be assessed through a static cost-benefit framework or requires dynamic simulation; this study argues that static frameworks are structurally incapable of identifying MCTs because threshold parameters emerge from dynamic interaction of financial, ecological, and institutional feedback loops.

Table 1 Novelty Positioning Matrix

Author Year	Title	Method	Key Finding	Research Gap / Relevance	Cluster
Nguyen & Phan (2020)	Carbon risk and corporate capital structure	Modified Altman Z-score	Carbon regulatory shock (Kyoto Protocol) causally increased default probability; financially constrained heavy emitters showed amplified distress effects.	Establishes causal FDT channel from regulatory shock to distress.	FDT
Lambertides & Tsoukni dis (2024)	Climate regulation costs and firms' distress risk	Merton option-based default probability model (1998–2019)	EU-ETS Phase III permit auctioning significantly increased market-implied bankruptcy probability for regulated European firms.	Quantifies default probability under cost-side regulatory pressure.	FDT
Ding et al. (2023)	Does carbon emission of firms aggravate risk of financial distress?	Z-score proxy; China 2008–2018	Higher corporate carbon emissions elevate financial distress risk, amplified for firms with low operating ability and weak credit access.	Documents compounded distress mechanism for carbon-exposed, financially constrained firms.	FDT
Adamolekun (2024)	Firm biodiversity risk, climate vulnerabilities, and bankruptcy risk	Altman Z-score & Zmijewski score	Biodiversity risk and climate vulnerability independently elevate bankruptcy likelihood; financial constraints compound effect for carbon-dependent firms.	First global evidence of ecological degradation as financial distress driver.	FDT

Author Year	Title	Method	Key Finding	Research Gap / Relevance	Cluster
Caldecott & Dericks (2017)	Empirical calibration of climate policy using corporate solvency	Altman Z-score; Kolmogorov-Smirnov test	Proposes corporate solvency metrics as objective calibration tools for climate policy stringency; introduces solvency floor concept.	Theoretical antecedent of MCT.	FDT
Zhang et al. (2024)	Dynamic interactions of carbon trading, green certificate and electricity markets	System Dynamics; first-order differential equations; time delay modeling	Coupling carbon and green certificate markets generates nonlinear price equilibria through endogenous feedback loops.	Validates SD for carbon market feedback analysis.	FST
Chi et al. (2022)	Impact of allocation methods on carbon emission trading under electricity marketization	System Dynamics; causal loop diagrams; Vensim	Grandfathering quota allocation outperforms benchmark methods for carbon trading vitality; policy-induced feedback generates counterintuitive outcomes.	Demonstrates SD capacity to capture carbon policy feedback dynamics.	FST
Purnomo et al. (2020)	Reconciling oil palm development and environmental conservation in Indonesia	System Dynamics; Value Chain Analysis; 30-year simulation	Indonesia peatland policy interventions generate multi-loop reinforcing feedback responses that single-variable analysis cannot predict.	Validates SD for Indonesia peatland policy context.	FST
Veen et al. (2025)	Can dMRV unlock industrial CO_2 capture in carbon markets?	Static DCF; NPV; break-even analysis	Digital MRV reduces financial burden of CCS/CDR projects by accelerating credit sales and shortening break-even timelines.	Direct empirical evidence MRV delay is financially material.	FST
Aji et al. (2024)	System dynamics modeling of geothermal potential in Indonesia	System Dynamics; Vensim; Indonesia state-owned enterprise case study	SD model captures feedback relationships between investment, regulatory incentives, and emission reduction in Indonesia's geothermal sector.	Validates SD methodology for Indonesia's environmental policy context.	FST
Jalilov et al. (2025)	Unveiling economic	Systematic	Peatland restoration yields substantial	Maps economic	Context

Author Year	Title	Method	Key Finding	Research Gap / Relevance	Cluster
	dimensions of peatland restoration in Indonesia	literature review	economic benefits but existing valuations fail to comprehensively capture trade-offs and opportunity costs.	landscape of restoration.	
Sheikh et al. (2025)	Unlocking private finance for nature	Systematic literature review	Private finance for NbS requires blended finance mechanisms to overcome high execution risks and limited returns.	Documents investor-level finance barriers.	Context
Applegate et al. (2022)	Agroforestry business models for tropical peatland restoration	Field investigation; economic synthesis	Eight agroforestry models can provide sustainable livelihoods while supporting peatland hydrological rehabilitation.	Empirical baseline for restoration operational models.	Context
Harrison et al. (2020)	Restoration concessions: a second lease on life for tropical forests?	Economic analysis; feasibility study	Restoration concessions are financially unviable without commodity integration due to high costs and low carbon prices.	Empirical evidence of financial distress in restoration entities.	Context
Kiely et al. (2021)	Assessing costs of Indonesian fires and benefits of peatland restoration	Emissions modeling & economic valuation	Restoring degraded peatlands would have reduced 2015 fire CO_2 emissions by 18% and saved USD 8.4 billion in economic losses.	Quantifies economic case for restoration; provides USD 28 billion damage baseline.	Context
Goldstein (2021)	Incompatible uncertainty in Indonesia's climate change mitigation projects	Qualitative analysis; interviews; document review	Scientific and financial uncertainty incompatibility stymies implementation of market-based climate mitigation projects in Indonesia.	Documents institutional uncertainty in Indonesia's carbon projects.	Context
Sari et al. (2021)	Innovative financing for peatland restoration in Indonesia	Cost estimation; financial mechanism review; BRG analysis	Indonesia's 2.49 Mha restoration mandate requires USD 4.6 billion through blended finance and green bonds.	Macro-level financing gap baseline.	Context
Liu & Liang (2020)	Costs and carbon sequestration for REDD+ in Indonesia	Cellular automaton & gain-loss carbon modeling	REDD+ opportunity costs will rise with oil palm expansion; plantation carbon sequestration has	Land-use opportunity cost baseline for Central Kalimantan.	Context

