SAVi Sustainable Asset Valuation

How to Make Investments in Land Rehabilitation Economically Viable:

Lessons learned from peatland and mangroves in Indonesia, a sustainable asset valuation assessment

IISD International Institute for Sustainable Development

UKaid from the British people

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About the Sustainable Asset Valuation methodology

Sustainable Asset Valuation (SAVi) is a simulation service that helps governments and investors value the many risks and externalities that affect the performance of infrastructure projects.

The distinctive features of SAVi are:

- Valuation: SAVi values, in financial terms, the material environmental, social, and economic risks and externalities of infrastructure projects. These variables are ignored in traditional financial analyses.
- Simulation: SAVi combines the results of systems thinking and system dynamics simulation with project finance modelling. We engage with asset owners to identify the risks material to their infrastructure projects and then design appropriate simulation scenarios.
- Customization: SAVi is customized to individual infrastructure projects.

For more information on SAVi: www.iisd.org/savi

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Executive Summary

This report presents the results of a Sustainable Asset Valuation (SAVi) assessment for peatland and mangrove restoration in Indonesia.

From our analysis, the following key messages emerge:

- **Money matters:** To make land rehabilitation long-lasting and more economically viable, local communities need an additional source of income (e.g., tourism or carbon storage payments). Otherwise, local communities turn to environmentally damaging activities, such as plantations and mining. This ultimately has less societal benefit than sustainable land management.
- **Land rehabilitation is a long-term effort:** One-time interventions, such as blocking peatland canals or restoring mangroves without monitoring and maintenance, are less effective than continuous management and stewardship. These long-term efforts can avoid land conversion and increase resilience to extreme events. However, long-term impacts may not play into decision making when future benefits are discounted.
- **Use packages of interventions instead of isolated measures:** Combining measures makes the projects more successful. Peatland restoration (blocking canals and planting trees) brings the largest benefits in combination with fire suppression and with monitoring to prevent the conversion of forest to plantations and mining. Planting mangroves works best when combined with ecotourism.

These results emerge from the assessment of land rehabilitation for peatland forest and mangroves in Indonesia.

Peatland forests provide services, including flood mitigation, fire control, non-timber forest products, and carbon storage. In Indonesia, peatlands have been deforested and drained to meet demand for plantations and mining. This leads to increased fire risks, large carbon emissions, and loss of valuable ecosystems. The Katingan Mentaya Project in Central Kalimantan aims to restore and protect peatland forest by blocking canals, planting trees, and responding more quickly to fires. This project is financed through carbon credits (Katingan Mentaya Project, 2021).

Mangroves protect coasts from floods, store carbon, and provide people with food and income. In Belitung, Indonesia, people have converted mangrove forests to tin mines, leading to environmental degradation and loss of ecosystem services. The Belitung Mangrove Park has been established on former tin mining land as an ecotourism site. The goal of this project is to create sustainable livelihoods that promote a healthy mangrove ecosystem (Indonesia Climate Change Trust Fund [ICCTF], 2019b, 2019a; Yusri et al., 2019).

This SAVi assessment uses system dynamics modelling and financial analysis to analyze restoration options for the Katingan peatlands and Belitung mangroves. We quantify the societal benefits and costs of several policy, land-use, and climate scenarios.

For peatlands, we find that:

- Blocking canals and revegetating peatland, while also monitoring land use and improving fire suppression, brings the highest net benefit for society (USD 4.136 million cumulatively by 2100). These benefits come primarily from avoided carbon emissions and other avoided fire impacts.
- Blocking canals helps raise the water table, but land-use monitoring is necessary to avoid continued deforestation and to mitigate emissions from peat decomposition.
- Fire suppression avoids damages, but it is not sufficient to prevent further peatland degradation.
- Restoring peatland and preventing land conversion for mining and plantations may lead to a decline in local wages and government revenue, but restoration avoids health impacts and flood damages. If carbon payments are invested locally, then restoration can provide more benefits for the community than business as usual (BAU).
- Under all climate scenarios, the package of interventions (peatland restoration, monitoring land, and fire suppression) performs better than isolated policies.

For mangroves, results show that:

- Investing in mangrove rehabilitation for Belitung is economically viable only if connected to the generation of an additional source of revenue, such as ecotourism. This income avoids the desire to convert land for mining.
- Ecotourism and mangrove restoration create more jobs than mining. Ecotourism in the area can generate wages of up to USD 1,600 per capita per year and forms a sustainable source of income for the local community.
- Extreme events are a threat to mangroves and the local economy. Stewardship activities may be necessary to encourage ecosystem recovery after a shock, particularly when considering cumulative impacts.
- Restoration is beneficial regardless of climate change scenario. If the tourism industry is supported, outcomes under different climate scenarios are similar.

Results of the integrated cost-benefit analyses are in Table ES1 and Table ES2.

Table ES1. Peatland restoration integrated cost-benefit analysis for the RCP 4.5 climate scenario. The combination of all policies creates the most value for society. Intervention costs include the upfront and recurring costs of blocking canals, monitoring the land, and fire suppression. All values are in USD million. Cumulative values calculated between 2010 and 2100.

Peatland integrated cost-benefit analysis: Policy scenario comparison

	BAU	Block canals	Monitor land	Block canals + monitor land	Suppress fires	Block canals + monitor land + suppress fires
Avoided cost of carbon emissions	0.00	1,928.32	3,296.66	3,296.02	420.96	3,405.36
Avoided flood damages	0.00	0.74	6.44	6.44	0.79	6.50
Avoided cost of fires	0.00	0.37	1,000.35	1,001.85	649.19	1,422.24
Household income	1,905.69	1,921.06	59.45	74.83	1,974.94	144.16
Intervention costs	0.00	70.60	53.99	124.59	20.17	144.75
Foregone government oil palm revenue	0.00	0.00	697.75	697.75	0.00	697.75
Total	**1,905.69**	**3,779.89**	**3,611.17**	**3,556.81**	**3,025.72**	**4,135.76**
Value compared to BAU	**0.00**	**1,874.20**	**1,705.48**	**1,651.12**	**1,120.03**	**2,230.07**

Table ES2. Mangrove restoration integrated cost-benefit analysis for the RCP 4.5 climate scenario. Ecotourism provides large benefits for the local community. All values are in USD million. Cumulative values calculated between 2010 and 2100.

Mangrove integrated cost-benefit analysis: Policy scenario comparison

	BAU	**Plant mangroves**	**Plant mangroves + ecotourism**	**Plant mangroves + ecotourism + local stewardship**	**Plant mangroves + ecotourism + permeable structures**	**Plant mangroves + ecotourism + unsustainable fishing**
Value of carbon storage	0.00	0.00	0.03	0.06	0.03	0.03
Flood damage from sea level rise, waves, and tsunamis	0.25	0.25	0.05	0.04	0.05	0.05
Household income	27.37	27.53	108.68	114.60	110.92	106.71
Mortality cost of mining	0.10	0.10	0.01	0.01	0.01	0.01
Construction costs	0.00	0.00	1.38	1.38	1.48	1.38
Maintenance costs	0.00	0.00	0.00	0.00	4.12	0.00
Total value	**27.03**	**27.19**	**107.26**	**113.22**	**105.28**	**105.29**
Value compared to BAU	**0.00**	**0.16**	**80.23**	**86.19**	**78.25**	**78.26**

Table ES3. How stakeholders can use the results

Stakeholder	Role in the project	How can the stakeholder use the results of the assessment?
Government	Design, implementation, and finance of nature-based infrastructure (NBI) projects	**Low-carbon development:** Policy-makers can use the results to **justify investments** in peatland and mangrove restoration and scale up such projects, as the assessment illustrates the considerable benefits for sustainable development. *For example, the peatland and mangrove restoration provides positive net benefits.* The results can help government authorities to acknowledge the projects' contribution to **low-carbon development and reaching climate commitments**. *For example, restoring the peatland forest avoids more than 1 billion tons of carbon dioxide emissions over 2010–2100, and the mangrove park can store up to 190,000 tons of carbon dioxide.* The results can also form the basis for mobilizing **funding for peatland and mangrove restoration**, including through carbon offset schemes. *For example, the peatland and mangrove projects provide carbon storage benefits of approximately USD 3 billion and USD 60,000, respectively.* **Policies and project design:** The results can help policy-makers **design successful projects** by combining interventions. *For example, the peatland restoration works best when combined with fire suppression and land-use monitoring.* Government authorities can also use the results to **develop economically viable, long-lasting projects** that benefit local communities. *For example, the mangrove valuation shows that local people depend on additional income from tourism to keep the mangroves.* Policy-makers can use the results to make decisions on topics like **health, flood protection, biodiversity conservation, mining, tourism, and economic development**. *For example, suppressing fires avoids health, economic, and education costs of about USD 650 million over 2010–2100, and the mangroves enable tourism income of up to USD 1,600 per capita per year.*

Stakeholder	Role in the project	How can the stakeholder use the results of the assessment?
Local communities, civil society organizations, and labour unions	Design, use, and management of NBI projects	Civil society organizations can use the results to **raise awareness** of the value of NBI. *For example, the benefits of the projects are far larger than the costs, but this is only apparent when considering system-wide, long-term impacts across multiple sectors.* Civil society organizations can also use the results to **promote and develop climate mitigation projects** that help local communities thrive. *For example, part of the carbon storage benefit from peatland restoration could be reinvested locally.* Labour unions can use the results to **support land management that promotes a just transition** to low-carbon development. For *example, in 2017, the labour union brought the Ministry of Environment and Forestry to Constitutional Court for peatland restoration regulation that limits timber plantations on peatland.*
Donors and funders	Funding of NBI projects	Donors can use the results to make the case for **further peatland and mangrove restoration projects**, as the results illustrate the considerable benefits for climate adaptation and mitigation. *For example, peatland restoration and conservation avoids approximately USD 1.4 billion in fire damages over 2010–2100.* Donors can include the results in their reporting to demonstrate the **impacts of their investments**. *For example, the mangrove restoration stores up to 190,000 tons of carbon dioxide and enables tourism income of USD 1,600 annually when the mangrove park is intact.*
Carbon offsetting sector	Funding of NBI projects	The carbon offsetting sector can use the results to **design effective, lasting carbon storage projects** that consider climate and economic dynamics. *For example, the peatland restoration avoids 1 billion tons of carbon dioxide emissions over 2010–2100 when combined with monitoring and fire suppression.*

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Glossary

Causal loop diagram: A schematic representation of key indicators and variables of the system under evaluation that shows the causal connections between them and contributes to the identification of feedback loops and policy entry points.

Discounting: A finance process to determine the present value of a future cash value.

Feedback loop: "A process whereby an initial cause ripples through a chain of causation ultimately to re-affect itself" (Roberts et al., 1983).

Indicator: Parameters of interest to one or several stakeholders that provide information about the development of key variables in the system over time and trends that unfold under specific conditions (United Nations Environment Program [UNEP], 2014).

Internal Rate of Return (IRR): An indicator of the profitability prospects of a potential investment. The IRR is the discount rate that makes the net present value of all cash flows from a particular project equal to zero. Cash flows net of financing give us the equity IRR.

Methodology: The theoretical approach(es) used for the development of different types of analysis tools and simulation models. This body of knowledge describes both the underlying assumptions used as well as qualitative and quantitative instruments for data collection and parameter estimation (UNEP, 2014).

Model transparency: The degree to which model structure and equations are accessible and make it possible to directly relate model behaviour (i.e., numerical results) to specific structural components of the model (UNEP, 2014).

Model validation: The process of assessing the degree to which model behaviour (i.e., numerical results) is consistent with behaviour observed in reality (i.e., national statistics, established databases) and the evaluation of whether the developed model structure (i.e., equations) is acceptable for capturing the mechanisms underlying the system under study (UNEP, 2014).

Net benefits: The cumulative amount of monetary benefits accrued across all sectors and actors over the lifetime of investments compared to the baseline, reported by the intervention scenario.

Net Present Value (NPV): The difference between the present value of cash inflows net of financing costs and the present value of cash outflows. It is used to analyze the profitability of a projected investment or project.

Scenarios: Expectations about possible future events used to analyze potential responses to these new and upcoming developments. Consequently, scenario analysis is a speculative exercise in which several future development alternatives are identified, explained, and analyzed for discussion on what may cause them and the consequences these future paths may have on our system (e.g., a country or a business).

Simulation model: Models can be regarded as systemic maps in that they are simplifications of reality that help to reduce complexity and describe, at their core, how the system works. Simulation models are quantitative by nature and can be built using one or several methodologies (UNEP, 2014).

Sustainable Internal Rate of Return (S-IRR): An indicator of the net benefit prospects of a potential investment. The S-IRR is the discount rate that makes the net present value of benefits from a particular project equal to zero.

Sustainable Net Present Value (S-NPV): The difference between the present value of benefits and avoided costs net of financing costs and the present value of cash outflows. It is used to analyze the net value of a projected investment or project.

1.0 Introduction

1.1 Peatland and Mangrove Restoration Are Important in Indonesia

Indonesia faces challenges such as natural disasters and depleted natural resources. Increasing floods, droughts, and major fire events impair economic development, threaten people's lives and livelihoods, and affect the climate and environment.

Peatland and mangrove degradation are examples of environmental issues with large socio-economic impacts. Draining peatlands leads to land subsidence, which increases flood risks. Moreover, the drained peat burns easily, leading to fires that threaten public health and emit large amounts of carbon dioxide (Sulaeman et al., 2021; World Bank, 2016, 2019). Peatlands cover about 10% of Indonesia's land area, and they were responsible for 40% of the country's greenhouse gas emissions from 2010 to 2016 (Jessup et al., 2020).

Damaging mangrove forests along Indonesia's coasts leads to erosion, increased flood risks, biodiversity loss, and reduced ecosystem services for local communities (EcoShape, n.d.; Hutchison et al., 2014). Mangroves also store large amounts of carbon that is emitted to the atmosphere when the ecosystems are degraded (Alongi, 2014; Kauffman et al., 2020).

The Indonesian government is working toward sustainability. The current 5-year development plan (2020–2024) sets the path for low-carbon development, and policy-makers are preparing a net-zero plan. According to the country's long-term climate strategy, the government intends to reach peak emissions in 2030 and net-zero emissions by 2060 (Republic of Indonesia, 2021; World Resources Institute [WRI], 2021).

In its nationally determined contributions, Indonesia commits to reducing greenhouse gas emissions by 29–41% by 2030. These commitments include efforts to restore 2 million hectares of degraded peatland by 2030, and to restore and better manage mangrove ecosystems (Republic of Indonesia, 2021; WRI, 2021).

Peatland and mangroves play a key role for climate action. Protecting and restoring these ecosystems avoids emissions and increases carbon sinks. Moreover, they provide a range of other benefits. For example, they regulate water flows and protect people from floods and fires. They supply clean water, timber, and food. Mangroves and peat forests are also home to diverse plants and animals and can be tourist destinations.

However, grasping the value of such nature-based infrastructure (NBI) is very challenging. The benefits are context specific. They differ across locations, evolve over time, and benefit a variety of people. The short-term economic gains of mining and plantations can make it difficult to recognize the long-term value of restoring and maintaining peatland forests and mangroves. Integrated assessments, like this Sustainable Asset Valuation (SAVi) valuation, highlight the social, economic, and environmental value of these ecosystems (Bechauf, 2021). These assessments can support low-carbon development and help identify suitable funding and stakeholder constellations.

1.2 Carbon Financing Is Used for Peatland Restoration in Kalimantan

In Central Kalimantan, peatland forest is increasingly converted into large-scale oil palm plantations and small-scale gold mines (Sills et al., 2014). These land-use changes create income for local communities, companies, and the government. However, lowered water tables lead to more fires and carbon emissions (Hooijer et al., 2012; Sulaeman et al., 2021).

In this report, we present the SAVi assessment for restoring the Katingan peatland forest in Central Kalimantan. Financing for the project comes from certified carbon credits that are sold to offset emissions in other locations and sectors. Working with local communities, the Katingan Mentaya Project aims to mitigate greenhouse gas emissions by preventing forest loss for plantations (Katingan Mentaya Project, 2021). The forest is a biodiversity hotspot and home to some of the world's most endangered species. Preserving the forest thus also helps to protect species like the Bornean Orangutan (Katingan Mentaya Project, 2021).

In this SAVi assessment, we quantify the ecosystem services and economic impacts of three policy interventions in the Katingan forest:

- Rewetting and reforesting degraded peatland
- Land-use monitoring to prevent further forest conversion
- Fire suppression to lessen the impact of burning

We also consider several land-use and climate scenarios. We combine this information in an integrated cost-benefit analysis and calculate the project's financial viability. In addition, we identify insights that could inform further peatland restoration.

1.3 Ecotourism Supports Mangrove Conservation in Belitung

The second NBI project assessed for this report is located on Belitung Island. We used the SAVi method to analyze the costs and benefits of Belitung Mangrove Park, a mangrove restoration and ecotourism site. The mangrove park was created by the local community forest group Seberang Bersatu in collaboration with the Indonesian Coral Reef Foundation TERANGI. Funding was provided by the Indonesia Climate Change Trust Fund (ICCTF) (Yusri et al., 2019). The project aims to sequester carbon, restore degraded land formerly used for tin mining, and create jobs in ecotourism (ICCTF, 2019b).

Belitung Mangrove Park covers about 52 hectares, including 1.5 hectares of restored mangrove forest. There is a track along the mangroves, a watchtower, an information centre, and other facilities for visitors (*Beranda HKM Seberang Bersatu*, 2021; Yusri et al., 2019). Community members are closely involved in the project by restoring mangroves, managing the park, and offering activities for tourists (ICCTF, 2019a, 2019b).

For this report, we modelled the economic value and long-term impacts of mangrove restoration. We consider interactions between mangroves and economic activities, including ecotourism, fishing, and tin mining. We simulate the impacts of climate change and extreme events and present an integrated cost-benefit analysis and financial assessment. From this, we identify policies that can support sustainable ecosystem management.

