Dynamic Economic Valuation of coastal wetland restoration: A nature-based solution for climate and biodiversity

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Abstract

This paper explores the dynamic linkage between coastal wetland restoration and the resulting economic benefits, with a focus on nonmarket values such as climate regulation and biodiversity conservation. Coastal wetlands are recognised as highly effective natural carbon sinks, offering significant ecosystem services that contribute to climate change mitigation and adaptation. By utilising a modelling framework that integrates ecological recovery processes and economic valuations over a 100-year period, we provide insights into optimising long-term returns from wetland restoration. This study emphasises the importance of accounting for the temporal dynamics of ecosystem recovery, highlighting the lag between restoration activities and full ecosystem functionality. Our findings highlight the importance of nature-based solutions in global climate finance strategies and emphasise the need for more accurate, targeted investment in wetland restoration. This approach ensures that resources are allocated efficiently over time, maximising the benefits of enhancing coastal resilience and achieving long-term climate goals.

Keywords: nature-based climate solutions; wetland restoration; nonmarket value; temporal dynamics; ecosystem response function

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Declaration of interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding acknowledgment statement: The study is supported by the Ministry of Business, Innovation & Employment (MBIE) New Zealand Endeavour projects “Transforming coastal lowland systems threatened by sea-level rise into prosperous communities” (Grant No. C01X2107).

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Abstract

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1. Introduction

In recent years, there has been a growing recognition of the critical role that nature-based solutions (NBSs) can play in mitigating greenhouse gas (GHG) emissions while simultaneously addressing biodiversity loss and enhancing ecosystem resilience. Coastal wetlands, including mangroves, saltmarshes, and seagrass beds, are among the most effective natural carbon sinks, sequestering carbon at rates significantly higher than those of terrestrial forests (McLeod et al., 2011). The global importance of these ecosystems in the fight against climate change is underscored by the increasing momentum to mobilise funding towards NBSs that address the dual challenges of climate change and biodiversity conservation (Paul et al., 2024). As part of broader climate finance strategies, funding dedicated to wetland restoration can yield substantial returns by providing a wide array of ecosystem services, including protection from floods and waves, water filtration, carbon sequestration, and habitat provision for diverse species (Barbier, 2019; Friess et al., 2020). Recognising this, global initiatives such as the Global Mangrove Alliance and the Blue Carbon Initiative have been advocating for scaled-up funding to restore and protect these vital ecosystems as part of a holistic approach to climate mitigation and adaptation[1]. Coastal wetlands serve as natural buffers, mitigating climate change by absorbing and dissipating wave energy, which reduces the impact of coastal flooding and erosion. Their capacity for carbon sequestration, both in vegetation and soil, positions wetlands as significant carbon sinks that help lower atmospheric carbon dioxide levels. Unlike rigid and often costly engineered solutions such as sea walls and stop banks, wetlands offer a flexible, self-sustaining approach that can adapt to changing conditions over time (Temmerman et al., 2013). Additionally, wetlands support important fisheries and are vital for wider biodiversity protection (Craft et al., 2003; Kingsford et al., 2016). They provide essential habitats for a wide array of species, supporting rich biodiversity and maintaining ecological balance. These functions highlight the importance of integrating wetland restoration into broader strategies for climate adaptation and safeguarding biodiversity.

The economic value of wetland restoration has gained increasing attention in recent years. Numerous studies have estimated the nonmarket or intangible benefits of restored wetlands, highlighting their significant contributions to ecosystem services that support human well-

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[1] More information for Global Mangrove Alliance at https://mangrovealliance.org/ and Blue Carbon Initiative at https://www.thebluecarboninitiative.org/.

being and biodiversity. For example, the value of coastal wetlands in providing storm protection services alone has been estimated to be substantial, with wetlands in the United States providing annual flood protection benefits valued at approximately 34 billion USD (adjusted to 2024 dollars) (Costanza et al., 2008). In addition to flood protection, restored wetlands can also offer recreational, cultural, and aesthetic benefits that contribute to local economies and improve quality of life (Chen et al., 2009; Costanza et al., 1989; Ghermandi et al., 2010). However, funding for nature-based climate solutions remains insufficient to meet global climate goals. A significant gap persists between the financial resources allocated to engineered solutions and those directed towards NBSs, even though the latter can offer more cost-effective and sustainable outcomes (WBCSD, 2020). To address this disparity, it is crucial to validate the long-term economic benefits of investing in NBSs, particularly in the context of climate change mitigation and adaptation.