Author Year	Title	Method	Key Finding	Research Gap / Relevance	Cluster
			minimal impact relative to discount rates.		
Murdiyarso et al. (2019)	Tropical peatlands under siege: evidence-based policies	Literature synthesis & policy analysis	Evidence-based policies and higher-tier emission factors are critical for mitigating GHG from tropical peatland conversions globally.	Biophysical and policy foundation for Tier 2 emission factor parameterization.	Context
Hansson & Dargusch (2018)	Financial cost of peatland restoration in Indonesia	Cost estimation	Completing Indonesia's 2-million-hectare restoration mandate requires over USD 4.6 billion.	Operational cost parameterization baseline for model.	Context

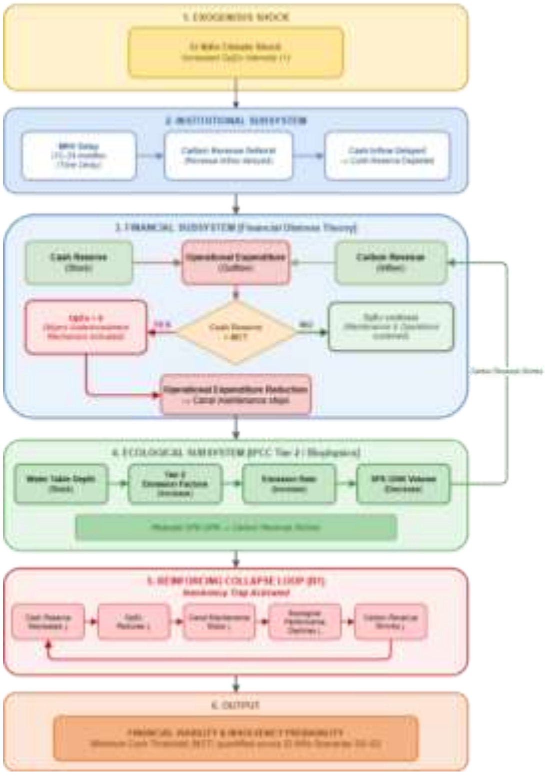

Figure 1. Conceptual Framework

METHODOLOGY

Research Design

This study employs a quantitative simulation approach using System Dynamics (SD) modeling as its primary research design. System Dynamics was chosen over other alternative quantitative methodologies for three reasons. First, phenomenon under study is inherently dynamic and contingent, with financial viability of peatland restoration companies during MRV waiting period being a temporal trajectory shaped by feedback loops, time delays, and non-linear threshold effects that cannot be captured by regression-based causal identification or static cost-benefit analysis. Second, SD methodology is theoretically grounded in Feedback Systems Theory (Forrester, 1961), where institutional rules and regulatory constraints can be mathematically operationalized as simulation parameters (Sterman, 2000). Third, SD allows stress testing across a range of exogenous shock scenarios without requiring real-time empirical observations of undocumented corporate financial collapse events in Indonesia's still-developing carbon market.

Data Sources and Unit of Analysis

This study uses secondary data in two categories. Quantitative Parameter Data includes historical rainfall and El Niño index data from BMKG; IPCC Tier 2 emission factors for tropical peatlands (IPCC 2013 Wetlands Supplement); annual operational and capital expenditure projections from published carbon Project Design Documents (PDDs); and historical IDXCarbon price data (2023–2025). Qualitative Structural Data includes regulatory text from SRN-PPI based on Presidential Regulation No. 98/2021, which is operationalized exclusively as discrete numerical time-delay parameters embedded in simulation equations.