2.0 Methodology

The SAVi assessment relies on systems thinking and system dynamics modelling to create a project-specific integrated cost-benefit analysis. We calculate the added benefits and avoided costs of restoring and conserving peatland forest and mangroves in Indonesia. We compare the value of these services to the investment costs and calculate the undiscounted net benefits, the net present value (NPV) accounting for the time value of money, the internal rate of return (IRR) and the benefit-to-cost ratio. We present the results under three climate change scenarios (Stocker et al., 2013):

1. A low-emissions scenario, Representative Concentration Pathway (RCP) 4.5, which assumes emissions peak around 2040 and then decline.
2. A medium-emissions scenario, RCP 6.0, which assumes emissions peak around 2080 and then decline.
3. A high-climate change scenario, RCP 8.5, which assumes emissions continue to increase until 2100.

Historical climate observations and climate projections come from Copernicus Climate Change Service, (2018), E.U. Copernicus Marine Service Information (2019a, 2019b), and Hersbach et al. (2019).

3.0 System Dynamics Models Reveal Impacts of Policy Interventions

We have developed two system dynamics models. One simulates the dynamics of the Katingan Peatland Forest in Central Kalimantan province. The other models mangroves and is calibrated to the Belitung Mangrove Park in Bangka Belitung province. In both cases, we consider the biophysical dynamics as well as human behaviour within the ecosystem. We calculate costs and benefits of the NBI and compare the cost to grey infrastructure that provides similar services.

The first step in the process was to create a causal loop diagram (CLD). A CLD is an analytical tool that captures the dynamics of a system. Arrows show causal relationships between variables. An arrow is labelled with a plus sign (+) if the two variables change in the same direction, that is an increase (decrease) in one causes an increase (decrease) in the other. A negative sign (-) indicates that the variables change in opposition directions. From these relationships, it is possible to identify feedback loops, which can either be balancing (B), whereby an increase (decrease) in a variable will ultimately lead to a decrease (increase) in the same variable, or reinforcing (R), in which an increase (decrease) in a variable causes a further increase (decrease) in that variable. By showing the relationships and feedbacks among key socio-economic and environmental indicators, a CLD exposes potential impacts of intervening in the system.

3.1 Peatland Dynamics Explain Patterns of Degradation and Restoration

Peat consists of partially decayed organic matter and is characterized by a high water table close to the surface (Basuki et al., 2021; Hooijer et al., 2010; Jaenicke et al., 2010). In Indonesia, large areas of peatland forests have been converted to agriculture, plantations, and mines.

Typically, canals are built to lower the water table (Basuki et al., 2021; Evans et al., 2019; Hooijer et al., 2012; Jaenicke et al., 2010). This makes the land more suitable for crops and easier to access, but the peat, no longer saturated with water, decomposes, releasing carbon into the atmosphere. This oxidation, as well as compaction of the drying peat and compression of peat below the water table, leads to land subsidence, which restricts groundwater recharge (Basuki et al., 2021; Evans et al., 2019; Hooijer et al., 2012; Jaenicke et al., 2010).

Drained peat is also susceptible to fires that are used to clear vegetation (Sulaeman et al., 2021). These fires smolder underground, are hard to control, and emit large amounts of carbon. As the peat burns, the land subsides further (Hooijer et al., 2010; Jaenicke et al., 2010; Sulaeman et al., 2021). Impacts from fires include damage to infrastructure, transportation, tourism, agriculture, health, education, industry, trade, and the environment (World Bank, 2016, 2019).

Peatlands retain large amounts of water. As the water table drops and vegetation is lost, the capacity of the land to hold water declines. This increases flooding, with negative economic, agricultural, and health impacts (Taufik et al., 2020; Uda et al., 2017).

Peat takes thousands of years to form and cannot be restored once it is lost (Hooijer et al., 2012; Jaenicke et al., 2010). However, rewetting and revegetating peatlands can prevent worsening damage. Blocking canals allows the water table to rise. This prevents further subsidence and emissions from decomposition and mitigates fires and flooding (Jaenicke et al., 2010; Page & Hooijer, 2016; Taufik et al., 2020).

Alternatively, monitoring, responding quickly to, and suppressing fires can slow their spread. However, this does not raise the water table. Thus, the peat continues to decompose, releasing carbon and lowering the land surface.

3.1.1 CLD DISPLAYS IMPORTANT REINFORCING FEEDBACKS

In Figure 1, we capture peatland dynamics in a CLD. The system contains multiple reinforcing feedback loops:

R1—as the water table declines, subsidence increases. This inhibits groundwater recharge, which leads to a lower water table.

R2—with a lower water table, there is less water retention, which decreases groundwater recharge. Hence, the water table continues to decline.

R3—fires become more frequent and severe when the water table is lower, which increases subsidence. This decreases groundwater recharge and lowers the water table, making the landscape more susceptible to fire.

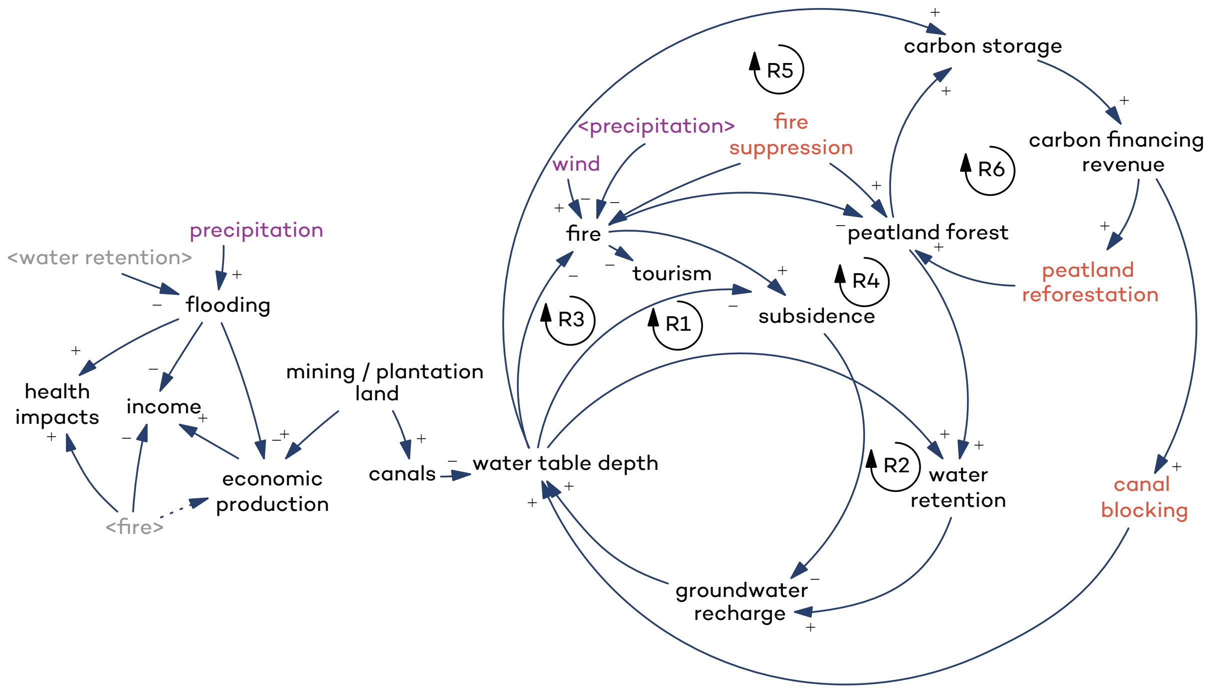
R4—fires burn forest. With less vegetation, there is less water retention and therefore, less groundwater recharge. This lowers the water table, which worsens fires.

R5—raising the water table decreases carbon emissions. As carbon storage increases, carbon financing provides money that can be reinvested in peatland rewetting to further raise the water table.

R6—more peatland forest leads to increased carbon storage. Revenue from carbon financing can be used to reforest more peatland.

These feedback loops show how degraded peatlands continue to emit carbon, further lowering the water table and worsening subsidence once the land has been drained. To mitigate these impacts, it is necessary to reverse the cycles by raising the water table and revegetating the landscape.

Figure 1. Peatland restoration CLD. Orange variables are possible policy interventions. Pink variables are climate inputs. Arrows show causality with plus and minus signs identifying positive and negative correlations, respectively. Feedback loops are labelled as either reinforcing (R) or balancing (B). See the text for a description of peatland dynamics and feedback loops in this system.



3.1.2 PEATLAND MODEL ASSUMPTIONS AND SCENARIOS

The system dynamics model is based on the following assumptions:

- Primary peatland forest is deforested to meet demand for large-scale oil palm plantations and small-scale gold mines. Land conversion is a source of carbon emissions. Secondary forest can be established for restoration.
- Canals are built on converted land. The water table is drained to the canal depth multiplied by the share of land with canals. Peatland subsidence and decomposition emissions are linearly related to the depth of the water table. Precipitation is the only source of water that can raise the water table.
- Fires burn vegetation and peat, contributing to land degradation. This releases additional carbon dioxide (CO_2) and negatively affects health, education, and economic activity, including tourism. High rainfall reduces the probability and extent of fires. As the water table drops, the peat burn depth increases.
- Land subsidence and deforestation increase the share of rainfall that becomes runoff. When runoff exceeds a threshold, a share of assets at risk are damaged from flooding. The total value of assets increases every year, and subsidence raises the fraction at risk.
- Forested areas provide income from non-timber forest products. Plantations, mining, and activities to restore and protect the forest create jobs. Oil palm exports also generate government revenue.

Numerical inputs for the model are in Appendix A (Table A1).

We model the following scenarios:

1. **Business as usual (BAU):** Land conversion for oil palm plantations and gold mines continues throughout the simulation. Primary forest is preferentially used for converted land. No restoration or protection activities are attempted.
2. **Block canals and restore land:** All canals on unused degraded land are blocked, and trees are planted. This transforms the degraded land into secondary forest and allows the water table to rise with precipitation.
3. **Monitor land and stop land conversion:** Land monitoring prevents deforestation for new plantations and mines.
4. **Suppress fires:** Fire suppression reduces the area burned by 25% compared to BAU when a fire occurs.
5. **Limited desired land conversion:** Desired land for oil palm plantations reaches a peak and stabilizes in 2030, while desired land for gold mining reaches a peak and stabilizes in 2040.
6. **No-preference land conversion:** The share of primary forest, secondary forest, and unused degraded land converted to plantations and mines is equal to the current share of each land cover class.

We run the model using precipitation and evaporation projections from RCP 4.5, RCP 6.0, and RCP 8.5 from Copernicus Climate Change Service (2018). Time series for each of these climate scenarios are shown in Appendix A (Figure A1, Figure A2, Figure A3, Figure A4, Figure A5, Figure A6).

For all scenarios, the model is run for 2010 to 2100. Policy interventions are implemented in 2025 and take effect immediately.

3.1.3 PEATLAND MODEL RESULTS AND DISCUSSION

Key findings from the system dynamics model are:

- Blocking canals and revegetating peatland, while also monitoring land use and improving fire suppression, brings the highest net benefit for society (USD 4.136 million cumulatively by 2100). These benefits come primarily from avoided carbon emissions and other avoided fire impacts.
- Blocking canals helps raise the water table, but land-use monitoring is necessary to avoid continued deforestation and to mitigate emissions from peat decomposition.
- Fire suppression avoids damages, but it is not sufficient to prevent further peatland degradation.
- Restoring peatland and preventing land conversion for mining and plantations may lead to a decline in local wages and government revenue, but restoration avoids health impacts and flood damages. If carbon payments are invested locally, then the restoration scenario can provide more benefits for the community than BAU.
- Under all climate scenarios, the package of interventions (peatland restoration, monitoring land, and fire suppression) performs better than isolated policies.

3.1.3.1 Restoring and Conserving Peatland Forests Creates Value for Society

As shown in Table 1, results indicate that enacting all policy interventions (blocking canals and revegetating, monitoring land to prevent further land conversion, and suppressing fires) generates the most value for society, with net benefits of USD 4.14 billion. The high value of restoring and protecting peatland forest comes primarily from avoided carbon emissions (USD 3.41 billion) and the avoided economic, health, and education costs of fires (USD 1.42 billion).

Blocking existing canals will raise the water table compared to BAU. However, without also monitoring the forest to prevent new land conversion, deforestation continues, the water table declines and emissions from peat decomposition rise (Figure 2, Figure 3, Figure 4). Although stopping land conversion reduces employment and public revenues, the lower fire damage and emissions result in net benefits of USD 1.65 billion. This figure grows to USD 4.14 billion when fire suppression is also added.

Suppressing fires without other interventions mitigates USD 649 million in fire damages and does not eliminate plantation and mining jobs. This indicates that, if the cost of fires could be avoided to a large extent, palm oil operations could provide more economic value than restoring the land. However, this is not true when considering environmental impacts and externalities. The water table depth falls, decomposition emissions continue and primary forest is lost (Figure 2, Figure 3, Figure 4). As a result, this scenario has societal net benefits of USD 3.03 billion, which is lower than the benefits of blocking canals and monitoring the land (Table 1).

Stopping new plantations and mining reduces employment opportunities in the area. When land conversion is allowed to continue, income totals over USD 1.9 billion, compared to less than USD 150 million when ecosystem monitoring prevents new plantations and mines. However, the avoided fire damage when all policies are implemented is almost USD 800 million greater than with fire suppression alone (Table 1). Much of this economic, health, and educational damage from fires would be borne by the local community. Avoiding these costs would partially offset the loss of income, but for full community buy-in, more benefits at the local level may be necessary. In Indonesia, the Village Fund is a mechanism to transfer money for sustainable development from higher-level government to villages (Sutiyono et al., 2018). Strengthening these types of fiscal incentives could make restoration more viable. For example, carbon offset revenue could be transferred to the local community.

Furthermore, private sector revenues or profits are not considered in this analysis, given that for the most part these are accrued and reinvested in locations other than our study area. However, because limiting oil palm expansion would decrease production, it is possible that ecosystem restoration would be met with resistance in the oil palm industry.

To reduce carbon emissions, it is necessary to minimize peat decomposition. Suppressing fires mitigates emissions compared to BAU but not as effectively as raising the water table. The scenarios that include monitoring the land to prevent deforestation have the highest water table (Figure 3). These are also the scenarios in which emissions are lowest (Figure 5). However, because the water table stabilizes at about 20 centimetres below the surface, decomposing peat continues to emit approximately 5 million t of CO_2 every year (compared to about 17 million t of CO_2 per year by the end of the century under BAU) (Figure 4).

Practically, when considering a societal perspective to evaluate oil palm expansion on peatland, we move from a value of USD 1.91 billion if current trends of land conversion continue, to USD 4.14 billion cumulatively by 2100. The transition is not trivial, given the important change in the sources of revenue generation. For the investment to be viable, it is essential that the costs of emissions and fires are acknowledged, estimated, and valued. Monetary benefits should be redirected to the local population to offset potential income reduction from other economic activity. In our analysis, considering the cost of carbon (USD 5/ton) already leads to meaningful outcomes of the investment, with the potential to trigger even more investments in land rehabilitation.

Table 1. Integrated cost-benefit analysis for the RCP 4.5 climate scenario. Intervention costs include the upfront and recurring costs of blocking canals, monitoring the land, and fire suppression. The combination of all policies creates the most value for society. All values are in USD million. Cumulative values calculated between 2010 and 2100.

Peatland integrated cost-benefit analysis: Policy scenario comparison

	BAU	Block canals	Monitor land	Block canals + monitor land	Suppress fires	Block canals + monitor land + suppress fires
Avoided cost of carbon emissions	0.00	1,928.32	3,296.66	3,296.02	420.96	3,405.36
Avoided flood damages	0.00	0.74	6.44	6.44	0.79	6.50
Avoided cost of fires	0.00	0.37	1,000.35	1,001.85	649.19	1,422.24
Household income	1,905.69	1,921.06	59.45	74.83	1,974.94	144.16
Intervention costs	0.00	70.60	53.99	124.59	20.17	144.75
Foregone government oil palm revenue	0.00	0.00	697.75	697.75	0.00	697.75
Total	**1,905.69**	**3,779.89**	**3,611.17**	**3,556.81**	**3,025.72**	**4,135.76**
Value compared to BAU	**0.00**	**1,874.20**	**1,705.48**	**1,651.12**	**1,120.03**	**2,230.07**

Figure 2. Area of primary peatland forest under RCP 4.5 for several policy scenarios. Scenarios that include monitoring the land prevent continued loss of primary forest.

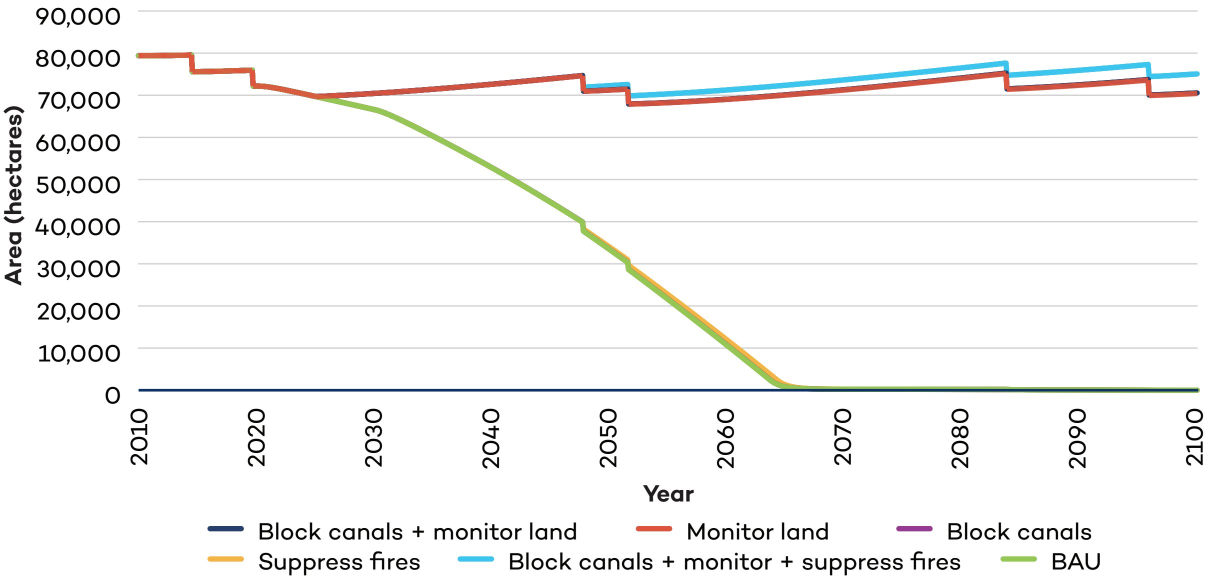


Figure 3. Water table depth under RCP 4.5 for several policy scenarios. Avoiding deforestation by monitoring the land is necessary to prevent the water table from declining. Blocking existing canals helps raise the water table.