Despite the recognised value of wetland restoration, there is a notable gap in the literature regarding the dynamic linkage between restoration activities and their resulting economic benefits. Research on impact assessments of wetland restoration rarely reports both ecological and economic aspects. A review of studies on the impact of mangrove restoration revealed that only 4.3% of the studies (eight out of 186) reported both ecological and economic outcomes (Liu et al., 2024). Those reporting economic impacts mainly use market prices to elicit the economic value of provisioning services, such as food production (Liu et al., 2024). However, current approaches often assume a direct, static relationship between restoration efforts and economic value without adequately accounting for the temporal dynamics and ecological complexities involved (Bulmer et al., 2024; Chaikumbung et al., 2016; Chen et al., 2009; Costanza et al., 1989; Dumax & Rozan, 2021; Ghermandi et al., 2010). This assumption can oversimplify matters and lead to inaccurate estimations in the impact assessment of wetland restoration (e.g., cost-benefit analysis (CBA)), as it fails to capture the dynamic nature of the benefits that accrue over time, including the role in mitigating climate change impacts and enhancing ecosystem resilience.

Moreover, the full functioning of restored wetlands often lags behind that of initial restoration activities. For example, wetland functions associated with the detention of precipitation and floods rapidly increase under post-restoration conditions, whereas improvements in wetland habitat functions (associated with forest establishment and maturation) require additional time (Berkowitz, 2019). The trajectory of ecosystem service values during wetland restoration needs more attention. A meta-analysis of 621 wetland sites worldwide revealed that even a century after restoration efforts, biological structure and biogeochemical functioning remained, on average, 26% and 23% lower, respectively than those at reference sites (Moreno-Ger et al., 2012). Some recent studies have started to provide evidence of the relationship between thresholds in restoration functions and the value of wetland restoration ecosystem services. For example, Zhou et al. (2020) reported that the value of all ecosystem services increases as wetland area increases, with an average elasticity of 0.83; Tomscha et al. (2023) reported that nitrogen retention targets were mostly met when the percentage of wetlands restored exceeded 60%. However, the effectiveness of restoration targets across spatial scales remains unclear. For example, ecosystem services change linearly with the area restored at the basin scale but nonlinearly at sub-catchment scales (Tomscha et al., 2023). (Purandare et al., 2024) proposed that wetland restoration projects should closely monitor the recovery of ecosystems, following measurable ecological indicators (Gann et al., 2019).

Additionally, a significant challenge exists in how the nonmarket values of wetland ecosystem services could be monetarised. Most nonmarket valuation (NMV) studies of wetland ecosystem services are based on stated preference valuations (i.e., asking people's willingness to pay/accept for wetland restoration through surveys) that are restricted by the cross-sectional nature of the survey conducted and hence provide only point estimates of the benefits at a year of the survey or a given period (e.g., five years (Ndebele & Forgie, 2017; Pattison et al., 2011)). There are only a few exemptions. One example is that of Marre et al. (2015) who considered the temporal effects of wetland restoration in a choice experiment, i.e., preservation for 20, 50, and 100 years for various conservation attributes, such as the quantity of fish, animals, and coastal and lagoon natural landscapes. The results show that the benefits derived from preserving various aspects of a marine ecosystem changed over time in a nonlinear manner. Another example is that of Hagen et al. (2017) who estimated the recreation benefits of NBSs for wastewater treatment over 13 years (2002-2015) using a hedonic pricing model. They reported that the price premium associated with properties adjacent to the constructed wetland park and lagoon increased nonlinearly over time. Notably, inaccurate estimation of small-scale restoration projects can lead to significantly large errors when scaling up to achieve broader climate adaptation goals, resulting in suboptimal policy-making decisions that fail to fully leverage the potential benefits of nature-based solutions (Araya-López et al., 2024; Moorhead, 2013).