Unit of analysis is a typological peatland restoration company operating under NEK/IDXCarbon framework or a generic entity whose financial parameters are representative of class of companies undertaking hydrological restoration under SRN-PPI verification regime. For primary parameterization, this study selected publicly listed Indonesian peatland restoration projects that met three selection criteria: dual institutional registration under SRN-PPI national registry and IDXCarbon exchange; ensuring that their operational parameters directly reflect financial architecture simulated by model; criterion satisfied by multiple publicly registered projects on Verra Registry operating under Indonesia's NEK framework; and having a concession scale representative of medium-sized tropical peatland restoration operations in Indonesia. This selection approach ensures that extracted parameters are institutional-structural and not idiosyncratic to any single operator. Two publicly listed Indonesian peatland restoration projects with verified carbon accounting datasets are included exclusively as cross-validation sources for parameter triangulation, confirming that baseline OpEx range and emission factor calibration are representative of broader class of restoration companies operating under NEK framework.

Model Parameterization

Table 2 presents IPCC Tier 2 emission factor parameters applied across scenarios. Table 3 presents IDXCarbon carbon price assumptions. Table 4 presents operational expenditure baseline parameters.

Table 2 IPCC Tier 2 Emission Factors by GWL Condition and Simulation Scenario

Condition	GWL depth	EF ($tCO_2e\ ha^{-1}\ yr^{-1}$)	Source	Scenario applied
Baseline	< 30 cm below surface	11.0	IPCC 2013 Wetlands Supplement	Baseline Scenario

Condition	GWL depth	EF ($tCO_2e\ ha^{-1}\ yr^{-1}$)	Source	Scenario applied
Moderate drying	30–50 cm	22.6 – 42.9	Hergoualc'h & Verchot (2014); Melling et al. (2017)	Moderate shock Scenario
El Niño — moderate	50–80 cm	55.0 – 73.0	Murdiyarso et al. (2019); Warren et al. (2022)	Extreme shock Scenario
El Niño — extreme	> 80 cm (fire risk)	73.0 – 100.0	Hooijer et al. (2010); Husnain et al. (2014)	Stress test Scenario
Post-OpEx	> 100 cm	> 100.0	Model-derived (reinforcing feedback loop activation)	Endogenous collapse Scenario

Note. EF values applied as annual average per hectare of active project area. GWL–CO_2 flux relationship is modeled as a piecewise linear function per IPCC Tier 2 guidance, with El Niño multipliers derived from Warren et al. (2022) non-linear correction factors.

Table 3 IDXCarbon Carbon Price Assumptions

Price scenario	IDR/tCO_2e	USD/tCO_2e	Source	Model use
Opening price (launch day, Sep 2023)	69,600	≈ 4.51	IETA Business Brief (2025); IDXCarbon official records	S1 upper bound
Baseline model price (2023 annual avg.)	**62,533**	**≈ 4.10**	**IEEFA (2025) — Two Years After Launch Report**	**S0, S1, S2 primary**
2024 annual average (declining market)	55,985	≈ 3.90	IEEFA (2025)	S2 conservative
March 2025 trough (5-month decline)	32,612	≈ 1.98	Lundgreen's Investor Insights (2025)	S3 stress test
Regulatory floor (minimum permissible)	200	≈ 0.01	ICAP Indonesia ETS Factsheet (2025)	Extreme condition test (Barlas, 1996)

Table 4 Operational Expenditure (OpEx) Baseline Parameters

Cost component	Unit cost (USD)	Basis	Source
Canal blocking maintenance (normal year)	USD 2–5 / tCO_2e avoided (≈ USD 150–375 / ha / yr)	Per ha of active restoration zone	Griscom et al. (2022, IOP Science); Evers et al. (2020)
Fire patrol & prevention (normal year)	USD 0.50–2.00 / ha / yr	Per project hectare	Indonesian peatland restoration PDDs (publicly registered, Verra Registry); BRG technical cost estimates
Additional fire patrol (El Niño — moderate)	+40–60% above baseline	El Niño multiplier applied to base patrol cost	Spracklen et al. (2021, Nature Communications); Lestari et al. (2024)
Emergency fire suppression (El Niño — extreme)	+150–300% above baseline	Based on 2015 fire event cost decomposition	Kiely et al. (2021) / Spracklen et al. (2021)
Total OpEx baseline (normal year, per project)			

MRV Administrative Delay Parameters

Administrative delay of SRN-PPI verification process constitutes central structural parameter of this model. MRV delay interval, stipulated as a 12–24 month verification cycle under Presidential Regulation No. 98/2021, is converted into a discrete time-delay function (ΔMRV) embedded within carbon revenue equation, such that no cash inflow is possible prior to ΔMRV months after field activity commencement. Table 5 presents MRV parameters and their qualitative-to-quantitative operationalization.