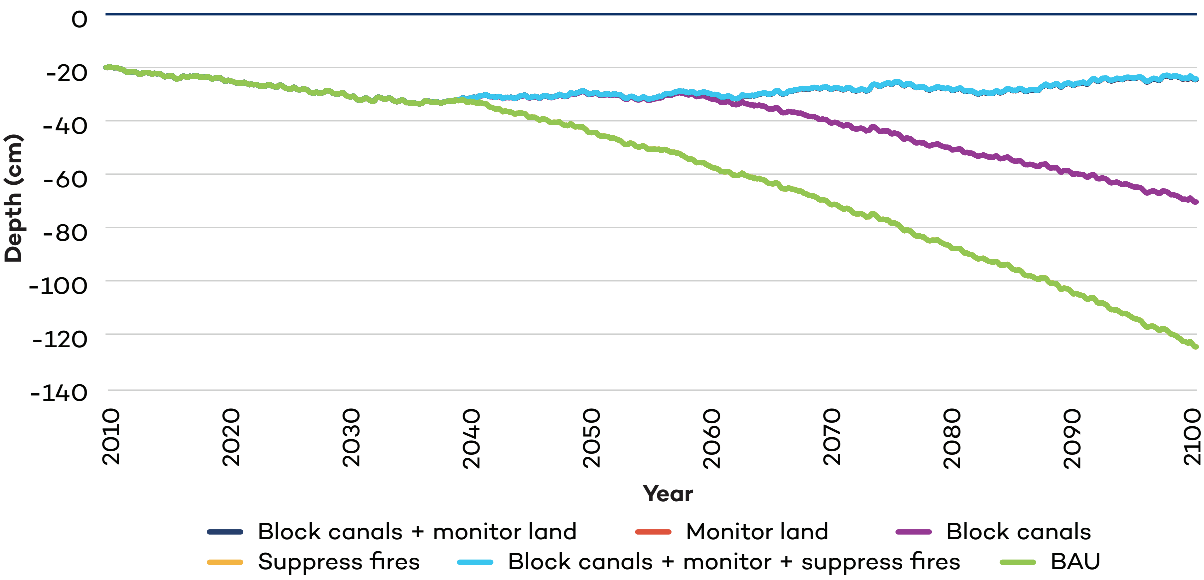


Figure 4. Annual carbon dioxide emissions from peat decomposition under RCP 4.5 for several policy scenarios. Emissions from peat decomposition continue to increase unless the water table is stabilized by blocking canals and/or preventing land conversion.

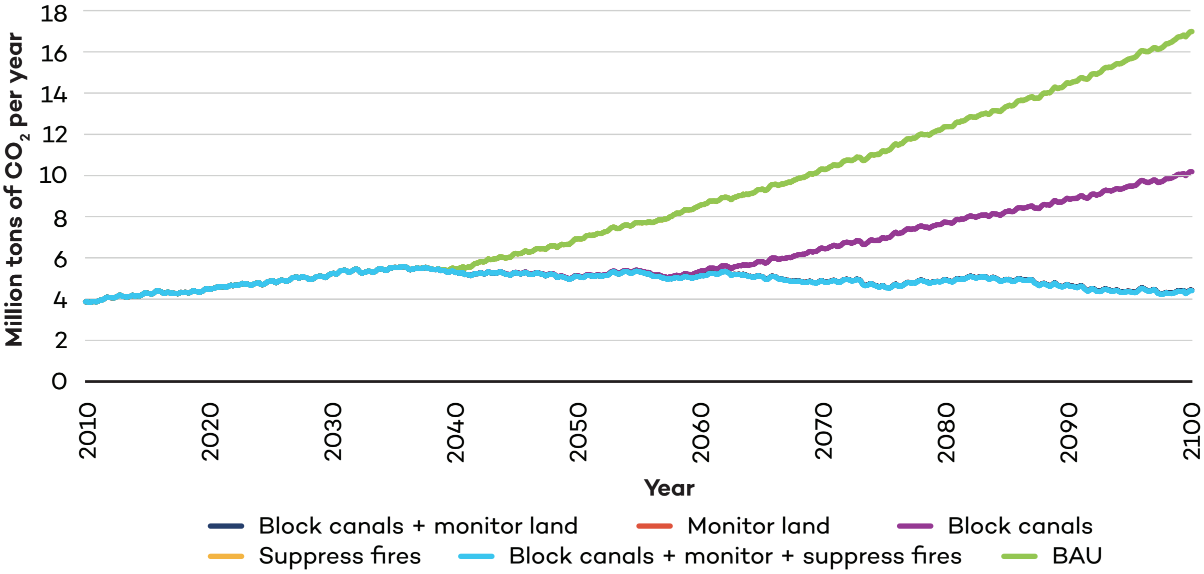
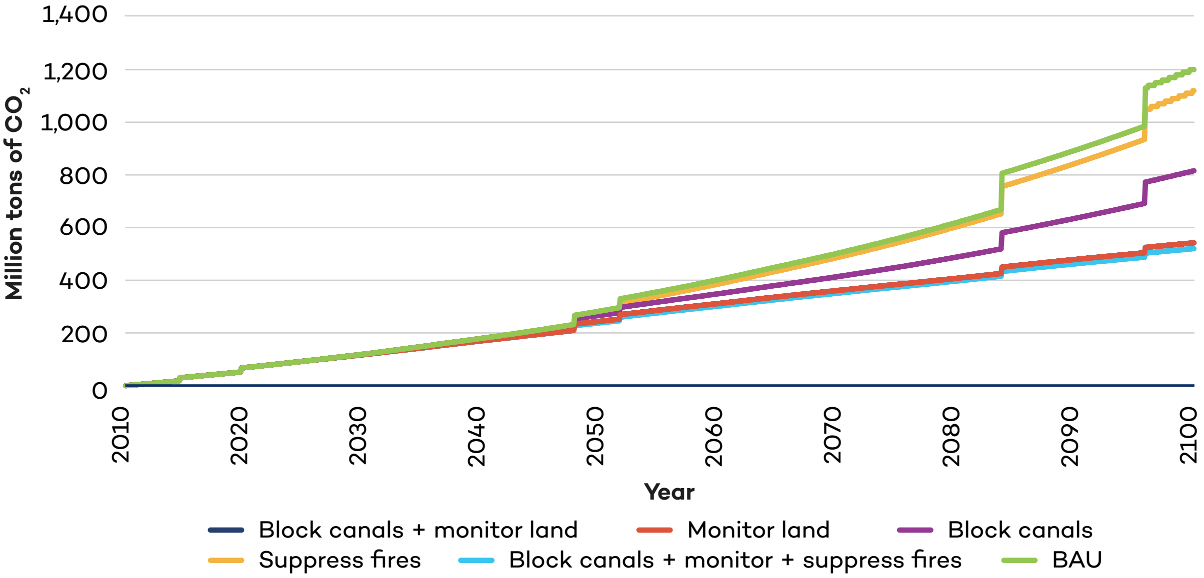


Figure 5. Cumulative total carbon emissions under RCP 4.5 for several policy scenarios. The occasional large annual increases are due to fires. Suppressing fires avoids some carbon emissions, but mitigating emissions from decomposition by blocking canals and preventing future deforestation has a larger impact on total emissions.



3.1.3.2 Land Conversion Scenarios Affect the Value of Policies

Results tables for the lower desired land conversion and non-preferential land conversion scenarios can be found in Appendix B. The scenarios with limited desired land conversion assume that deforestation for mining and plantations stops naturally. That is, monitoring the land is not necessary. For this reason, blocking canals and monitoring the land has total net benefits of USD 255 million, which is a small increase over the USD 240 million with no policy interventions. Including fire suppression increases cumulative net benefits to over USD 834 million. Net benefits are highest when all policies are enacted, but if land conversion stops on its own, then the largest policy impact comes from stopping the spread of fires, rather than blocking canals and revegetating (Table B1).

When primary forest, secondary forest, and degraded land are targeted equally for land conversion, avoided costs are smaller than those under BAU (Table B2). This is because primary forest is more resistant to burning, stores more carbon, and retains more water than secondary forest or degraded land. Thus, without interventions, costs from floods, emissions, and fires are higher when primary forest is targeted. This suggests that the value of the interventions is higher when there is more external pressure (e.g., from oil palm plantations) to clear primary forest.

3.1.3.3 Sustainable Peatland Management Provides Value Under a Range of Climate Scenarios

Under all climate scenarios, the policy interventions generate USD 1.13 billion–2.23 billion more than BAU (Table 2). Differences in precipitation explain the small variation across climate scenarios.

Under RCP 8.5, there is more rainfall overall than in the lower climate change scenarios, but there are several years in which the dry season precipitation is lowest under RCP 8.5 (Figure A1, Figure A3, Figure A5). Thus, under BAU, fires occur most frequently and are most severe under RCP 4.5 and are least frequent and severe under RCP 6.0. For this reason, the value of fire mitigation is largest under RCP 4.5 and smallest under RCP 6.0.

The impact of precipitation on avoided emissions depends on both fires and the water table. With fewer and less severe fires under a rainier climate scenario, emissions from fires, without any interventions, are smaller. We would, therefore, expect a lower avoided cost of emissions. However, more precipitation also means that the water table can recover more effectively (Figure 6). This lowers emissions further and increases the avoided cost of carbon. The avoided cost of emissions is largest under RCP 8.5 (Table 2). Thus, the increase in avoided costs due to a higher water table has a larger impact than the decrease in avoided costs due to fewer and less severe fires.

More precipitation also increases flood damages. This explains why avoided flood damages are highest under RCP 8.5, but this benefit is small compared to the avoided costs of emissions and fire damage.

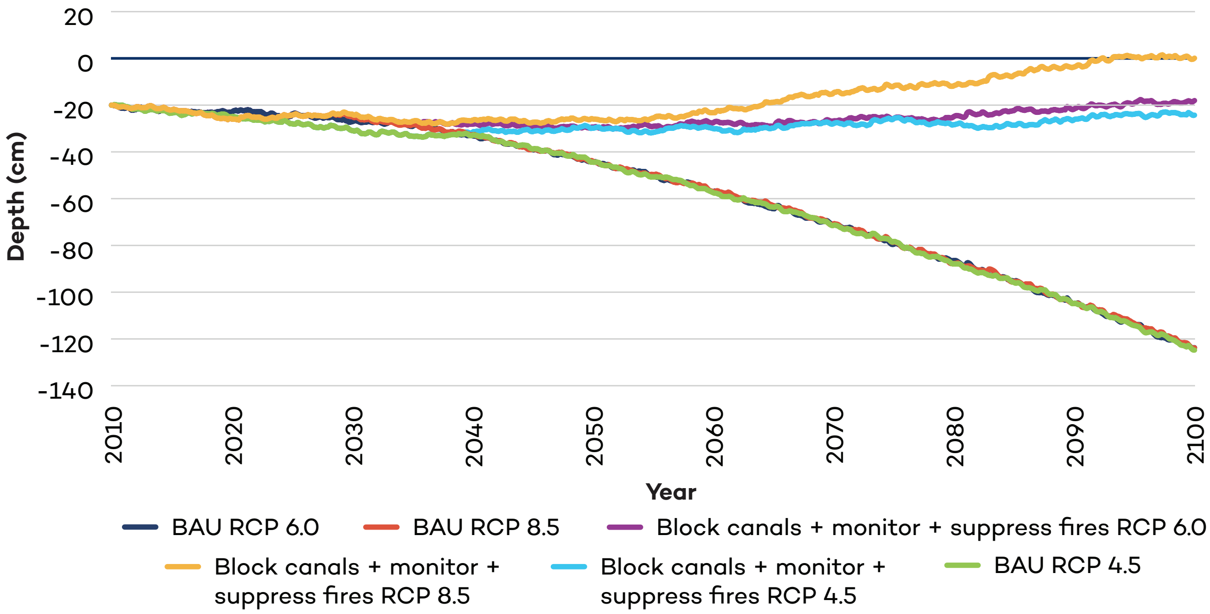
Despite these differences, the project performs well under all climate scenarios included in this analysis.

Table 2. Integrated cost-benefit analysis for BAU and a scenario with all policy interventions under three climate change scenarios. Intervention costs include the upfront and recurring costs of blocking canals, monitoring the land, and fire suppression. The policies provide more value when fires are more severe. All values are in USD million. Cumulative values calculated between 2010 and 2100.

Peatland integrated cost-benefit analysis: Climate scenario comparison

	RCP 4.5		RCP 6.0		RCP 8.5	
	BAU	Block canals + monitor land + suppress fires	BAU	Block canals + monitor land + suppress fires	BAU	Block canals + monitor land + suppress fires
Avoided cost of carbon emissions	0.00	3,405.36	0.00	2,953.70	0.00	3,611.71
Avoided flood damages	0.00	6.50	0.00	4.92	0.00	8.82
Avoided cost of fires	0.00	1,422.24	0.00	779.28	0.00	1,203.15
Household income	1,905.69	144.16	1,905.99	144.55	1,905.59	144.14
Intervention costs	0.00	144.75	0.00	144.75	0.00	144.75
Foregone government oil palm revenue	0.00	697.75	0.00	697.75	0.00	697.75
Total	**1,905.69**	**4,135.76**	**1,905.99**	**3,039.95**	**1,905.59**	**4,125.31**
Difference	**2,230.07**		**1,133.96**		**2,219.72**	

Figure 6. Water table depth for BAU and a scenario with all policy interventions under three climate change scenarios. The water table rises more quickly under the climate scenario with the highest rainfall (RCP 8.5).



3.2 Mangroves Provide Diverse Ecosystem Services

Tin mines in Belitung, Indonesia, have encroached on mangrove forests (Yusri et al., 2019). From 1997 through 2009, an average of 54.5 ha of mangroves were lost every year in the Toboali and Tukak Sadai sub-district in Bangka Belitung province. This loss increased to 112 ha per year over 2009–2014 (Sari & Rosalina, 2016). Although tin mining is a source of income for people in Belitung, it is dangerous, and many miners are injured or killed every year (Hodal, 2012). Furthermore, land conversion comes with a decline in ecosystem services. The loss of mangroves creates negative externalities, including carbon emissions, decline in fishery production, erosion, and flooding.

Mangroves store large amounts of carbon (Kauffman et al., 2020). They actively sequester carbon, in both above-ground biomass and in large pools of dead biomass, which decay very slowly (Alongi, 2014; Kustiyanto, 2019). When these ecosystems are destroyed, the carbon is released into the atmosphere.

As the base of the food chain, mangroves support a range of economically valuable aquatic species. They shelter fish from predators and provide habitat and nursery grounds. Molluscs and crustaceans live in their soft soils (Hutchison et al., 2014). As mangroves disappear, so do the fish that depend on them, and fishery productivity declines (Aburto-Oropeza et al., 2008; Hutchison et al., 2014; Sukardjo, 2004).

Mangroves protect coastlines by mitigating erosion and flood impacts. For example, dense root networks trap sediment. This protects against erosion and can lead to net coastal accretion (Spalding et al., 2014; Thampanya, 2006). Furthermore, mangroves attenuate waves and surge, effectively lowering the water level, leading to less flood damage (Menéndez et al., 2020; Spalding et al., 2014). They can also reduce the hydrodynamic force of tsunamis (Spalding et al., 2014; Yanagisawa et al., 2010). However, as the ecosystem degrades, a coastline may switch from accreting to eroding and become more vulnerable to flooding (Spalding et al., 2014; Winterwerp et al., 2013).

Not only are mangroves threatened by anthropogenic activities, but large waves, such as storm surges and tsunamis, can damage the trees (Smith et al., 2009; Yanagisawa et al., 2010). Additionally, cumulative disturbances may trigger a permanent change of state, converting a mangrove forest to a fundamentally different ecosystem (Smith et al., 2009).

Restoring mangroves often includes planting seedlings. However, these seedlings have low survival rates (Kathiresan & Bingham, 2001; Winterwerp et al., 2020). Another nature-based approach is to build temporary off-shore permeable barriers that can reduce wave energy while allowing sediment to pass through. This, ultimately, may restore the sediment balance so that an eroding coastline reverts to a state of net accretion (Winterwerp et al., 2020). Working with nature in this way can promote and sustain mangrove recovery (EcoShape, n.d.; Winterwerp et al., 2013, 2020). Ecotourism can also encourage mangrove survival by establishing a sustainable source of income (Basyuni et al., 2018; Yusri et al., 2019).

Other coastal defence strategies include built structures. For example, breakwaters are off-shore structures built parallel to the coastline. They reduce wave height, but their effect on erosion is unclear. Some studies report that breakwaters increase erosion, while others find that breakwaters lead to net accretion (Narayan et al., 2016; Ranasinghe & Turner, 2006).