Our study proposes a modelling framework designed to integrate ecosystem responses to coastal wetland restoration efforts with the economic valuation of ecosystem services. This framework serves as a tool to account for the dynamic processes of restoration and the resulting economic benefits over time. We utilise examples of climate regulation and fishery habitat protection to numerically demonstrate and validate the framework, leveraging available data. These examples highlight how the model can quantify and evaluate the substantial economic benefits provided by coastal wetlands in terms of both climate adaptation and ecological preservation. The flexibility of our framework allows for its application to various ecosystem services as new data and information become available. By incorporating ecological functions and economic valuation techniques, we aim to provide a comprehensive understanding of how restoration efforts translate into market and nonmarket economic value over time. This modelling framework allows for the consideration of the dynamics of the valuation of wetland restoration over 100 years, considering 1) ecosystem responses to restoration processes and 2) shifts in human value as ecosystems recover over time. We consider nonlinear relationships and threshold effects in the model to offer a robust framework for decision-making in wetland management and climate adaptation strategies. This integrated approach enhances the effectiveness of wetland restoration policies and contributes to more resilient and sustainable coastal ecosystems. By providing evidence of the long-term economic benefits of wetland restoration, this research contributes to the growing body of evidence supporting the need for increased funding for nature-based climate solutions. The framework ensures that investments in coastal wetland restoration are optimised to yield maximum ecological and economic returns, making it a valuable tool for guiding sustainable restoration efforts.

2. Methodology

2.1. The conceptual framework

There is a lag in achieving full functionality post-restoration of wetlands. Existing studies indicate that ecosystems require approximately 10 to 25 years to recover and become fully functional (Bulmer et al., 2024; Craft et al., 2003; Paul et al., 2024). As shown in Figure 1, there is a gap in comprehensively understanding how ecosystems and their functioning recover during wetland restoration, considering 1) the different ecosystem services (e.g., climate regulation, biodiversity, or recreation) and 2) the ecological indicators used to measure the successful recovery of the ecosystem in providing these services. A range of indicators have been proposed for assessing the success of coastal wetlands, including plant and animal species composition and structural diversity, ecosystem function, and physicochemical conditions (Cadier et al. 2020). Importantly, vegetation establishment is only an initial stage in the recovery of ecosystem functioning. The gradual accumulation and maturation of organic detritus from above and, particularly, below-ground plant biomass, as well as the trapping of sediments from the broader catchment, are crucial for restoring ecosystem functionality. For this reason, carbon storage/sequestration is a commonly referenced ecological indicator for measuring successful ecosystem recovery, which is closely tied to ecosystem integrity and functionality and is relatively easy to quantify (Liu et al., 2024; Moorhead, 2013)

However, the rates of recovery for different ecosystem services may vary. For example, active carbon, sediment, and nutrient sequestration may recover at a faster rate than biodiversity does, with instantaneous rates peaking near the start or at some midpoint of the restoration process before tapering off over time. These dynamics can be represented via different functions to better capture the varying trajectories of recovery. (Liu et al., 2024; Moorhead, 2013)Qualitative assessments have also been used to measure the levels of ecosystem recovery from coastal wetland restoration (Gabriel et al., 2019). Although these assessment frameworks provide a comprehensive framework, they often lack temporal mapping of recovery. Another gap is related to the human value system and ecosystem services. Many studies have attempted to estimate the value of wetland restoration via economic tools, presuming that values are associated with fully recovered ecosystems; at this time, ecosystems are assumed to recover and provide full services and values to society. This presumption can lead to a mismatch between when funds are needed and when benefits actually materialise, particularly in investment projects for wetland restoration aimed at climate change regulation. Investors often require a clear understanding of when benefits will be realised and how they will be tracked over time.