Table 5 MRV Administrative Delay Parameters: Qualitative Source and Quantitative Operationalization

Parameter	Value	Qualitative source (regulation / document)	Operationalization into model parameter
SRN-PPI standard verification cycle	12–24 months	Presidential Regulation No. 98/2021, Article 68; SRN-PPI SOP	Converted to ΔMRV time-delay parameter in Eq. (4): revenue inflow = 0 for t < t_shock + ΔMRV
Model baseline MRV delay (ΔMRV)	**18 months**	**Rahmawati & Pratama (2023); Santoso et al. (2022) — midpoint of 12–24 month range**	**Primary ΔMRV in Eq. (4); baseline for S0, S1, S2 scenarios**
Optimistic delay — sensitivity test (dMRV)	12 months	Veen et al. (2025) — digital MRV lower bound projection	ΔMRV = 12 in Eq. (4); applied exclusively in S4 policy sensitivity scenario
Pessimistic delay — stress test	24 months	UNFCCC CDM historical average; Rahmawati & Pratama (2023)	ΔMRV = 24 in Eq. (4); applied in S3 stress-test scenario
Minimum operational standard — canal maintenance	Regulatory threshold	BRG Technical Guidelines (2021); Indonesian peatland restoration PDDs (operational minimum standards)	Operationalized as binary decision rule in Eq. (5): OpEx_canal = 0 triggers insolvency trap feedback
Time to insolvency trap (no buffer, S2 conditions)	~14 months post-shock	Model-derived; consistent with Discussion section finding	Emergent output of Eqs. (1)–(6) interaction; not a direct parameter input
Simulation time horizon	60 months (5 years)	Covers full MRV cycle + post-recovery period	Sets loop termination condition in Vensim FINAL TIME = 60 months

Five simulation scenarios are defined to systematically examine model behavior across a range of climate and market conditions, addressing both research questions and satisfying Barlas' (1996) three validation tests. Table 6 presents scenario specifications.

Table 6 Simulation Scenario Specifications

Scenario	GWL (cm)	El Niño	Carbon price	MRV delay	Expected outcome
S0	< 30	None	IDR 62,533	18 months	Solvent; model output validated against PDD projections (Behavior Reproduction Test)
S1	30–50	Moderate (2019-type)	IDR 55,985	18 months	Cash stress; minimum threshold approached but not breached; operations remain viable
S2	50–80	Extreme (2015-type)	IDR 55,985	18 months	Threshold breached ~14 months post-shock; insolvency trap activated; cost-cutting triggers ecological feedback
S3	> 80	Extreme + price collapse	IDR 32,612	24 months	Rapid financial collapse; secondary ecological feedback loop triggered; reinforces Extreme Condition Test (Barlas, 1996)
S4	50–80	Extreme (2015-type)	IDR 55,985	12 months	Policy sensitivity test: whether accelerated dMRV (Veen et al., 2025) structurally prevents insolvency trap under S2 conditions

System Dynamics model is operationalized through a series of stock-and-flow equations that mathematically encode the causal relationships depicted in conceptual model. Model contains one primary stock variable (corporate cash reserve), two rate variables (OpEx outflow and carbon revenue inflow), and one delay function (MRV administrative pipeline). Following equations constitute formal mathematical structure of simulation.

Equation (1): Cash Reserve accumulation:

$$\boldsymbol{CR_t = CR_{(t-1)} + R_t - OpEx\,Total_t \ldots} \quad (1)$$

Where:

CR_t = Corporate cash reserve at time t (IDR)

R_t = Carbon revenue inflow at time t (IDR/month)

$OpEx\,Total_t$ = Total operational expenditure outflow (IDR/month)

Equation (2): CO_2 emission as a function of Groundwater Table Level:

$$\boldsymbol{E_t = EF(GWL_t)\ x\ \alpha \ldots}\textbf{(2)}$$

$$\boldsymbol{EF(GWL_t) = \alpha + \beta\ x\ GWL_t}$$

Where:

$\boldsymbol{E_t}$ = Total CO_2 emissions at time t (tCO_2e/year)

$\boldsymbol{EF}$ = Emission factor, linear function of GWL depth (IPCC Tier 2)

α = 11.0 tCO_2e/ha/yr (baseline, GWL < 30 cm)

β = GWL sensitivity coefficient (calibrated from Warren et al., 2022)

A = Active project area (ha)

Equation (3): GWL evolution under El Niño and canal maintenance:

$$\boldsymbol{GWL_t = GWL_{(t-1)} + \delta \mathrm{ElNino}_t - \Pi\ x\ OpEx\ Canal_t \ldots}(3)$$

Where:

$\boldsymbol{\delta \mathrm{ElNino}_t}$ = GWL decline rate due to El Niño (cm/month), activated by ONI (Oceanic Niño Index) threshold

Π = Canal blocking effectiveness coefficient (calibrated from publicly registered Indonesian peatland restoration PDDs and hydrological field measurements)

$\boldsymbol{x\ OpEx\ Canal_t}$ = Canal maintenance expenditure at time t (IDR/month)