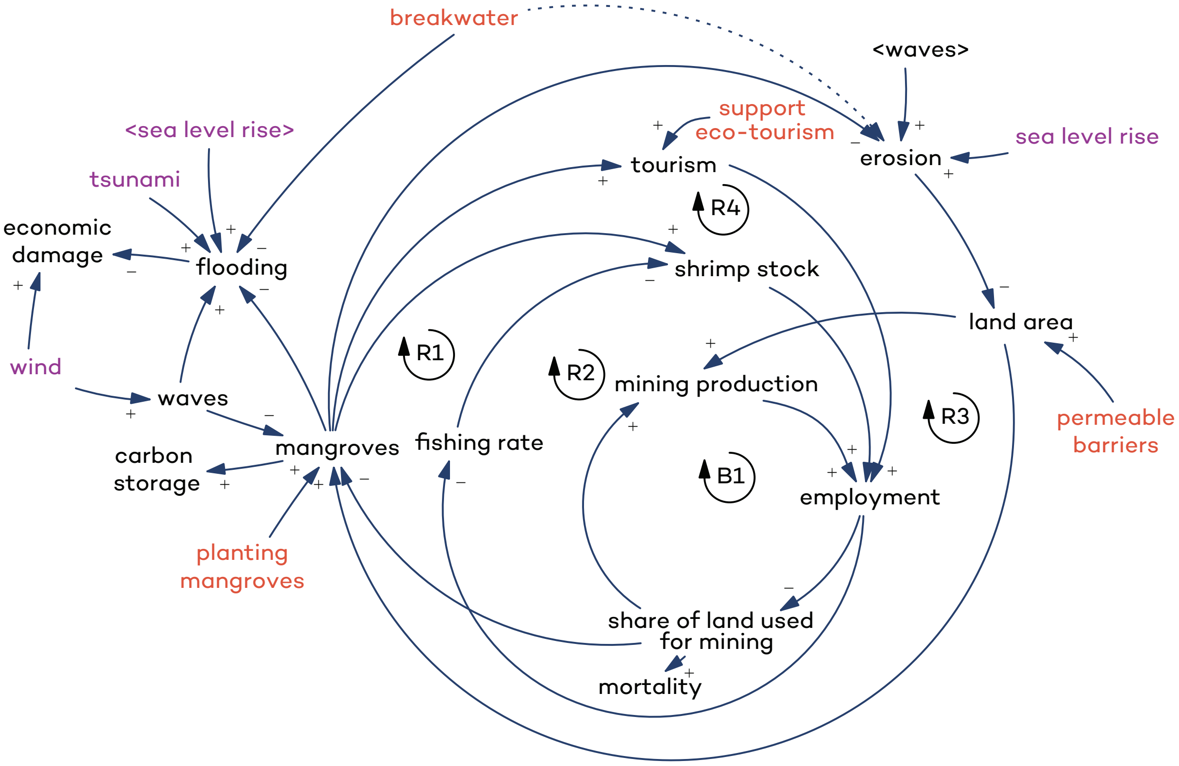
3.2.1 CLD SHOWS FEEDBACK BETWEEN MANGROVES AND ECONOMIC ACTIVITY

Figure 7 shows the CLD for Belitung Mangrove Park. The system contains multiple feedback loops that explain the dynamics of degrading and restoring mangroves:

- R1—As mangroves degrade, fish habitat and nursery grounds are destroyed. This lowers income from fishing, so mining expands. This encroaches further on mangrove area.
- R2—If employment declines, there is pressure to catch more fish. With a higher fishing rate, the fish stock declines, which leads to less employment from fisheries.
- B1—Converting mangroves to mines increases tin production. This creates jobs, and there is less need for new mines.
- R3—Mangroves mitigate erosion, and as the forest matures, they trap sediment. Thus, there is more land area for mangroves to colonize.
- R4—Mangrove restoration supports tourism. This creates sustainable jobs for the local community and reduces the desire for mines. This allows mangroves to expand.

These feedbacks demonstrate that converting land to tin mines creates a vicious cycle of mangrove destruction. Investing in restoration and ecotourism can reverse this cycle and switch the system to a sustainable state with an economy supported by fishing and tourism.

Figure 7. Mangrove restoration CLD. Orange variables are possible interventions. Pink variables are hydrometeorological inputs. Arrows show causality with plus and minus signs identifying positive and negative correlations, respectively. The dashed arrow from "breakwater" to "erosion" indicates that the direction of correlation is inconclusive. Feedback loops are labelled as either reinforcing (R) or balancing (B). See the text for a description of mangrove dynamics and feedback loops in this system.



3.2.2 MANGROVE MODEL SCENARIOS AND ASSUMPTIONS

The system dynamics model is based on the following assumptions:

- Mangrove forests are destroyed to meet demand for tin mines. Tin mining incurs a cost of increased mortality. Mangroves will slowly colonize abandoned mining land. Seedlings can be planted on bare land but are less likely to survive than mangroves that are recruited naturally.
- When the mangrove forest is wider than 500 metres, there is net accretion seaward of the mangroves, assuming no storm impacts. Land erodes when the forest width falls below 500 metres. Waves higher than a fixed threshold damage mangroves and erode the land. Waves smaller than the threshold have no impact, positive or negative, on mangroves. The total land area changes according to net erosion (erosion - accretion).
- Wave height is linearly related to wind speed. Two tsunami events are assumed to take place in 2060 and 2088. The total water level is wave height, including tsunamis, added on top of sea level, which is assumed to increase linearly throughout the century. We note that Belitung, located between Sumatra and Kalimantan islands, is not susceptible to tsunamis. Nevertheless, we include this dynamic in the model to assess the impact of extreme events on the health of mangroves and quantify the costal resilience and avoided damage offered by mangroves more broadly. The impact of tsunamis can also shed light on the effect of economic shocks, such as the COVID-19 pandemic.

- Mangroves reduce the level of water that could damage coastal assets, and wider mangrove forests do so more effectively. Alternatively, a breakwater can lower the wave height. Flood damage occurs when the effective water level exceeds a threshold. The assets at risk increase linearly with time. Furthermore, it is possible for new developments to be built on deforested areas. The only impact of these new developments is to increase the assets at risk of flooding. We justify excluding any costs associated with these developments by assuming that their costs and benefits (excluding flood damages) are equal.
- Mangroves actively sequester carbon at a rate proportional to the area of mangrove forest. Destroying mangroves emits carbon dioxide.
- The mangrove shrimp stock naturally grows and shrinks to approach a carrying capacity that depends on the total mangrove area. Shrimp are harvested at a rate proportional to the size of the stock.
- The number of tourists per year depends on the size of the mangrove forest. If resources are invested in supporting ecotourism, then there are more visitors per hectare of mangroves. Following a tsunami, the number of tourists per hectare decreases for several years.
- Shrimp harvesting, tourism, mining, mangrove restoration projects, and breakwater maintenance and construction create jobs and generate income for the local community. If total income falls below the desired income, more land is deforested to create tin mines, and the shrimp harvesting rate increases. Alternatively, if there is consensus that mangroves generate sustained revenues over time, then conservation, rehabilitation, and local stewardship can emerge and prevent land conversion.

Numerical inputs for the model with references are in Appendix A (Table A2).

We have assessed several scenarios:

1. **BAU:** Mangroves steadily decline due to competition from tin mining, climate impacts (e.g., sea level rise), and other meteorological events (e.g., tsunamis). Shrimp harvesting becomes unsustainable, and the fishery collapses.
2. **Unsustainable fishing:** The shrimp harvesting rate is higher than the growth rate, so the shrimp population declines with time.
3. **Plant mangroves:** Mangroves are planted on old tin mining land one time only.
4. **Develop ecotourism:** The local community focuses on developing ecotourism, which increases the number of visitors per hectare of mangrove forest.
    a. **Local stewardship:** The community develops ecotourism and plants mangroves on old tin mining land instead of converting land to tin mines when wages fall below the desired amount.
5. **Permeable structures:** Off-shore permeable structures are built to trap sediment, creating more land for mangroves.
6. **Build new developments:** When mangroves are deforested, new developments are built on the bare land.
7. **Breakwater:** An off-shore, submerged breakwater is constructed, which lowers wave height.

We run the model using wind speed projections from RCP 4.5, RCP 6.0 and RCP 8.5 (Copernicus Climate Change Service, 2018). Time series for each of these climate scenarios are shown in Appendix A (Figure A7, Figure A8, Figure A9). Appendix A also includes the historical wind and wave data used to calibrate the model (Figure A10, Figure A11, Figure A12, Figure A13) taken from E.U. Copernicus Marine Service Information (2019a, 2019b).

Sea level is assumed to increase linearly at a rate that depends on the climate scenario. Cumulative sea level rise by 2100 relative to 2005 is assumed to be 530 millimetres under RCP 4.5, 550 millimetres under RCP 6.0 and 740 millimetres under RCP 8.5 (Church et al., 2013). We did not have local sea level rise projections and so used the median predicted value for global mean sea level rise from the Intergovernmental Panel on Climate Change Fifth Assessment Report but recognize that sea level rise in Indonesia is expected to be higher than the global average (Carson et al., 2016; Church et al., 2013). It is, therefore, likely that we have underestimated the flood protection benefits of mangroves.

For all scenarios, the model is run for 2010–2100. Policy interventions are implemented in 2020 and take effect immediately.

3.2.3 MANGROVE MODEL RESULTS AND DISCUSSION

Key results include:

- Investing in mangrove rehabilitation for Belitung is economically viable only if connected to the generation of an additional source of revenue, such as ecotourism. This income avoids the desire to convert land for mining.
- Ecotourism and mangrove restoration create more jobs than mining. Ecotourism in the area can generate wages of up to USD 1,600 per capita per year and forms a sustainable source of income for the local community.
- Extreme events that cause widespread damage are a threat to mangroves and the local economy. Stewardship activities may be necessary to encourage ecosystem protection and recovery after a shock, particularly when considering cumulative impacts.
- Restoration is beneficial regardless of climate change scenario. If the tourism industry is supported, outcomes under different climate scenarios are similar.

3.2.3.1 Conserving Mangroves Enables a Sustainable Income Source

The effects of land cover on income are a primary difference among the policy scenarios simulated in this assessment. Impacts on carbon storage, flooding, and mortality are much smaller.

The results show that without developing ecotourism, mangrove restoration does not last. In the BAU scenario and the planting mangroves scenario (without ecotourism), the shrimp fishery and current tourism industry cannot provide the desired amount of income. Without an alternative source of income, deforestation for mining continues. This eventually leads to a near-total loss of mangroves and a corresponding decline in shrimp stock (Figure 8, Figure 9, Figure 10). The cumulative value for the scenarios without ecotourism over 2010–2100 is approximately USD 27 million, compared to over USD 100 million when ecotourism is included (Table 3).

Successful mangrove restoration requires local stakeholder involvement (Winterwerp et al., 2020). Although the impact of planting mangroves is negligible, with cumulative net benefits only USD 135,000 greater than BAU (Table 3), these types of activities may encourage community engagement. If this is true, then the social impacts of planting mangroves, combined with the income from ecotourism, may be necessary to restore the ecosystem.

Ecotourism would create a sustainable source of revenue, and the model predicts that tourism income would be up to USD 1.6 million (USD 1,600 per capita) per year (Figure 11). We estimate that mining generates approximately USD 19 per hectare per year. Thus, even if the full 52 hectares were used for mining, income would be less than USD 1,000 per year, which is a fraction of the income from ecotourism. Ecotourism also supports a variety of local jobs (estimated to be over 800 when the mangrove park is at its maximum size). Including jobs from fishing, planting mangroves, and building and maintaining permeable structures, simulated household income rises to about USD 1,800 per capita per year in the sustainable scenario, not considering tsunami damage.

Ecotourism can discourage the transition to mining, but the system is vulnerable to shocks. In the modelling, a tsunami in 2060 destroys approximately 40 hectares of primary mangroves (Figure 8). In the short term, tourism wages drop to less than USD 200,000 (USD 200 per capita) per year. After the immediate disruption, the industry can partially recover, but due to the large area lost, the system is unable to return to the pre-tsunami state before the second tsunami hits.

After the second tsunami, the mangrove forest is too small for ecotourism jobs to support the local population. In this case, pressure to resume mining may arise (Figure 8, Figure 9). Alternatively, if there is local stewardship, such that the community recognizes the value of protecting mangroves and resists the urge to convert land for mining, the mangroves can regrow. Even with stewardship, the ecosystem does not fully recover by the end of the century. However, the area of primary mangrove forest is increasing in the year 2100, a trend that would likely continue if there are no external shocks.

If the local community recognizes the value of mangroves and resists pressures to start mining again, then more value is generated in the long run. With a cumulative value of USD 113 million over 2010–2100, the stewardship scenario generates the highest societal net benefits. Thus, the value of ecotourism and related investments may be higher when sustainability is guaranteed. This suggests that economic support may be necessary to weather short-term disruptions. Nevertheless, over time, local stewardship may increase net benefits by USD 6 million compared to the ecotourism without local stewardship scenario (Table 3).

Considering a situation in which tsunamis do not occur, which is more probable for Belitung, the benefits of restoring and protecting the ecosystem would be larger. The primary effect of the simulated tsunamis is damage to mangroves and a resulting decline in fishing and tourism income. Without tsunamis, these added benefits would be greater. Although the avoided flood damage would be less than in the case with tsunamis, this benefit is much smaller than the income from activities that rely on mangroves, suggesting that total benefits and avoided costs would be greater without tsunamis.

Resilience to tsunami impacts can be extrapolated to other sudden shocks, such as the COVID-19 pandemic. It is unlikely that a socio-economic shock would have a direct impact on the area of mangroves, and so recovery could happen faster than when the mangroves are destroyed. However, any sharp decline in tourism revenue, if large enough, could increase demand for other livelihoods that may result in less value over time.

For example, when the fishing rate is unsustainable, total net benefits are USD 105 million, approximately USD 2 million lower than when fishing is sustainable (Table 3).

Permeable barriers have been promoted as a way to work with nature to restore the sediment balance in coastal environments (EcoShape, n.d.; Winterwerp et al., 2020). In our simulations, such structures are not necessary for sediment to accumulate. This may be due to our simplified representation of coastal geomorphology. Our model indicates that the cost of installing and maintaining permeable barriers is greater than their benefits. However, if we assume that these barriers have a larger effect on sedimentation (say, by increasing accretion by 1.3 metres, instead of 0.5 metres), then the model shows that, when combined with ecotourism, they may generate more value than planting mangroves. This highlights the need for detailed, location-specific hydrodynamic models. Such models can more accurately assess the impact of NBI on coastal morphology.

In all scenarios, the carbon storage benefit is small. Accounting for accretion, the study area never exceeds 60 hectares. Thus, although mangroves sequester large amounts of carbon per hectare, mangroves in this small area can store a limited amount.

Similarly, flood damages are small compared to other impacts (Table 3, Table 4). One reason for this is that, even under BAU, our model estimates that, except for a temporary dip in 2060, there are still 100 metres of mangroves until the second tsunami hits (Figure 12). This means that there is sufficient protection to avoid most damages from wind waves. In line with our assumptions, the damages are higher if new developments are built on cleared land. Also, maintaining mangroves or constructing a breakwater mitigates some damage, but we have assumed that mangroves are more effective (Figure 13).

If a breakwater is installed and ecotourism is developed, then the results are similar to those from planting mangroves with ecotourism (Table 3, Table 4). We have assumed, based on scientific literature, that breakwaters have no impact on erosion and are less effective than mangroves at attenuating waves. Due to these assumptions, breakwaters, on their own, reduce cumulative net benefits. Again, this highlights the importance of creating a sustainable revenue stream.

In conclusion, investment in mangrove rehabilitation for Belitung is economically viable if connected to the generation of an additional source of revenue. To avoid side effects and support sustainable development, the socio-economic and environmental contribution of mangroves must be clarified. Flood resilience improves with the rehabilitation of mangroves, but the study area does not include many buildings and infrastructure, making this a secondary argument. In other locations, the flood protection benefit could be more pronounced. With more potential flood damage, it may be that restoration can avoid significant damages from climate impacts.

Table 3. Integrated cost-benefit analysis for the RCP 4.5 climate scenario. Ecotourism provides large benefits for the local community. All values are in USD million. Cumulative values calculated between 2010 and 2100.

Mangrove integrated cost-benefit analysis: Policy scenario comparison

	BAU	**Plant mangroves**	**Plant mangroves + ecotourism**	**Plant mangroves + ecotourism + local stewardship**	**Plant mangroves + ecotourism + permeable structures**	**Plant mangroves + ecotourism + unsustainable fishing**
Value of carbon storage	0.00	0.00	0.03	0.06	0.03	0.03
Flood damage from sea level rise, waves, and tsunamis	0.25	0.25	0.05	0.04	0.05	0.05
Household income	27.37	27.53	108.68	114.60	110.92	106.71
Mortality cost of mining	0.10	0.10	0.01	0.01	0.01	0.01
Construction costs	0.00	0.00	1.38	1.38	1.48	1.38
Maintenance costs	0.00	0.00	0.00	0.00	4.12	0.00
Total value	**27.03**	**27.19**	**107.26**	**113.22**	**105.28**	**105.29**
Value compared to BAU	**0.00**	**0.16**	**80.23**	**86.19**	**78.25**	**78.26**

Table 4. Integrated cost-benefit analysis for the RCP 4.5 climate scenario assessing the impact of new developments and breakwaters. As assumed in the model, new developments increase potential flood damage, and breakwaters are less effective than mangroves at mitigating damage. Cumulative values calculated between 2010 and 2100. All values are in USD million.

Mangrove integrated cost-benefit analysis: Grey infrastructure assessment

	BAU	Plant mangroves + ecotourism + new developments	Breakwater	Breakwater + plant mangroves + ecotourism
Value of carbon storage	0.00	0.03	0.00	0.03
Flood damage from sea level rise, waves, and tsunamis	0.25	0.19	0.16	0.04
Household income	27.37	108.68	27.86	109.19
Mortality cost of mining	0.10	0.01	0.10	0.01
Construction costs	0.00	1.38	0.25	1.63
Maintenance costs	0.00	0.00	0.20	0.20
Total value	**27.03**	**107.12**	**27.16**	**107.34**
Value compared to BAU	**0.00**	**80.09**	**0.13**	**80.31**

Figure 8. Primary mangrove forest under RCP 4.5 for several policy scenarios. Mangroves are vulnerable to tsunamis but can continue growing if managed sustainably.