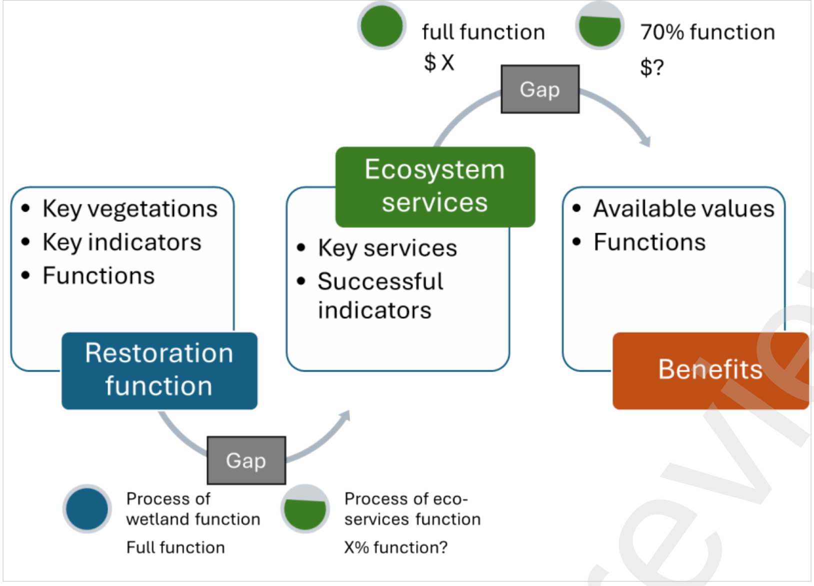
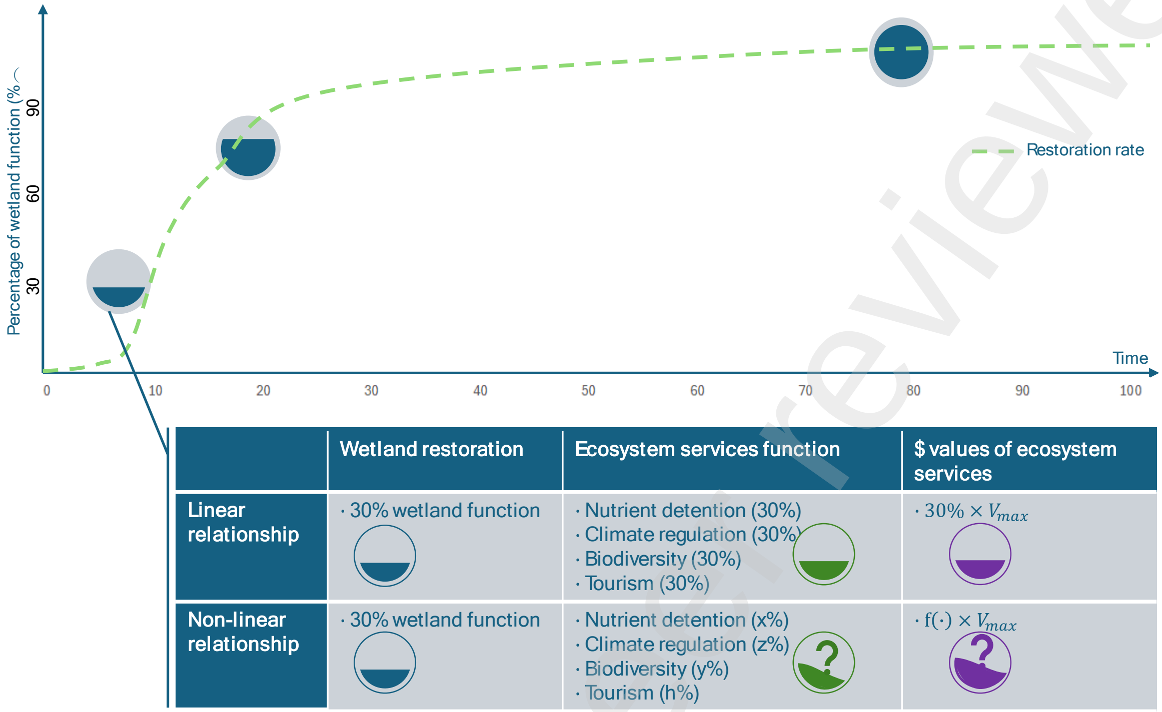


Figure 1. Gaps in wetland restoration evaluation and the conceptual framework for valuing the associated benefits. Source: Authors.