Equation (4): Revenue with administrative time delay:

$$R_t = 0, if\ t < t_0 + \Delta\mathrm{MRV};\ P_{Carbon} \times\ SPE_t, if\ t \geq t_0 + \Delta\mathrm{MRV} \ldots (4)$$

$$SPE_t = A\ \times [EF_{BAU} - E_t] \ldots (4a)$$

Where:

ΔMRV = MRV administrative delay (18 months, baseline)

P_{Carbon} = IDXCarbon price (IDR 62,533/tCO_2e, baseline)

SPE_t = Eligible carbon credits at time t (tCO_2e)

EF_{BAU} = Business-as-usual emission factor (no project scenario)

Equation (5): Binary decision gate at minimum cash threshold:

$$\mathrm{Decision}_t = \mathrm{Eliminate\ OpEx_{canal}} \mathrm{if}\ CR_t < \mathrm{MCT};\ \mathrm{Normal\ operations\ if}\ CR_t \geq \mathrm{MCT} \ldots (5)$$

$$MCT = OpEx\,Total_{Avg} \times \Delta\mathrm{MRV} \ldots (5a)$$

Where:

MCT = Minimum Cash Threshold (IDR) - primary model output

$OpEx\,Total_{Avg}$ = Average monthly total OpEx under El Niño conditions

Equation (6): Reinforcing feedback triggered by Decision = Cut

IF Decision(t) = 'Cut': $\mathrm{OpEx_{canal(t)}} = 0$ → GWL(t)declines faster → E(t)increases → SPE(t)decreases
→ R(t)decreases further
→ CR(t)depletes faster. This reinforcing loop constitutes INSOLVENCY TRAP mechanism.
Reversal requires external capital injection > MCT

Credibility of model was established through three structural validation tests following Barlas (1996) where a Behavioral Reproduction Test was conducted by comparing baseline simulated emission trajectory S0 with historical PDD projections, followed by an Extreme Condition Test by exposing model to boundary conditions and a Dimensional Consistency Test by ensuring all equations maintain mathematically consistent units across biophysical

(tCO_2e/ha/year) and financial (IDR/month) sectors. Figures 2 and 3 present conceptual framework and conceptual model, respectively.

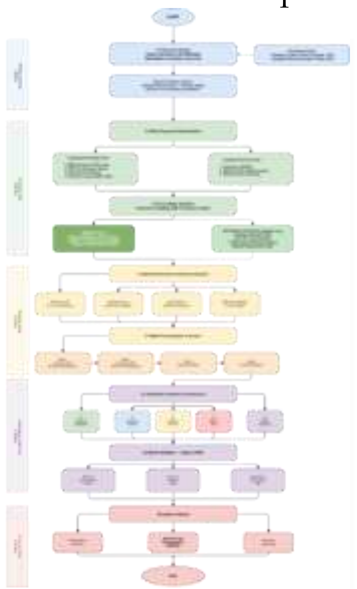

Figure 2. Conceptual Model

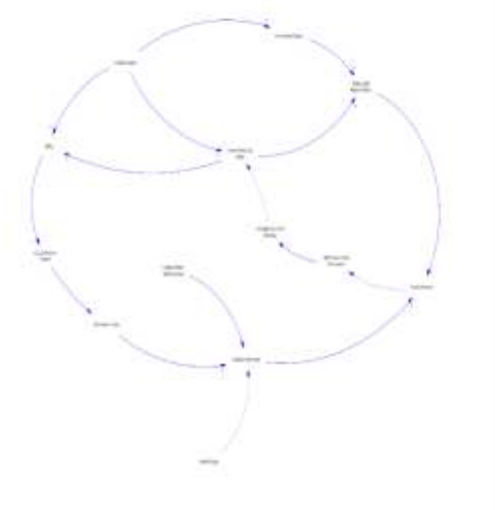

Figure 3. Causal Loop Diagram

RESEARCH RESULT

This section presents simulation results from five scenarios structured around three interdependent subsystems of model financial subsystem (Cash Reserve dynamics), ecological subsystem (WTD and SPE-GRK trajectories), and institutional subsystem (MRV delay and carbon revenue receipt timing). All monetary values are expressed in Indonesian Rupiah (IDR) unless otherwise stated.

Baseline: Financial Viability Under Normal Conditions

Under S0 conditions, model produces three behavioral patterns consistent with Behavior Reproduction Test expectations. First, Cash Reserve initiates at IDR 103.45 billion and follows a linear decline of approximately IDR 3.83 billion per month throughout pre-revenue period (Months 0–17), reflecting continuous OpEx outflows with no offsetting revenue which consistent with Myers' (1977) prediction of systematic reserve depletion under fixed cost obligations. At Month 18, first carbon revenue spike of approximately IDR 81 billion arrests decline, producing characteristic sawtooth pattern recurring at Months 36 and 54