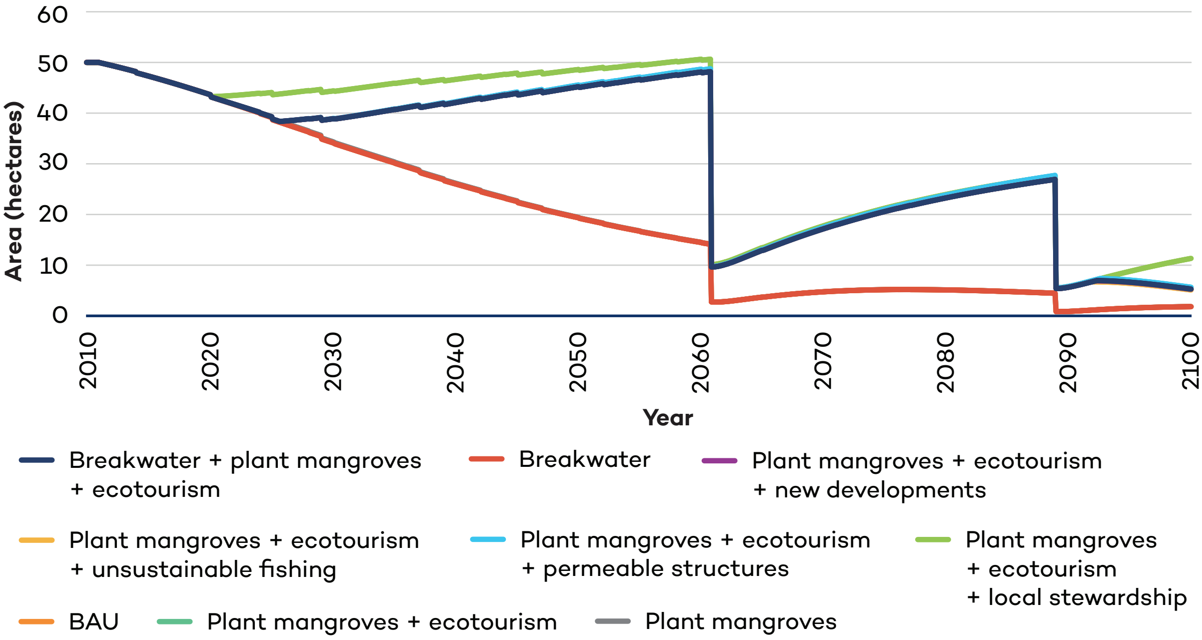


Figure 9. Active mining land under RCP 4.5 for several policy scenarios. Pressure to convert land for mines increases when income is low.

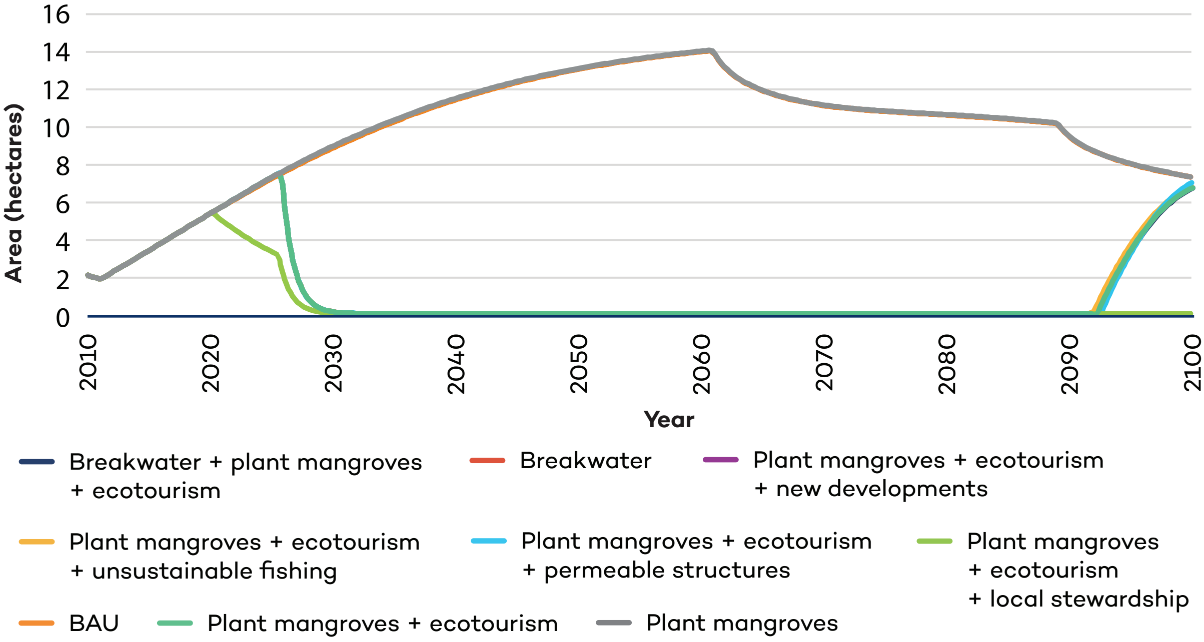


Figure 10. Shrimp stock under RCP 4.5 for several policy scenarios. The shrimp stock declines when fishing is unsustainable or when mangroves are lost.

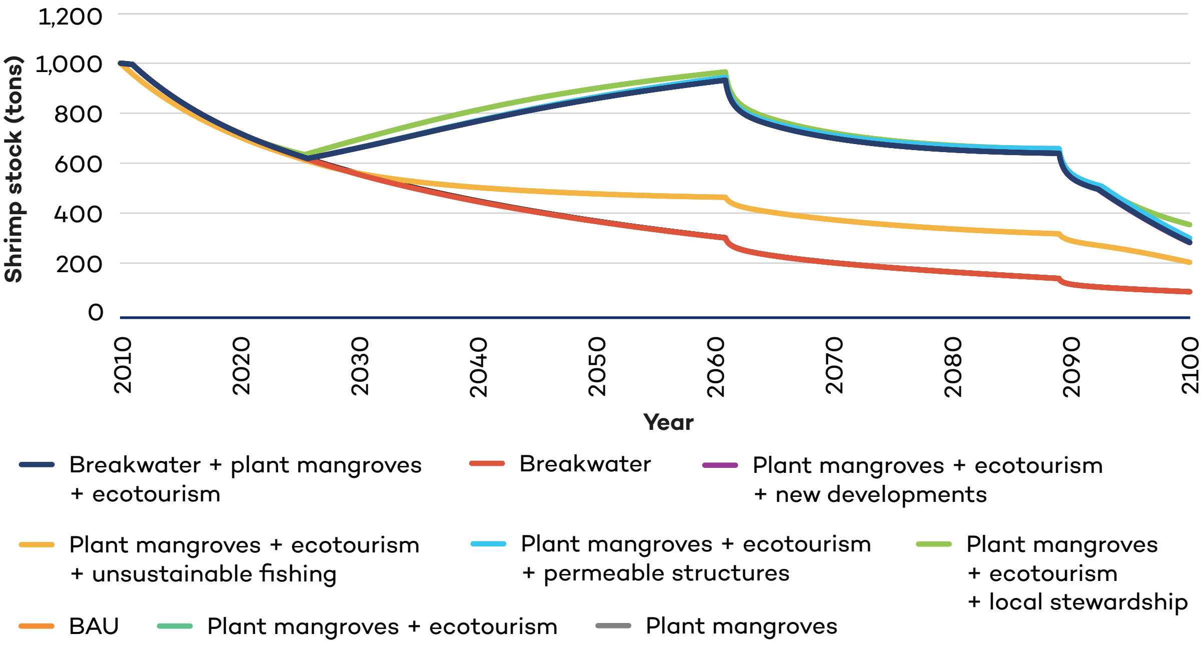


Figure 11. Annual tourism income under RCP 4.5 for several policy scenarios. Tourism wages are higher when ecotourism is supported, and income depends on the area of mangroves.

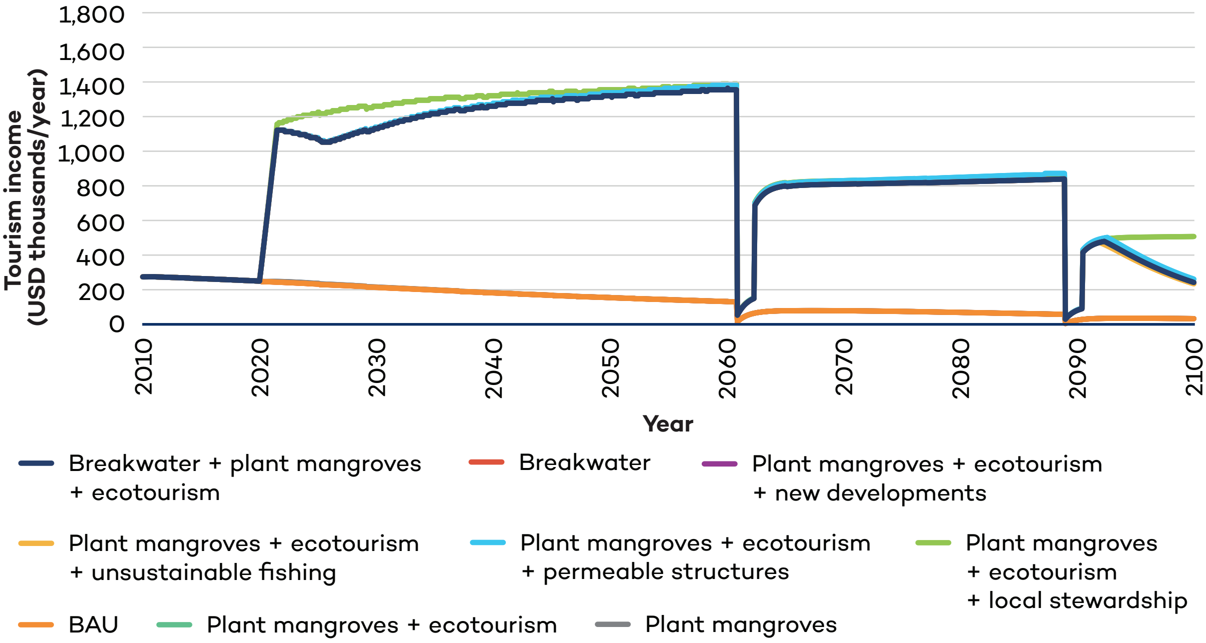


Figure 12. Total mangrove width including primary and secondary mangroves under RCP 4.5 for several policy scenarios. In all scenarios, mangroves are wide enough to mitigate most flood damage for at least the first half of the simulation.

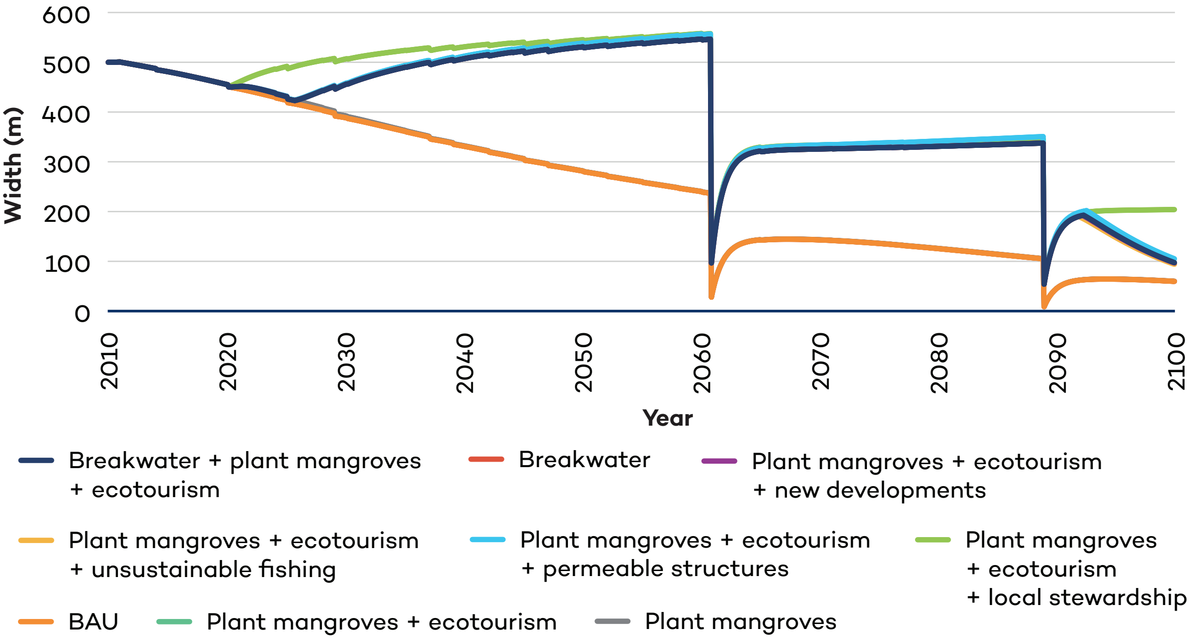
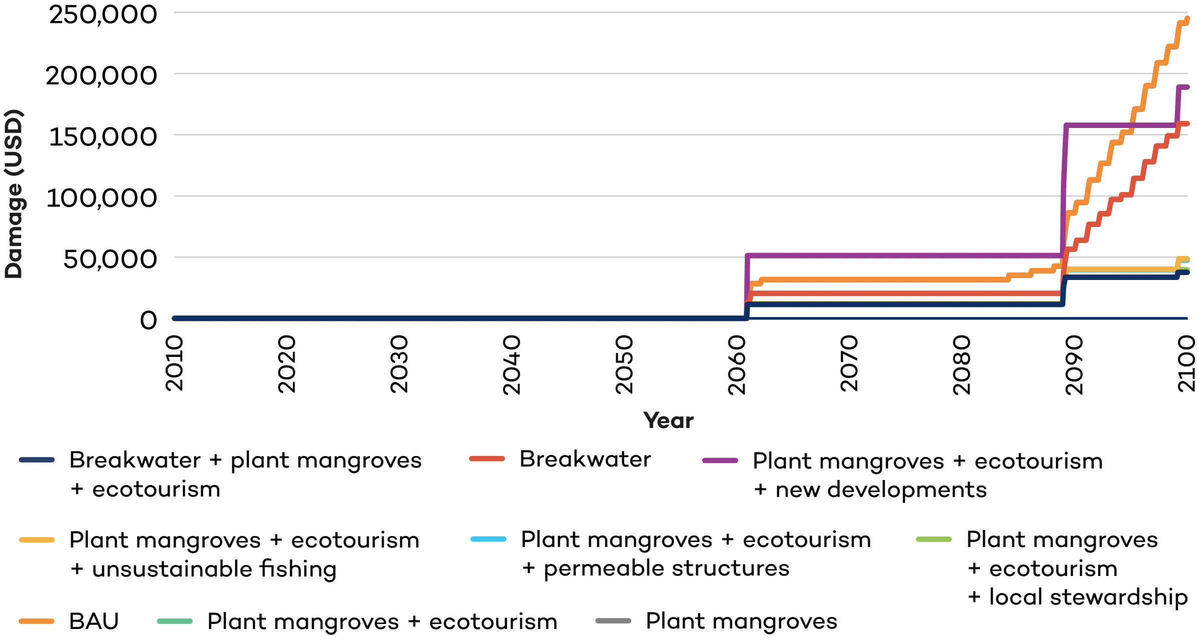


Figure 13. Cumulative flood damage under RCP 4.5 for several policy scenarios. Flood damages are due primarily to tsunamis. Wind waves also cause damage when mangroves are lost.



3.2.3.2 Value of Mangrove Restoration Is Similar Across Climate Scenarios

The model results do not depend strongly on climate change. There are slight differences in the size of the mangrove forest due to variation in erosion from waves and sea level rise across the three climate scenarios. Nevertheless, with sustainable management, there is sufficient mangrove area to support ecotourism and fishing regardless of climate scenario (Table 5).

Table 5. Integrated cost-benefit analysis for the RCP 4.5, RCP 6.0, and RCP 8.5 climate scenarios and policy scenarios: BAU and mangrove restoration with ecotourism and local stewardship. Results are similar across scenarios. All values are in USD million. Cumulative values calculated between 2010 and 2100.

Mangrove integrated cost-benefit analysis: Climate scenario comparison

	RCP 4.5		**RCP 6.0**		**RCP 8.5**	
	BAU	**Plant mangroves + ecotourism + local stewardship**	**BAU**	**Plant mangroves + ecotourism + local stewardship**	**BAU**	**Plant mangroves + ecotourism + local stewardship**
Value of carbon storage	0.00	0.06	0.00	0.06	0.00	0.06
Flood damage from sea level rise, waves, and tsunamis	0.25	0.04	0.28	0.05	0.41	0.05
Household income	27.37	114.60	27.09	113.23	27.35	114.37
Mortality cost of mining	0.10	0.01	0.10	0.01	0.10	0.01
Construction costs	0.00	1.38	0.00	1.38	0.00	1.38
Maintenance costs	0.00	0.00	0.00	0.00	0.00	0.00
Total value	**27.03**	**113.22**	**26.72**	**111.84**	**26.85**	**112.99**
Difference	**86.19**		**85.12**		**86.14**	

3.3 Model Limitations

As with any model, the system dynamics models are sensitive, to varying degrees, to the underlying assumptions and inputs. For example, as discussed above, the cost effectiveness of permeable barriers depends on the assumed amount of sediment they trap. Similarly, the number of jobs and amount of income created by mangrove ecotourism would change with different inputs. The relative impacts of breakwaters and mangroves also depend on our assumptions.

In the peatland model, emissions factors, the subsidence rate, and fire probability and severity are examples of parameters that could change the results. Furthermore, we have shown that underlying assumptions about desired land conversion affect the value of the various policies.

Many, but not all, of our assumptions are based on scientific studies (Table A1, Table A2). Thus, although the numerical outputs may not be exact, we can have confidence in the simulated dynamics, which are consistent with the scientific literature.

In the peatland model, we can safely conclude that the value of carbon emissions justifies restoration. We can also have confidence in the relative effectiveness of policy interventions—for example, the importance of raising the water table and preventing further land conversion, which can be supplemented by fire suppression.

With mangroves, the model correctly conveys that it is important to establish sustainable income-generation activities. Mangrove restoration is viable if such income streams are available. From the model, we also know that the system is vulnerable to external shocks. Furthermore, sustainable management can encourage ecosystem recovery after an extreme event and enables continued employment opportunities.