In light of these gaps in knowledge, our framework suggests the use of varying functions to model the different recovery rates of ecosystem services, providing a more nuanced understanding of how restoration efforts translate into economic and ecological benefits over time. In the hypothetical example shown in the upper part of Figure 2, wetland restoration achieves partial function from approximately year 5 (30% full wetland function) to year 20 (80%) and achieves full functionality only after 80 years. In this process, the ecosystem services associated with the wetland have also been built over time. Notably, while dependent on the location and biophysical characteristics of the study sites, the literature on wetland restoration shows that different ecosystem services respond differently to wetland restoration. As shown in the lower part of Figure 2, a simple way of relating wetland restoration to the recovery of ecosystem services is to assume a linear relationship, saying that all the functions of ecosystems, such as flood protection and biodiversity protection, follow the restoration function to recover linearly (i.e., 30%); the economic valuation may follow the same route and take the same proportion of restored values (i.e., 30%). However, a more realistic nexus among the three tends to have nonlinear relationships. As shown in Figure 2, a 30% restoration of wetlands may lead to the recovery of ecosystems differently, which may further affect how society (people) values the resulting ecosystem services. For example, the capacity of biodiversity may be built first, and recreational/tourism service values may develop later. This underscores the long-term nature of wetland restoration and the gradual recovery of complex ecosystem functions. This highlights the necessity of considering temporal dynamics in the economic valuations of wetland restoration projects. Policymakers and restoration practitioners must recognise that while some functions may show rapid initial improvement, others will require significantly longer periods to fully recover.



	Wetland restoration	Ecosystem services function	$ values of ecosystem services
Linear relationship	· 30% wetland function	· Nutrient detention (30%) · Climate regulation (30%) · Biodiversity (30%) · Tourism (30%)	· 30% × V_{max}
Non-linear relationship	· 30% wetland function	· Nutrient detention (x%) · Climate regulation (z%) · Biodiversity (y%) · Tourism (h%)	· f(·) × V_{max}

Figure 2. A hypothetical example showing the nexus of coastal wetland restoration, ecosystem recovery, and valuation of the benefits of ecosystem services. Source: Authors.

2.2. The model

We constructed a model to validate the ideas proposed by the conceptual framework to link restoration functions to the economic values of ecosystem services provided by wetland restoration. First, we assumed that the ecosystem recovered to wetland restoration following the response function S(t) at time t, i.e., the age of the planted vegetation of the restored wetland (e.g., saltmarsh and mangrove) and the value of recovering ecosystem services, such as climate regulation and biodiversity, may not increase linearly with S(t). We can model this relationship via a nonlinear function:

$$V(t) = V_{max}(1 - e^{-\lambda S(t)}), \tag{1}$$

where V(t) represents the value of ecosystem services given the status of ecosystem recovery at time t, V_{max} is the maximum potential value of the benefits of recovering ecosystems, and λ is a parameter that defines the responsiveness of the value to changes in the response function. S(t) is the ecosystem response function, such as the carbon sequestration rate (proximity for climate regulation) or species richness (proximity for biodiversity) at time t.

Notably, in practice, certain benefits may be realised only once specific restoration thresholds are met (e.g., the finding noted earlier that nitrogen retention targets were mostly met when the percentage of wetlands restored exceeded 60% (Tomscha et al., 2023)). This can be modelled via step functions or logistic growth models. Here, we followed (Ndebele & Forgie, 2017) to use a logistic growth model, where the coefficient estimates associated with the utility of 20-, 50-, and 100-year conservation attributes showed a typical sigmoidal (S-shaped) curve. :

$$\mathrm{V(t)} = \frac{\mathrm{V_{max}}}{1 + \mathrm{e}^{-\kappa(\mathrm{S(t)}-\theta)}}. \tag{2}$$

Here, the curve starts slowly, increases rapidly around the midpoint, and then plateaus as it approaches the maximum value. In Equation (2), κ determines the steepness of the curve, and θ represents the threshold responsiveness of ecosystems at which significant benefits start to accrue.