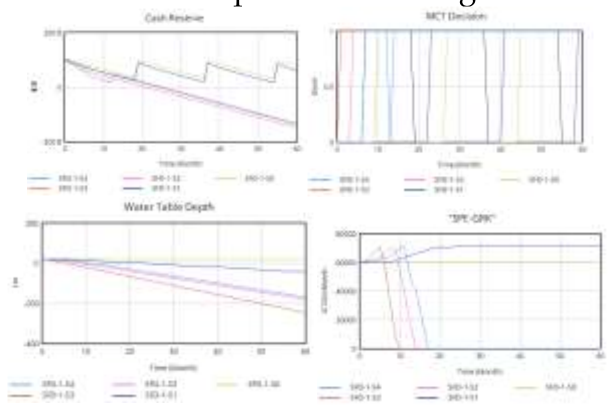

Figure 4. System Dynamic Result

Critically, Cash Reserve never descends below MCT threshold across 60-month horizon, confirming solvency under baseline conditions consistent with PDD financial viability projections. Second, WTD stabilizes at 20 cm throughout simulation, reproducing BRGM's operational target of maintaining GWL at ≤ 40 cm below surface (BRGM, 2023). Third, SPE-GRK ramps from approximately 60,000 to a plateau of 72,000 tCO_2e/month by Month 8, consistent with empirical evidence that peatland hydrological stabilization requires 6–12 months post-intervention (Applegate et al., 2022).

Moderate El Niño: Cash Stress Without Systemic Collapse

Under S1, Cash Reserve depletion accelerates to approximately IDR 5.36 billion per month, about 40% above S0 baseline, as El Niño multiplier inflates OpEx through emergency canal maintenance and fire patrol costs, consistent with Spracklen et al. (2021) and Lestari et al. (2024). Cash Reserve before first revenue spike approaches IDR 6.9 billion, below MCT of IDR 68.97 billion, activating MCT Decision rule. However, because rule reduces OpEx to emergency minimum, burn rate slows sufficiently to prevent Cash Reserve from reaching zero before Month 18 payment arrival.

MCT Decision activation in S1 is periodic rather than permanent, reflecting alternating periods of stress and partial recovery corresponding to revenue spike cycle.

WTD declines gradually to approximately −40 cm by Month 60, but remains below EF_BAU across most of simulation, preserving a positive SPE-GRK throughout. This stressed but solvent behavioral mode represents boundary condition predicted by Myers' (1977) underinvestment theory.

Extreme El Niño: Insolvency Trap and Ecological Collapse

S2 produces most theoretically significant behavioral outcome of this model, where mutually reinforcing activation and persistence of R1 insolvency trap feedback loop occur. Cash Reserves deplete by Rp 9.58 billion per month under normal operations, reaching MCT threshold around Month 4. Unlike S1, MCT Decision in S2 switches to 1 and remains permanent, as emergency cut OpEx rate (Rp 3.83 billion per month) is insufficient to halt depletion given simultaneous absence of Carbon Revenue.

Permanent activation of MCT Decision completely eliminates Canal Effect, thus eliminating only mechanism capable of mitigating groundwater level decline caused by El Niño conditions. Without Canal Effect and with a Groundwater Level Decrease of up to 3.5 cm $month^{-1}$, Groundwater Level Depth (WTD) crosses zero threshold at approximately Month 6 and subsequently enters a dry peat regime.

This transition triggers a nonlinear increase in Emission Factor (EF), which intersects baseline emission rate (EF_{BAU} = 100 $tCO_2e\ ha^{-1}\ yr^{-1}$) when WTD reaches approximately −24 cm, corresponding to approximately Month 11. Consequently, SPE-GHG decreases to zero at approximately Month 14, permanently eliminating only inflow to Cash Reserve stock.

Thereafter, system enters a deterministic debt trajectory, with cash balance reaching approximately minus IDR 150 billion at Month 60. This system exhibits a mutually reinforcing pattern of behavior in which cash reserve depletion leads to canal shutdown, triggering a decrease in water table depth (WTD), removal of SPE-GHG, permanent revenue losses, and ultimately further acceleration of cash reserve depletion. This pattern is an empirical manifestation of reinforcing feedback loop R1 proposed in conceptual framework.

Policy Intervention: Accelerated MRV

S4 applies conditions of S2 with one policy intervention: ΔMRV is reduced from 18 to 12 months. First Carbon Revenue spike arrives in Month 12, with a surge of IDR 40.3 billion compared to IDR 60.5 billion under S2 because shorter accumulation window reduces total credits available per cycle. Net deficit per cycle under S4 is minus IDR 74.6 billion compared to minus IDR 112.0 billion under S2, a 33% increase, but not enough to shift cycle from deficit to surplus. Consequently, trajectories of S4's Cash Reserves and SPE-GRK are nearly identical to those of S2 after Month 20: collapse occurs over same timeframe, and insolvency trap is active with same permanence. This suggests that accelerating MRV alone, without accompanying OpEx reductions or carbon price increases, does not prevent ecological-financial collapse under El Niño conditions equivalent to S2.