In both cases, the models demonstrate how the system components interact under several policy scenarios to produce more (or less) desirable outcomes, as indicated by the estimated net benefits. The models expose how policies create value and the systemic impacts of interventions.

4.0 Financial Indicators Give Additional Insight

The financial analysis uses the outputs from the system dynamics model to calculate the IRR, benefit-to-cost ratio (BCR), and NPV of each scenario compared to BAU. In all cases, we calculate the societal IRR, BCR, and NPV, which we call the S-IRR, S-BCR, and S-NPV, and the conventional IRR, BCR, and NPV. The S-IRR, S-BCR, and S-NPV include all indicators from the system dynamics models. The conventional calculations include only cash flows, excluding the avoided costs and other externalities. For these calculations, we use a discount rate of 8.5%.

4.1 Avoided Costs Justify Investments in Peatland Restoration

Most peatland investments considered in this model have a BCR less than one and negative NPV when we do not consider the value of emissions, cost of flood damages, and cost of fires (Table 6). The exception to this is suppressing fires, which has an unreasonably high IRR of 534.7%.

The high IRR for fire suppression is due to the large number of jobs created, and therefore high wages, for fire suppression. While this may seem unfeasible, we justify the high wages for fire suppression using the following information:

- The International Labour Organization estimates that forest restoration and conservation creates 281–458 full-time equivalent jobs (FTE) per USD 1 million in annual investment (Payen & Lieuw-Kie-Song, 2020).
- The Katingan Mentaya Project employs over 400 local people to protect the forest from fires and employs a total of over 500 people (Katingan Mentaya Project, 2021). We, therefore, assume that fire suppression employs 450 people full-time, and blocking canals/monitoring to prevent land conversion employs an additional 100 people full-time.
- In our model, when all policy interventions are implemented, the annual investment is approximately USD 1.9 million, and employment from conservation activities is 550 FTE. Thus, we estimate approximately 290 FTE per USD 1 million invested annually, which falls at the low end of the estimate from the International Labour Organization.
- Annual wages per FTE are assumed to be the average wages for agriculture, forestry, hunting, and fishing in Central Kalimantan. We assume that jobs created by the Katingan Mentaya Project must pay roughly the same as other jobs in the region. If this were not the case, local residents would seek out other opportunities.

We, therefore, see that we can validate the number of jobs created and wages using the International Labour Organization's study. Nevertheless, based on these data, we would expect that the breakdown of jobs would be more heavily weighted toward blocking canals and monitoring land to prevent conversion than toward suppressing fires. We justify assuming that more people are employed in fire suppression based on the project-specific information available from Katingan Mentaya Project (2021).

All investments are economically viable when we include externalities in the analysis. Except for fire suppression, the IRR is between 11% and 18%, and the BCR is 1.64–4. 0. Fire suppression has a high BCR for the same reason it has a high IRR, that is, it generates a lot of employment with a relatively small investment. The S-NPV for all policies ranges from USD 11 to USD 46 million, suggesting that these policies can create value for society.

The negative conventional benefit-to-cost ratios in Table 6 are because preventing land conversion results in lower wages and less government revenue. Therefore, the direct benefits of these scenarios are negative. This highlights the fact that carbon payments must be implemented effectively and transferred to local communities to stimulate action.

Furthermore, incentives for sustainable agriculture and ensuring access to markets for local produce could increase community buy-in. If businesses manage land near villages, a land management tax or fee that is allocated to preventing fires and water drainage would promote more sustainable activities. These interventions should be accompanied by a moratorium on land conversion and/or relocating palm oil production and similar activities from peatlands to mineral land.

Table 6. Financial indicators for peatland forest restoration and protection using a discount rate of 8.5%. Except for fire suppression, interventions have a positive NPV and BCR greater than one only when externalities are included.

Peatland management financial indicators

	IRR (%)		BCR		NPV (USD million)	
	Societal	**Conventional**	**Societal**	**Conventional**	**Societal**	**Conventional**
Block canals	15.2%	-	3.65	0.17	28.38	-8.84
Monitor land	16.0%	-	4.00	-13.09	19.83	-93.28
Block canals + monitor land	11.0%	-	1.64	-4.9	11.04	-102.08
Suppress fires	534.7%	534.7%	19.1	3.33	45.84	5.89
Block canals + monitor land + suppress fires	17.8%	-	3.20	-3.85	43.66	-96.18
Block canals	15.2%	-	3.65	0.17	28.38	-8.84

Financial indicators for the limited and no-preference land conversion scenarios are in Appendix B (Table B3, Table B4). These results suggest that, even when including the avoided costs, blocking canals and monitoring the land is not a worthwhile investment under these land conversion scenarios. This is because the benefits provided by these interventions are to maintain primary forest and to raise the water table. With less pressure to remove primary forest, the first of these benefits is less important. Because future benefits are discounted and it takes time for the water table to recover, the latter benefit is also small.

4.2 Income From Ecotourism Justifies Mangrove Restoration

For mangrove conservation, tourism income creates most of the value. Because we include the tourism wages in both the conventional and societal financial indicators, externalities are not needed to justify the investments. In fact, in all scenarios, the sustainable IRR, BCR, and NPV are only slightly larger than the conventional values (Table 7).

The high IRR and BCR of planting mangroves arise from the fact that investment costs for this scenario are very low and that it stimulates jobs in the short term. However, this strategy does not maintain the mangroves over longer time scales. Hence, the NPV is much lower than that of the other interventions. Only the breakwater without ecotourism performs worse than planting mangroves alone (Table 7).

In line with the results discussed above, the stewardship scenario performs best according to these indicators. Similarly, when combined with ecotourism, permeable barriers and the breakwater are less attractive than planting mangroves and establishing tourism without these additional interventions (Table 7).

Interestingly, the unsustainable fishing scenario emerges as more favourable than some of the others (Table 7). This is because with unsustainable fishing, there is high fishing income near the beginning of the simulation, but these benefits decline as the shrimp stock is depleted. When future impacts are discounted, it appears desirable to overexploit resources in the short term at the expense of future opportunities.

Table 7. Financial indicators for mangrove restoration and protection. Activities, such as tourism, that depend on the mangroves generate significant value over the long run.

Mangrove management financial indicators

	IRR (%)		BCR		NPV (USD million)	
	Societal	**Conventional**	**Societal**	**Conventional**	**Societal**	**Conventional**
Plant mangroves	1,597.4%	1,596.9	24.24	24.19	0.088	0.087
Plant mangroves + ecotourism	66.5%	66.4%	9.27	9.17	10.84	10.71
Plant mangroves + ecotourism + local stewardship	73.3%	71.9%	10.28	10.13	12.21	12.00
Plant mangroves + ecotourism + permeable structures	58.8%	58.7%	6.17	6.10	10.32	10.19
Plant mangroves + ecotourism + unsustainable fishing	66.1%	66.0%	9.35	9.25	10.94	10.81
Plant mangroves + ecotourism + new developments	66.5%	66.4%	9.27	9.17	10.83	10.71
Breakwater	0.7%	0.0%	0.26	0.26	-0.21	-0.21
Breakwater + plant mangroves + ecotourism	55.6%	55.5%	7.70	7.62	10.63	10.50

5.0 NBI Performs Better Than Grey Alternatives

Indonesia's updated Nationally Determined Contribution submitted to the United Nations Framework Convention on Climate Change in 2021 indicates that reducing 2030 emissions by 1,166 t would cost USD 322.86 billion (Republic of Indonesia, 2021). Assuming this absolute reduction is maintained for 70 years through 2100, this would correspond to 78,120 t CO_2e avoided or USD 4.13 million per t CO_2e. For peatland, the block canals + monitor + suppress fires scenario avoids 3,951 t of emissions at a cost of USD 144.8 million, equal to USD 36,600 per t CO_2e. This quick "back of the envelope" calculation suggests that reducing emissions by restoring peatlands may be significantly cheaper than other grey or green strategies.

With mangroves, we have simulated the impact of a constructed breakwater. Because the results are primarily dependent on income from ecotourism, the breakwater on its own has a minimal impact on benefits, while incurring construction and maintenance costs. These costs, combined with our assumptions about its impacts on wave height and sediments, lead to lower net benefits when the breakwater is constructed compared to BAU (Table 4). Our model shows that to generate value, well-paying jobs are critical. Mangroves can support such jobs, while breakwaters do not. Although ecotourism is possible even if a submerged breakwater is constructed, the grey infrastructure does not add value for money.

6.0 Conclusion

In this report we have presented a SAVi assessment of peatland and mangrove restoration and conservation in Indonesia. We have calibrated system dynamics models using data from the Katingan Peatland Project in Central Kalimantan and the Belitung Mangrove Park in Belitung. We calculated undiscounted net benefits, IRRs, benefit-to-cost ratios, and NPVs for several policy options.

From our analysis, the following key messages emerge:

- **Money matters:** To make land rehabilitation lasting and more economically viable, local communities need an additional source of income (e.g., tourism or carbon storage payments). Otherwise, local communities turn to environmentally damaging activities, such as plantations and mining. This ultimately has less societal benefit than sustainable land management.
- **Land rehabilitation is a long-term effort:** One-time interventions, such as blocking peatland canals or restoring mangroves without monitoring and maintenance, are less effective than continuous management and stewardship. These long-term efforts can avoid land conversion and increase resilience to extreme events. However, long-term impacts may not play into decision making when future benefits are discounted.
- **Use packages of interventions instead of isolated measures:** Combining measures makes the projects more successful. The peatland restoration (blocking canals and planting trees) brings the largest benefits in combination with fire suppression and with monitoring that prevents the conversion of forest to plantations and mining. Planting mangroves works best when combined with ecotourism.

These results provide insight into how similar restoration projects could be done in other locations. They also show that impacts on the local community are critical for success.

Ecosystem restoration is an important part of climate change mitigation and adaptation. Both peatlands and mangroves store large amounts of carbon and increase resilience to extreme events. Our results show that sustainable management has high societal value under all simulated climate scenarios. Investing in nature to restore peatlands and mangroves in our study locations provides a cost-effective way to address climate change and support communities.

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Appendix A. Model Inputs

A.1 Katingan Peatlands

A.1.1 PARAMETER VALUES

Table A1. Parameter inputs for the Katingan Peatland system dynamics model

Parameter	Unit	Value/ equation	Source	Study location
Share of water that becomes groundwater	percent	20%	DHI (2021)	Central Kalimantan
Time for canals to drain water table	year	1	Assumed	N/A
Canal depth	cm	85	Rais et al. (2020)	Central Kalimantan
Time to block canals	year	10	Assumed	N/A
Initial water table depth	cm	-20	Rais et al. (2020)	Central Kalimantan
Initial peat depth	cm	300	DHI (2021)	Central Kalimantan
Initial subsidence	cm	0	Assumed	N/A
Impact of water table on subsidence	cm/year	-0.0431 x water table depth – 1.24	Evans et al. (2019)	Sumatra
Impact of subsidence on runoff	dimensionless	Increases from 0.1 to 0.97 as subsidence increases from 0 to 400 cm	Assumed	N/A
Impact of forest on runoff	dimensionless	Decreases from 1 to 0.3 as share of primary forest increases from 0 to 1	Assumed	N/A

Parameter	Unit	Value/ equation	Source	Study location
Total study area	ha	149,800	Katingan Mentaya Project (2021)	Katingan Peatlands
Initial primary forest share	percent	53%	Sills et al. (2014)	Katingan Peatlands
Initial secondary forest share	percent	0	Assumed	N/A
Initial unused degraded land share	percent	47%	Sills et al. (2014)	Katingan Peatlands
Initial oil palm plantation share	percent	0	Assumed	N/A
Initial gold mining land share	percent	0	Assumed	N/A
Time for secondary forest to establish	year	20	Assumed	N/A
Time for secondary forest to mature to primary forest	year	200	Assumed	N/A
Trees planted per year	trees/year	50,000	Katingan Mentaya Project (2021)	Katingan Peatlands
Trees planted per hectare	trees/ha	1,111	Hansson & Dargusch (2018)	Indonesia
Time to convert land	year	1	Assumed	N/A
Plantation lifetime	year	50	Assumed	N/A

Parameter	Unit	Value/ equation	Source	Study location
Mine lifetime	year	50	Assumed	N/A
Desired plantation land	ha	Increases from 0 to 100,000 by 2100 (BAU) Increases from 0 to 6,000 by 2030 (limited desired land conversion)	Assumed based on Sills et al. (2014)	Katingan Peatlands
Desired mining land	ha	Increases from 0 to 10,000 by 2100 (BAU) Increases from 0 to 2,000 by 2040 (limited desired land conversion)	Assumed based on Sills et al. (2014)	Katingan Peatlands
Percent of land monitored	percent	100%	Assumed	N/A
Baseline plantation burn share	percent	50%	Assumed	N/A
Baseline mining land burn share	percent	50%	Assumed	N/A
Baseline secondary forest burn share	percent	50%	Assumed	N/A
Baseline primary forest burn share	percent	5%	Assumed based on Nikonovas et al. (2020)	Sumatera and Kalimanta
Baseline unused degraded land burn share	percent	50%	Assumed	N/A
Fire probability	Percent/year	5%	Assumed	N/A

Parameter	Unit	Value/ equation	Source	Study location
Increase in fire probability due to drought	percent	1,000%	Assumed	N/A
Four-month total precipitation drought threshold	mm	650	Field & Shen (2008)	Southern Kalimantan
Percent increase in burn extent due to drought	percent	20%	Assumed	N/A
Percent decrease in burn extent due to fire suppression	percent	25%	Assumed	N/A
Peat burn depth	cm	10 cm with 40 cm of subsidence 51 cm with 100 cm of subsidence 816 cm with 1,000 cm of subsidence	Jaenicke et al. (2010); Sulaeman et al. (2021)	South Sumatera and Central Kalimantan
Peat density	g/cm^3	0.19	Rais et al. (2020)	Central Kalimantan
Economic cost per hectare burned (including damage to infrastructure, agriculture, industry, trade, tourism, transportation, and the environment)	USD/ha	8,315.05	World Bank (2019)	Indonesia

Parameter	Unit	Value/ equation	Source	Study location
Health cost per hectare burned	USD/ha	58.08	World Bank (2016)	Indonesia
Education cost per hectare burned	USD/ha	13.08	World Bank (2016)	Indonesia
Peat emissions factor	t CO_2/kg	0.001637	Setyawati et al. (2017)	Central Kalimantan
Primary forest above-ground biomass emissions factor	t C/ha	169	Saragi et al. (2016)	Central Kalimantan
Secondary forest above-ground biomass emissions factor	t C/ha	79	Saragi et al. (2016)	Central Kalimantan
Plantation above-ground biomass emissions factor	t C/ha	45	Agus et al. (2013)	Indonesia
Mining above-ground biomass emissions factor	t C/ha	0	Agus et al. (2013)	Global
Degraded land above-ground biomass emissions factor	t C/ha	118	Agus et al. (2013)	Indonesia
Peat emissions from decomposition	t CO_2/ha/year	-0.84 x water table depth + 9	Hooijer et al. (2012)	Riau and Jambi
Initial total assets	USD	100,000	Assumed	N/A
Annual change in total assets	USD/year	100	Assumed	N/A

Parameter	Unit	Value/ equation	Source	Study location
Share of assets at risk	percent	Increases from 48.1% to 95.4% as subsidence increases from 0 cm to 525 cm	Deltares (2015)	Rajang Delta peatlands, Sarawak, Malaysia
Precipitation flooding threshold	mm	475	Wösten et al. (2008) and WRI (personal communication, July 10, 2021)	Central Kalimantan
Percent of assets at risk damaged at precipitation threshold	percent	25%	Wösten et al. (2008) and WRI (personal communication, 2021)	Central Kalimantan
Percent increase damaged above precipitation threshold	percent	Same as percent increase in precipitation relative to threshold	Assumed	N/A
Suppress fires construction costs	USD	113,292	Assumed based on Sills et al. (2014)	Katingan Peatlands
Suppress fires annual costs	USD/year	267,781	Assumed based on Sills et al. (2014)	Katingan Peatlands
Concession fees for blocking canals and revegetating	USD	3,200,200	Sills et al. (2014)	Katingan Peatlands
Cost to block canals and revegetate	USD/year	20,000	Hansson & Dargusch (2018)	Indonesia
Cost to monitor ecosystem	USD/year	720,948	Sills et al. (2014)	Katingan Peatlands

Parameter	**Unit**	**Value/ equation**	**Source**	**Study location**
Average mining wage	USD/FTE	2,128.7	Statistics Indonesia (2020)	Central Kalimantan
Average plantation wage	USD/FTE	2,128.7	Statistics Indonesia (2020)	Central Kalimantan
Average wage for ecosystem restoration and protection	USD/FTE	2,050.18	Statistics Indonesia (2020)	Central Kalimantan
Average wage for fire prevention	USD/FTE	2,050.18	Statistics Indonesia (2020)	Central Kalimantan
Non-timber forest products income per hectare of forest	USD/ha/year	0.68	Simangunsong et al. (2020)	Kampar Peninsula
Employment per hectare of plantation	FTE/ha/year	0.25	Sinaga (2013)	Indonesia
Employment per hectare of mines	FTE/ha/year	0.0067	Atteridge et al. (2018)	Indonesia
Employment from blocking canals and revegetating	FTE/year	100	Katingan Mentaya Project (2021)	Katingan Peatlands
Employment from fire prevention	FTE/year	450	Katingan Mentaya Project (2021)	Katingan Peatlands
Government revenue per hectare of oil palm plantation	USD/ha/year	201.34	Purnomo et al. (2020)	Indonesia
Carbon price	USD/t CO_2	5	Satrio (2021)	Indonesia

A.1.2 COPERNICUS CLIMATE DATA: PRECIPITATION AND EVAPORATION

Figure A1. Projected precipitation under RCP 4.5 from Copernicus Climate Change Service, 2018. Coordinates: -2.537, 113.16.