Table 7 Cross-Scenario Simulation Output Summary

Scenario	Cash Reserve Nadir (IDR)	Month MCT First Breached	SPE-GRK Collapse Month	WTD at Month 60 (cm)	Solvency Status
S0	~IDR 34.5 B (Month 17)	Never	No collapse	+20 (stable)	SOLVENT
S1	~IDR 6.9 B (Month 17)	~Month 2 (periodic, recovers)	No collapse	−40 (declining)	STRESSED
S2	< 0 (Month 18 onward)	~Month 4 (permanent)	Month ~14	−170	INSOLVENT
S3	< 0 (earlier than S2)	~Month 2 (permanent)	Month ~9	< −175	INSOLVENT (accelerated)
S4	< 0 (Month 18 onward)	~Month 4 (permanent)	Month ~14	−170	INSOLVENT (dMRV insufficient)

Note. MCT = Minimum Cash Threshold = IDR 68.97 B (baseline). IDR 1 B = IDR 1,000,000,000.

Table 8 MCT Quantification Across Scenarios

Scenario	OpEx/Month (IDR)	ΔMRV (months)	Required MCT (IDR)	MCT × 1.5 Initial Reserve (IDR)	Adequacy Assessment
S0 (Baseline)	3.83 B	18	68.97 B	103.45 B	ADEQUATE — surplus IDR 34.5 B above MCT
S1 (Moderate El Niño)	5.36 B (+40%)	18	96.55 B	103.45 B	MARGINAL — buffer only IDR 6.9 B above adjusted MCT
S2 (Extreme El Niño)	9.58 B (+150%)	18	172.42 B	103.45 B	INADEQUATE — shortfall IDR 68.97 B; collapse inevitable
S3 (Stress Test)	15.33 B (+300%)	24	367.82 B	103.45 B	GROSSLY INADEQUATE — shortfall IDR 264.37 B

Scenario	OpEx/Month (IDR)	ΔMRV (months)	Required MCT (IDR)	MCT × 1.5 Initial Reserve (IDR)	Adequacy Assessment
S4 (dMRV=12, S2)	9.58 B (+150%)	12	114.95 B	103.45 B	STILL INADEQUATE — shortfall IDR 11.5 B despite dMRV

Note. Required MCT = OpEx per Month × ΔMRV. IDR 1 B = IDR 1,000,000,000.

DISCUSSION

Feedback Loop Structure and Financial Viability

First research question asks how feedback loop structure between WTD biophysical dynamics, El Niño-driven operational cost burdens, and MRV time delays jointly affects financial viability of peatland restoration companies. Simulation results demonstrate that financial viability is not determined by any single variable in isolation but by interaction timing between three structural elements: rate at which El Niño-driven GWL decline erodes ecological asset base, rate at which ΔMRV delay withholds compensating revenue inflows, and rate at which El Niño-amplified OpEx exhausts cash buffer. This finding extends Forrester's (1961) foundational insight that system behavior is determined by feedback structure rather than parameters, confirming that specific architecture of Indonesia's SRN-PPI framework creates an inherent structural vulnerability incapable of mitigation through market-level interventions alone.

Simulation S1 is theoretically important because it reveals that R1 loop is not unconditionally active. Under moderate El Niño conditions, MCT Decision rule functions as a corrective negative feedback mechanism (balancing loop B1) that partially offsets R1 dynamics by reducing rate of cash outlays as reserves approach a threshold, consistent with Myers' (1977) rational underinvestment prediction. Critical difference between S1 and S2 is that in S1, underinvestment response is sufficient to delay collapse until revenues arrive, whereas in S2, rate of decline in GWL is too rapid for B1 loop to compensate before WTD crosses ecological catastrophe threshold. This threshold behavior, bifurcation between distressed but solvent conditions and irreversible collapse, is not predictable solely from individual parameter values, as it arises from interaction of three simultaneously operating feedback loops—precisely class of structural behavior identified by Zhang et al. (2024) and Chi et al. (2022) as essentially inaccessible to regression-based methods.

Minimum Cash Threshold Quantification and Policy Implications

Second research question examines minimum Cash Reserve Threshold Restoration (MCT) that restoration companies must maintain to prevent degradation of ecological infrastructure during Monitoring, Reporting, and Verification (MRV) period under extreme climate conditions. Simulation results presented in Table 8 indicate that required MCT can be expressed as:

$$MCT = OpEx(\text{El Niño Multiplier}) \times \Delta\text{MRV}$$

Under baseline conditions (S0), standard MCT of IDR 68.97 billion is sufficient to maintain operational continuity. Given an initial cash reserve of IDR 103.45 billion, system retains a safety buffer of approximately IDR 34.5 billion. However, under moderate El Niño conditions (S1), effective MCT increases to

IDR 96.55 billion, reducing available safety buffer to approximately IDR 6.9 billion, representing a decline of nearly 79% relative to baseline scenario. Under extreme El Niño conditions (S2), required MCT rises substantially to IDR 172.42 billion, exceeding initial cash reserve by IDR 68.97 billion. Consequently, available financial resources become insufficient to sustain canal operations throughout MRV period, rendering insolvency a structurally unavoidable outcome within model.