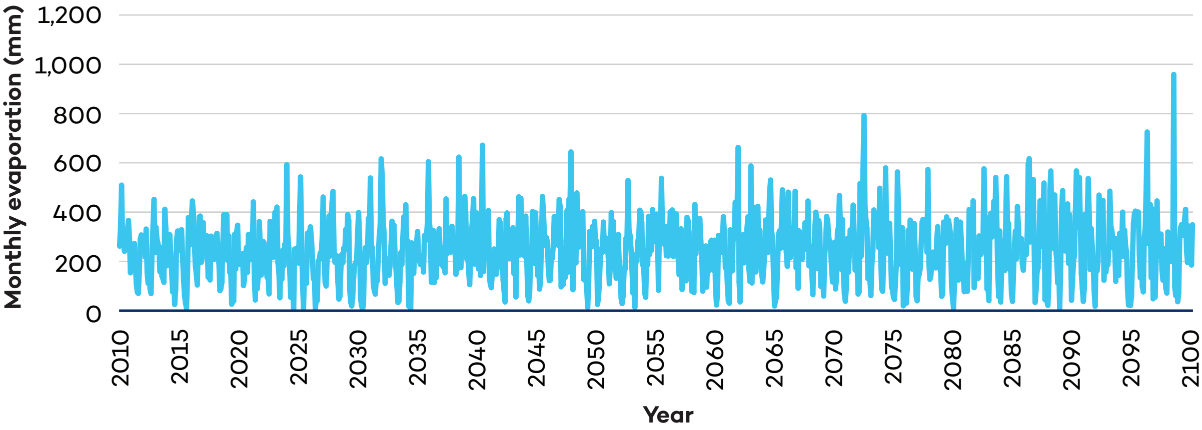


Figure A2. Projected evaporation under RCP 4.5 from Copernicus Climate Change Service, 2018. Coordinates: -2.537, 113.16.

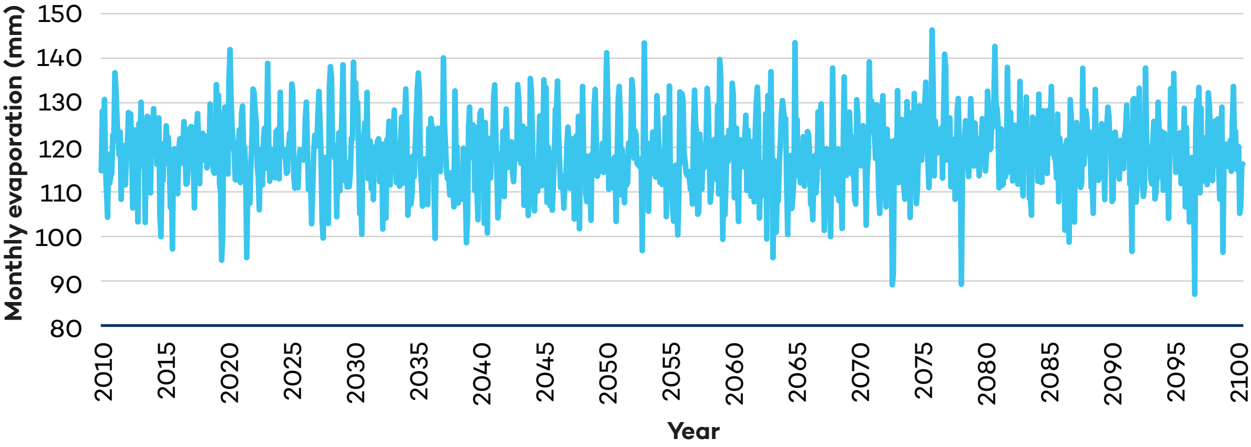


Figure A3. Projected precipitation under RCP 6.0 from Copernicus Climate Change Service, 2018. Coordinates: -2.537, 113.16.

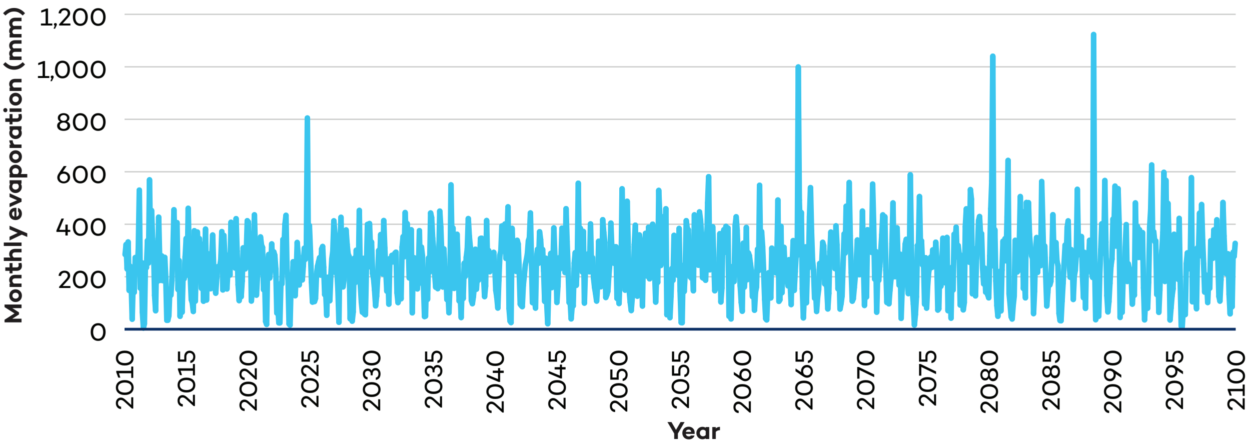


Figure A4. Projected evaporation under RCP 6.0 from Copernicus Climate Change Service, 2018. Coordinates: -2.537, 113.16.

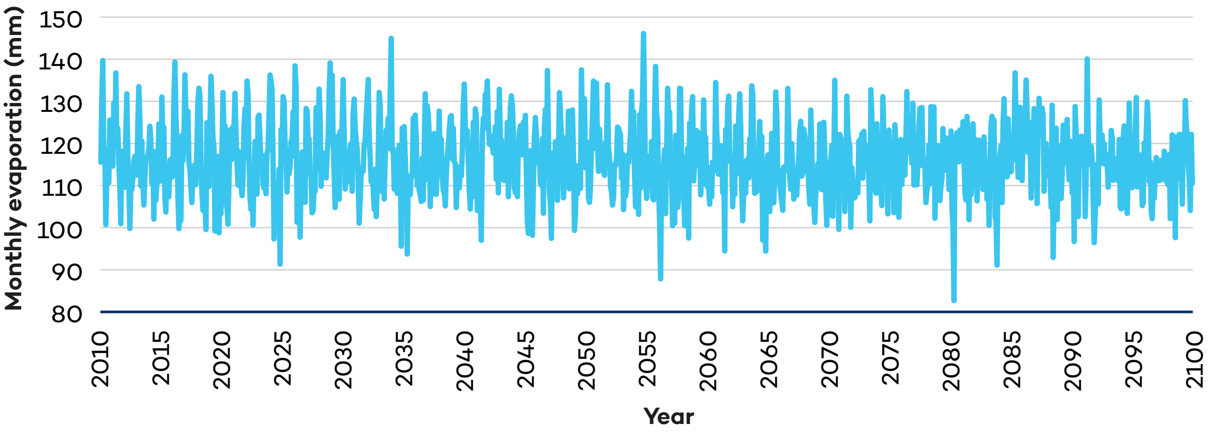


Figure A5. Projected precipitation under RCP 8.5 from Copernicus Climate Change Service, 2018. Coordinates: -2.537, 113.16.

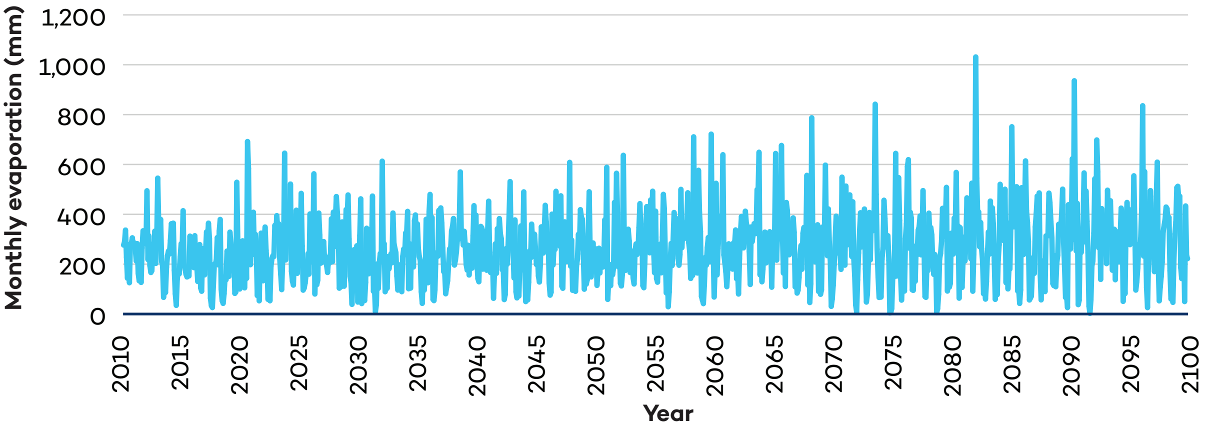
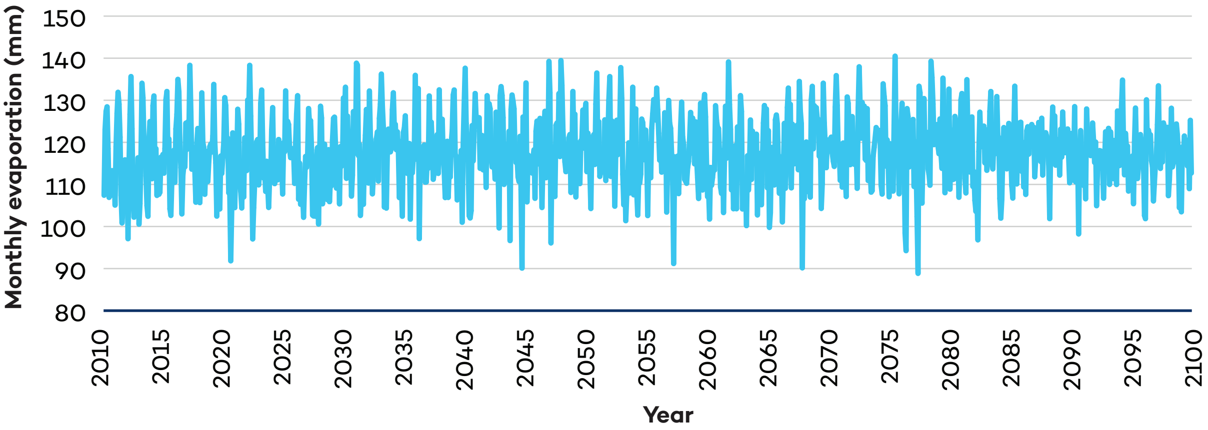


Figure A6. Projected evaporation under RCP 8.5 from Copernicus Climate Change Service, 2018. Coordinates: -2.537, 113.16.



A.2 Belitung Mangrove Park

A.2.1 PARAMETER VALUES

Table A2. Parameter inputs for the Belitung Mangrove Park system dynamics model

Parameter	Unit	Value/equation	Source	Study location
Time to plant mangroves	year	1	Assumed	N/A
Time to build permeable structures	year	1	Assumed	N/A
Initial total area	ha	52	Beranda HKM Seberang Bersatu (2021)	Belitung Mangrove Park
Initial active mining land	ha	2	Assumed	N/A
Initial abandoned mining land	ha	0	Assumed	N/A
Initial primary mangrove forest	ha	50	Assumed	N/A
Initial secondary mangrove forest	ha	0	Assumed	N/A
Initial planted mangrove seedlings	ha	0	Assumed	N/A
Initial bare land in front of mangroves	ha	0	Assumed	N/A
Time to deactivate unwanted mines	year	1	Assumed	N/A
Mine lifetime	year	10	Assumed	N/A
Share of desired tin mines cleared	1/year	0.01	Assumed	N/A

Parameter	Unit	Value/equation	Source	Study location
Time for mangroves to colonize bare land in front of mangroves	year	2	Assumed	N/A
Share of bare land in front of mangroves that erodes (excluding area colonized by mangroves)	Percent/ year	50%	Assumed	N/A
Time for mangroves to mature	year	20	Yanagisawa et al. (2010)	Banda Aceh
Length of mangrove park	m	1,000	Assumed	N/A
Net erosion assuming no wave impacts or permeable structures	m/year	Decreases from 5 m/year with no mangroves to -6 m/year when mangroves are 1 km wide	Thampanya (2006)	Thailand
Cumulative sea level rise in 2100	mm	530 (RCP 4.5) 550 (RCP 6.0) 740 (RCP 8.5)	Stocker et al. (2013)	Global
Wave vs. wind regression slope	s	0.1189 (May–October) 0.3308 (November–April)	Calculated from E.U. Copernicus Marine Service Information (2019a, 2019b)	Belitung Mangrove Park
Wave vs. wind regression intercept	m	0.1815 (May–October) -0.0871 (November–April)	Calculated from E.U. Copernicus Marine Service Information (2019a, 2019b)	Belitung Mangrove Park

Parameter	Unit	Value/equation	Source	Study location
Percent reduction in wave + sea level rise water height per metre of mangroves	percent/m	0.4%	Spalding et al. (2014)	Global
Minimum wave height that damages mangroves	m	1.5	Assumed	N/A
Average tsunami height	m	4	Assumed	N/A
Tsunami height standard deviation	m	1	Assumed	N/A
Percent reduction in tsunami height per metre of mangroves	percent/m	0% when mangroves less than 300 m wide. Increases to 30% per metre as mangrove width increases to 1,000 m	Spalding et al. (2014)	Global
Effective water level flooding threshold	mm	1,000	Assumed	N/A
Percent of assets damaged by flooding	percent	20%	Assumed	N/A
Initial assets at risk	USD	10,000	Assumed	N/A
Annual change in assets at risk	USD/year	100	Assumed	N/A
Value added on unused land	USD	50,000	Assumed	N/A
Time to develop unused land	year	5	Assumed	N/A

Parameter	Unit	Value/equation	Source	Study location
Mangrove area threshold for development on unused land	ha	48	Assumed	N/A
Percent of mangroves destroyed by waves	percent	10% when maximum wave height is 4 m higher than historical average 25% when maximum wave height is 5 m higher than historical average 100% when maximum wave height is 14 m higher than historical average	Assumed based on personal communication with WRI (2021)	N/A
Percent of primary mangroves destroyed by tsunami	percent	80%	Yanagisawa et al. (2010)	Banda Aceh
Percent of secondary mangroves destroyed by tsunami	percent	100%	Yanagisawa et al. (2010)	Banda Aceh
Planted mangrove seedling death rate	percent/ year	15%	Kathiresan & Bingham (2001)	Global
Initial carbon stored per hectare of mangrove forest	t C/ha	1,016.5	Kauffman et al. (2020)	Global
Carbon sequestered per hectare of mangrove forest	t C/ha/ year	5	Kustiyanto (2019)	Mahakam Delta, Indonesia

Parameter	Unit	Value/equation	Source	Study location
Shrimp stock change excluding harvesting	kg/year	0.15 x (carrying capacity – stock) x stock/carrying capacity	Assumed	N/A
Shrimp carrying capacity per hectare of mangroves	kg/ha	40,000	Assumed	N/A
Sustainable fishing rate	percent/year	8%	Assumed	N/A
Unsustainable fishing rate	percent/year	12%	Assumed	N/A
Tourists per hectare without ecotourism support	person/year/ha	59.4	Yusri et al. (2019)	Belitung Mangrove Park
Tourists per hectare with ecotourism support	person/year/ha	269.2	Yusri et al. (2019)	Belitung Mangrove Park
Tourists per hectare during tsunami recovery period	Person/year/ha	59.4	Assumed based on Yusri et al. (2019)	N/A
Time for tourism industry to recover from tsunami	year	1.5	Assumed based on Yusri et al. (2019)	Belitung Mangrove Park
Maximum tin mining area with which ecotourism can occur	ha	1	Assumed	N/A
Jobs per tourist	FTE/person	0.005	Assumed	N/A
Average tourism wage	USD/FTE	1,783.7	Statistics Indonesia (2020)	Bangka Belitung
Tin mining jobs per hectare	FTE/ha	0.0095	PT Timah (2019a, 2019b)	Indonesia

Parameter	Unit	Value/equation	Source	Study location
Average mining wage	USD/FTE	2,003.49	Statistics Indonesia (2020)	Bangka Belitung
Jobs per hectare for planting mangroves	FTE/ha	20	Assumed	N/A
Average mangrove planting wage	USD/FTE	1,826.74	Statistics Indonesia (2020)	Bangka Belitung
Jobs per kilometre of permeable barrier built	FTE/km	7	(EcoShape, n.d.)	Northern Java
Average wage for building permeable barriers	USD/FTE	1,826.74	Statistics Indonesia (2020)	Bangka Belitung
Jobs per kilometre of permeable barrier maintained	FTE/km	3	Assumed	N/A
Average wage for maintaining permeable structures	USD/FTE	1,826.74	Statistics Indonesia (2020)	Bangka Belitung
Jobs per kilometre of breakwater built	FTE/km	7	Assumed equal to permeable barriers	N/A
Average wage for building breakwater	USD/FTE	2,003.49	Statistics Indonesia (2020)	Bangka Belitung
Jobs per kilometre of breakwater maintained	FTE/km	3	Assumed equal to permeable barriers	N/A
Average wage for maintaining breakwater	USD/FTE	2,003.49	Statistics Indonesia (2020)	Bangka Belitung
Desired per capita wages	USD/ person/ year	1,000	Assumed	N/A

Parameter	Unit	Value/equation	Source	Study location
Population supported by Belitung Mangrove Park area	person	1,000	Assumed	N/A
Deaths per hectare of tin mines	person/ ha/year	0.000196	Hodal (2012)	Bangka Belitung
Value of statistical life	USD/ person	592,000	Viscusi & Masterman (2017)	Indonesia
Cost to plant seedlings per hectare	USD/ha	2,182.1	Direktorat Jenderal Konservasi Sumber Daya Alam Dan Ekosistem (2018)	Indonesia
Cost to maintain planted seedlings per hectare	USD/ha	314.72	Direktorat Jenderal Konservasi Sumber Daya Alam Dan Ekosistem (2018)	Indonesia
Required years of maintenance for planted seedlings	year	3	Direktorat Jenderal Konservasi Sumber Daya Alam Dan Ekosistem (2018)	Indonesia
Construction cost per metre of permeable structures	USD/m	103.75	Wilms et al. (2020)	Central Java
Maintenance cost per metre of permeable structures	USD/m	51.87	Wilms et al. (2020)	Central Java

Parameter	Unit	Value/equation	Source	Study location
Ecotourism infrastructure cost	USD	1,376,467	Indonesia Climate Change Trust Fund (2019b)	Belitung Mangrove Park
Time to build ecotourism infrastructure	year	1.5	Yusri et al. (2019)	Belitung Mangrove Park
Carbon price	USD/t CO_2	5	Satrio (2021)	Indonesia
Breakwater construction price per metre of coastline	USD/m	250	Narayan et al. (2016)	Vietnam
Time to construct breakwater	year	1	Assumed	N/A
Breakwater maintenance cost per metre of coastline	USD/m/year	2.5	Jonkman et al. (2013); Oppenheimer et al. (2019)	Global
Water level reduction due to breakwater	mm	200	Narayan et al. (2016)	Vietnam

A.2.2 COPERNICUS CLIMATE DATA: WIND SPEED AND WATER LEVEL

Figure A7. Projected wind speed under RCP 4.5 from Copernicus Climate Change Service, 2018. Coordinates: -2.772, 107.6.