Simulation S4 directly tests most common policy recommendation in MRV reform literature: accelerating verification cycle (Veen et al., 2025; Rahmawati & Pratama, 2023). Results show that reducing ΔMRV from 18 to 12 months under equivalent conditions S2 reduces deficit per cycle by 33% but does not prevent bankruptcy. Simulation reveals that revenue reduction associated with shorter accumulation window (IDR 40.3 billion versus IDR 60.5 billion per surge) partially offsets liquidity benefits of earlier payment timing. This challenges policy consensus that accelerated ΔMRV is a sufficient intervention to improve viability of restoration companies under climate stress. Effectiveness of accelerated MRV as a policy depends on intensity of El Niño: it may be sufficient under moderate shocks (S1) but is structurally inadequate under extreme shocks (S2), as root cause of collapse is not payment delay itself, but level of OpEx amplification relative to ecological asset base.

Therefore, effective interventions require addressing cost-amplifying side of feedback loop, not just timing of revenue receipts. Three complementary mechanisms emerge: a pre-funded contingency reserve capitalized to an El Niño-adjusted MCT level prior to project commencement, consistent with blended financing architecture proposed by Sheikh et al. (2025); a contingency liquidity facility activated upon MCT breach that provides interest-free bridge financing until next MRV issuance cycle, with reference to parametric climate insurance instruments reviewed by Adamolekun (2024); and regulatory MCT disclosure requirements that require PDDs submitted under SRN-PPI framework to include scenario-specific MCT projections calibrated to historical frequency of ENSO for project's geographic location.

Theoretical Contributions and Novelty Positioning

Novelty of this study lies in three distinct contributions. First, it extends Financial Distress Theory (FDT) to realm of revenue delays in nature-based carbon markets. Existing empirical FDT literature universally examines financial distress from cost side of carbon regulation. This study demonstrates that Myers' (1977) underinvestment mechanism operates with equal force on revenue side when institutional processes impose mandatory delays between ecological activity and financial realization. Critical difference is that in nature-based carbon context, underinvestment response destroys not industrial capital but living ecological infrastructure whose water table, peat moisture content, and hydrological conditions support future credit generation, making indirect costs of financial distress (Warner, 1977; Weiss, 1990) irreversible rather than simply costly.

Second, this study reorients modeling of carbon market dynamics systems from sector level to corporate level, incorporating ecological feedbacks that determine future revenue capacity. Existing SD carbon market studies (including Zhang et al. (2024), Chi et al. (2022), and Purnomo et al. (2020)) operate at market or sector level without addressing internal financial dynamics of individual market participants. By constructing a firm-level SD model that integrates cash reserve dynamics with WTD trajectories and IPCC Tier 2 emission factors as endogenous variables, this study demonstrates that most policy-relevant questions in nature-based carbon markets are essentially corporate-level questions.

Third, this study introduces a dynamically derived MCT benchmark as first quantifiable solvency threshold for nature-based carbon project operators under Indonesian SRN-PPI framework. While Caldecott and Dericks (2017) proposed theoretical architecture of a solvency floor for climate policy calibration, no prior study has operationalized a specific, ecologically-sensitive financial threshold applicable to restoration companies in emerging carbon markets. Scenario-specific MCT values produced by this study are directly applicable to project finance structuring, investor due diligence, and regulatory standard-setting.

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that financial viability of peatland carbon restoration projects is determined not only by their long-term ecological potential or profitability, but also by their ability to withstand short-term liquidity constraints. In response to first research question, System Dynamics model reveals a critical temporal mismatch in feedback loop structure whereby exogenous El Niño climate shocks and resulting maintenance operational costs instantly and continuously deplete companies' cash reserves, while financial compensation for avoided emissions is essentially trapped by 12–24-month administrative MRV delay. In response to second research question, study asserts that restoration companies must secure a certain Minimum Cash Threshold capable of supporting ecological infrastructure costs in real time throughout entire MRV lead time. Failure to maintain this threshold inevitably triggers an insolvency trap, forcing management to slash maintenance budgets, which then leads to irreversible secondary ecological collapse and an exponential surge in Tier 2 emissions.

ADVANCED RESEARCH

The study has a number of methodological limitations, which also point to future research directions. The simulation model is parameterized from a single typological project design document calibrated to a medium-sized concession in Indonesia’s tropical peatland sector. In this model, carbon prices are treated as static scenario parameters, abstracting away from the observed volatility of IDXCarbon from its September 2023 opening through its March 2025 trough. Relationship between WTD and Emission Factors is modelled as a piecewise linear function, consistent with the IPCC Tier 2 guidance.

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