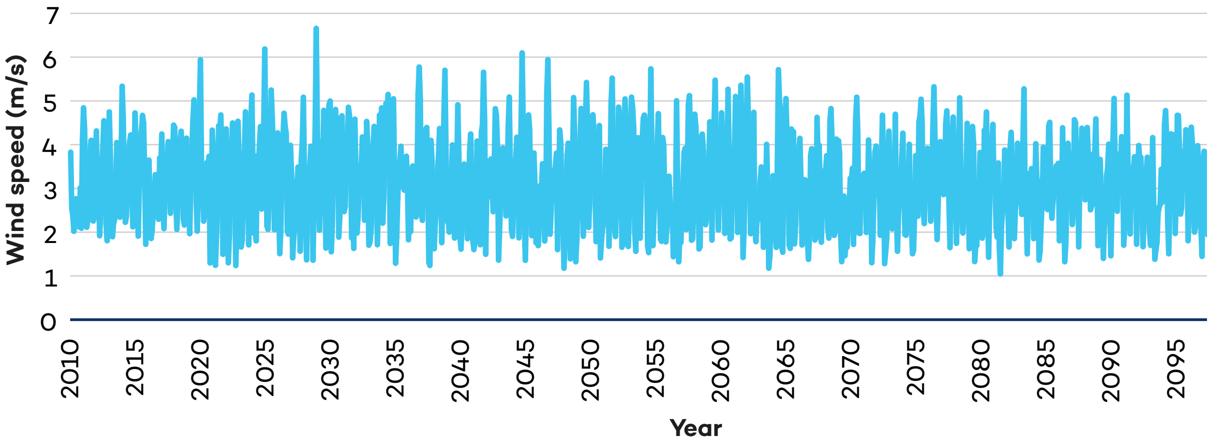


Figure A8. Projected wind speed under RCP 6.0 from Copernicus Climate Change Service, 2018. Coordinates: -2.772, 107.6.

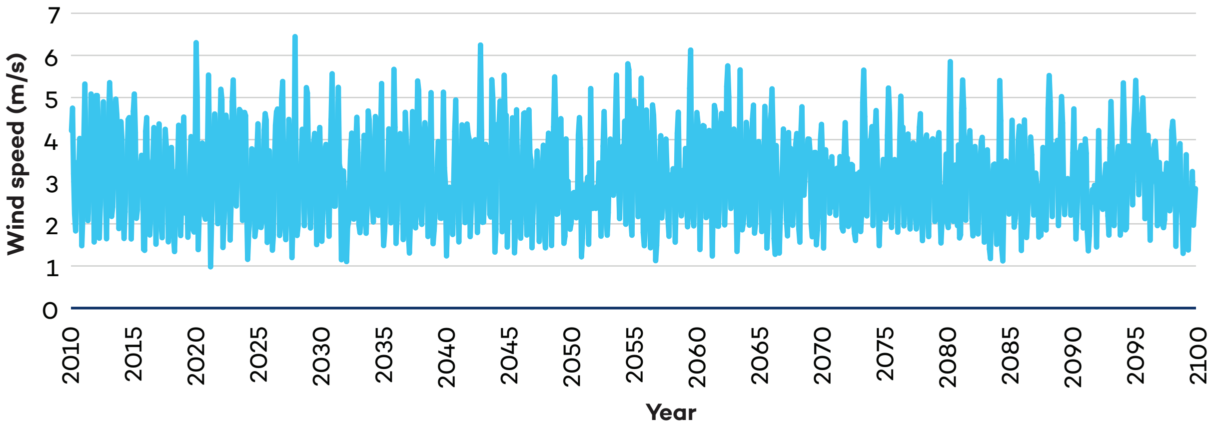


Figure A9. Projected wind speed under RCP 8.5 from Copernicus Climate Change Service, 2018. Coordinates: -2.772, 107.6.

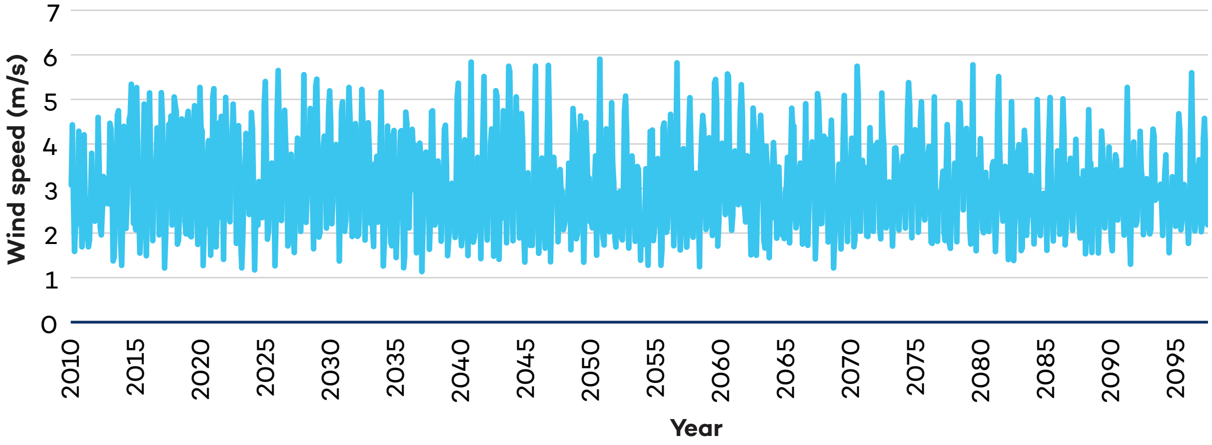


Figure A10. Historical monthly maximum wave height from E.U. Copernicus Marine Service Information, 2019a. Coordinates: -2.76, 107.59

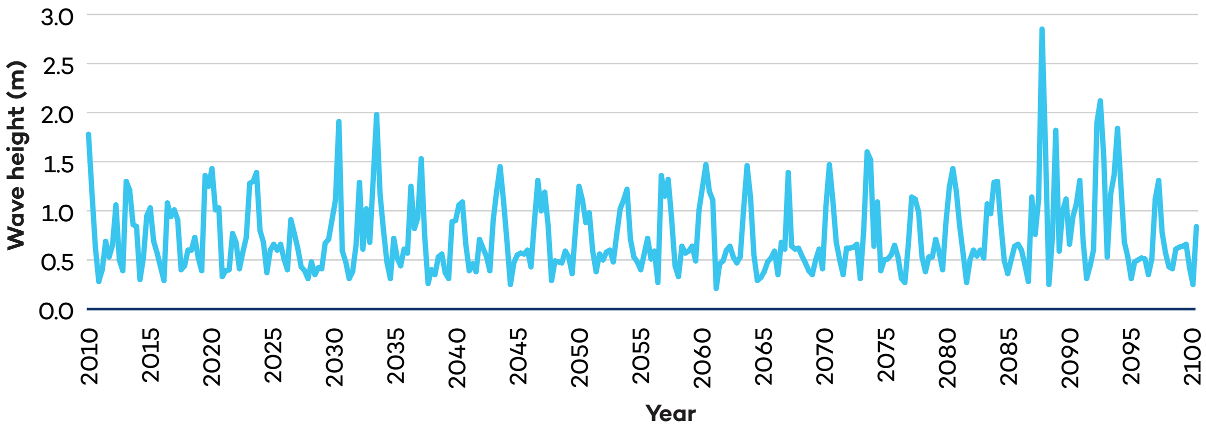


Figure A11. Historical monthly average wind speed from E.U. Copernicus Marine Service Information, 2019b. Coordinates: -2.76, 107.59 –

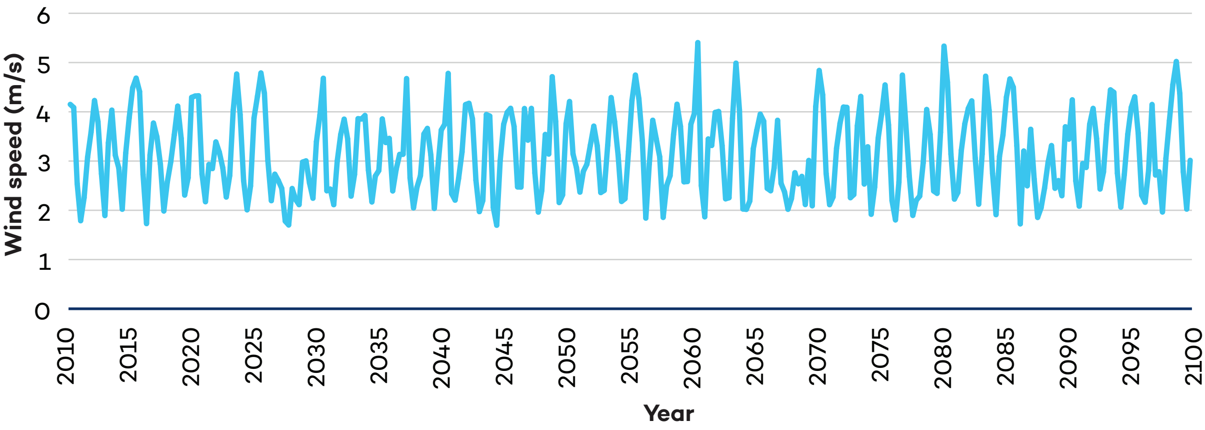


Figure A12. Regression of monthly maximum wave height vs. monthly average wind speed for May–October. Data from (E.U. Copernicus Marine Service Information, 2019b, 2019a). Coordinates: -2.76, 107.59

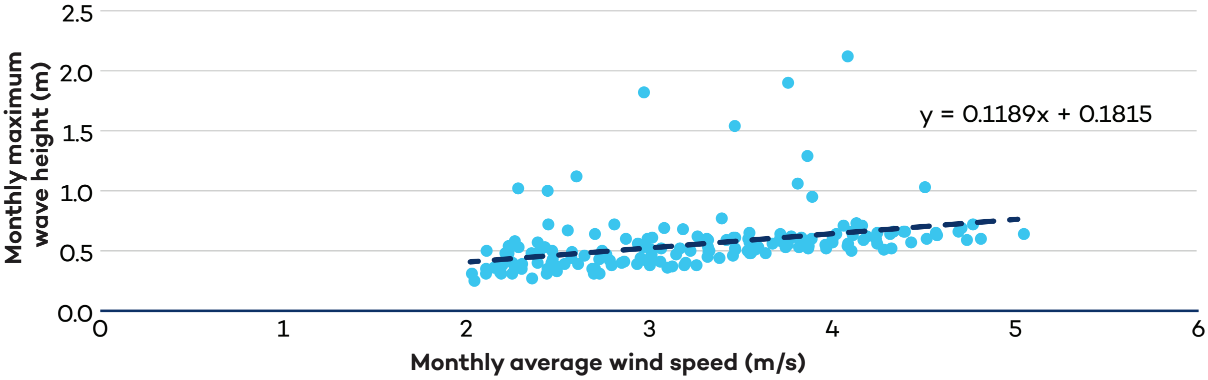
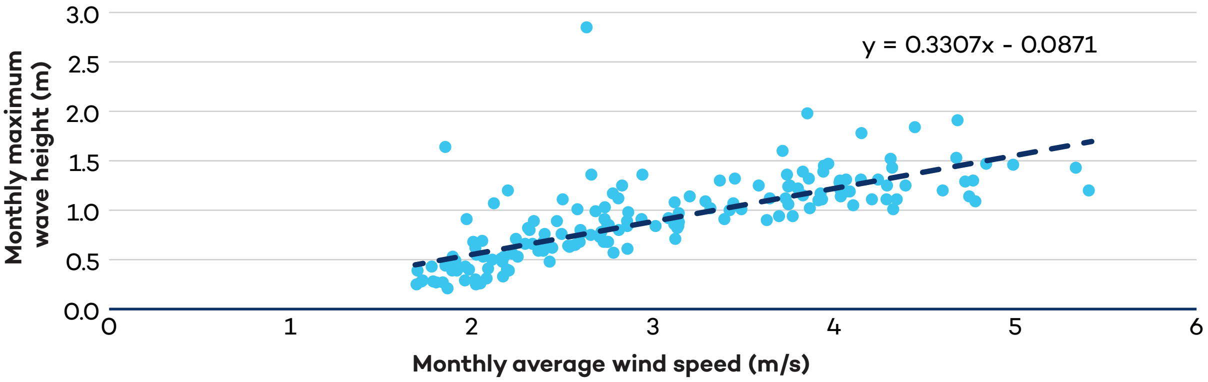


Figure A13. Regression of monthly maximum wave height vs. monthly average wind speed for November–April. Data from E.U. Copernicus Marine Service Information, 2019b, 2019a. Coordinates: -2.76, 107.59



Appendix B. Results Tables for Alternative Peatland Conversion Assumptions

B.1 Integrated Cost-Benefit Analysis

Table B1. Peatland integrated cost-benefit analysis for the RCP 4.5 climate scenario assuming desired land conversion reaches a peak and stabilizes in 2030 for oil palm plantations and in 2040 for gold mining. Intervention costs include the upfront and recurring costs of blocking canals, monitoring the land, and fire suppression. All values are in USD million. Cumulative values calculated over 2010–2100. Avoided costs and damages are relative to the limited land conversion scenario with no interventions.

Peatland integrated cost-benefit analysis: Limited land conversion

	Limited land conversion	Limited land conversion + block canals + monitor land	Limited land conversion + suppress fires	Limited land conversion + block canals + monitor land + suppress fires
Avoided cost of carbon emissions	0.00	180.47	119.09	289.81
Avoided flood damages	0.00	0.12	0.10	0.18
Avoided cost of fires	0.00	191.88	466.37	612.27
Household income	239.64	74.83	308.97	144.16
Intervention costs	0.00	124.59	20.17	144.75
Foregone government oil palm revenue	0.00	67.69	0.00	67.69
Total	**239.64**	**255.03**	**874.36**	**833.98**
Value relative to no interventions	**0.00**	**15.39**	**634.72**	**594.34**

Table B2. Peatland integrated cost-benefit analysis for the RCP 4.5 climate scenario assuming primary, secondary, and degraded forest are all targeted equally for land conversion. Intervention costs include the upfront and recurring costs of blocking canals, monitoring the land, and fire suppression. All values are in USD million. Cumulative values calculated over 2010–2100. Avoided costs and damages are relative to the no-preference land conversion scenario with no interventions.

Peatland integrated cost-benefit analysis: No-preference land conversion

	No-preference land conversion	**No-preference land conversion + block canals + monitor land**	**No-preference land conversion + suppress fires**	**No-preference land conversion + block canals + monitor land + suppress fires**
Avoided cost of carbon emissions	0.00	3,060.46	367.94	3,168.58
Avoided flood damages	0.00	2.33	0.18	2.39
Avoided cost of fires	0.00	574.23	544.84	989.32
Household income	1,906.64	74.86	1,975.85	144.18
Intervention costs	0.00	124.59	20.17	144.75
Foregone government oil palm revenue	0.00	697.75	0.00	697.75
Total	**1,906.64**	**2,889.55**	**2,868.65**	**3,461.98**
Value relative to no interventions	**0.00**	**982.91**	**962.01**	**1,555.34**

B.2 Financial Analysis

Table B3. Financial indicators for the limited land conversion scenarios. Values are relative to the limited land conversion scenario with no interventions.

Peatland management financial indicators: Limited land conversion

	IRR (%)		BCR		NPV (million USD)	
	Societal	**Conventional**	**Societal**	**Conventional**	**Societal**	**Conventional**
Limited land conversion + block canals + monitor land	0.3%	-	-0.04	-1.14	-18.03	-36.93
Limited land conversion + suppress fires	534.7%	534.7%	14.72	3.33	34.74	5.89
Limited land conversion + block canals + monitor land + suppress fires	13.5%	-	1.74	-0.57	14.59	-31.03

Table B4. Financial indicators for the no-preference land conversion scenarios. Values are relative to the no-preference land conversion scenario with no interventions.

Peatland management financial indicators: No-preference land conversion

	IRR (%)		**BCR**		**NPV (million USD)**	
	Societal	**Conventional**	**Societal**	**Conventional**	**Societal**	**Conventional**
No-preference land conversion + block canals + monitor land	4.6%	-	-0.28	-4.9	-22.17	-102.11
No-preference land conversion + suppress fires	534.7%	534.7%	16.52	3.33	39.29	5.89
No-preference land conversion + block canals + monitor land + suppress fires	10.8%	-	1.51	-3.85	10.07	-96.21

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