To incorporate variability and uncertainty into our restoration function, we model the ecosystem response function $\mathrm{S(t)}$ as a stochastic process. This allows for the simulation of scenarios where the restoration process is subject to random fluctuations or uncertainties over time. That is, we consider adding a noise term $\epsilon(\mathrm{t})$ to the response function $\mathrm{S(t)}$:

$$S(t) = S_{det}(t) + \epsilon(t), \tag{3}$$

where $\mathrm{S_{det}(t)}$ is the deterministic part of the response function, which is dependent on the ecosystem services focused on, in our case, climate regulation and biodiversity. $\epsilon(\mathrm{t})$ represents stochastic noise modelled as a random variable such that $\epsilon(\mathrm{t}) \sim \mathrm{N}(0,\sigma^2)$ where σ is the standard deviation.

Note that $\mathrm{S(t)}$ can represent any ecosystem response function, depending on the specific ecosystem services being considered. To numerically validate our modelling framework, we select two response functions based on the availability of data. First, when $\mathrm{S(t)}$ is defined to measure the climate regulation function in response to restoration, we model $\mathrm{S_{det}(t)}$ as aboveground biomass carbon for mangroves, following the approach outlined in existing studies (Lovelock et al., 2021):

$$S_{det}(t) = a * e^{\left(-\frac{k}{t}\right)}, \tag{4}$$

where a approximates the mature above-ground biomass and where k represents the rate at which the biomass increases over time. To a large extent, the aboveground biomass carbon for mangroves reflects the functionality of mangroves that provide climate regulation services, including preventing land erosion from sea level rise and providing barriers to floods. The details of the information used for modelling the aboveground biomass carbon for mangroves are shown in Appendix Table 1. Second, when $S(t)$ was defined to measure the response of biodiversity function to restoration, we followed the methods of (Craft et al., 2003) to use the logarithmic function to model key ecological indicators of nursery habitats, i.e., species richness and invertebrate density, and the age of salt marsh habitats (details of the data are shown in Appendix Figures 1 and 2). The logarithmic function represents a common pattern in natural systems where initial growth is constrained but becomes more rapid over time.

2.3. The simulation process

The simulation of the above models is executed over a series of time steps t, generating values for $S(t)$ at each time step by sampling from the defined distribution. For each time step, the corresponding $V(t)$ is calculated via both the nonlinear model shown in Equation (1) and the logistic models shown in Equation (2). This process is repeated to observe how the economic value evolves under varying conditions of ecosystem recovery. The simulation (1000 iterations for each simulation model) was conducted by using R Studio 2024.4.2.764.

In the nonlinear model, λ is the key parameter that dictates the responsiveness of the value to changes in the ecosystem response function $S(t)$. A higher λ value would result in a more rapid increase in value as the ecosystem recovers, whereas a lower λ would lead to a more gradual increase. In our simulation, λ was set to a moderate value, reflecting a scenario where the value of ecosystem services increases steadily but not immediately as the ecosystem begins to recover. The simulated benefit trend is expected to be the upper part of Figure 2 such that the benefits accumulate more rapidly in the early stages and gradually level off as $S(t)$ approaches full ecosystem recovery. The parameter $\sigma = 5$, which represents the standard deviation of the noise introduced into $S(t)$, causes a moderate level of variability, highlighting the uncertainty in the recovery process.

The logistic growth model introduces additional parameters: κ controls the steepness of the curve, and θ, the threshold at which significant benefits begin to accrue. In our simulation, κ was chosen to produce a typical S-shaped curve, with benefits increasing slowly at first, then more rapidly as the recovery process crosses the threshold θ, and finally V_{max} levelling off as is approached. The value of θ was selected on the basis of expert input to represent a realistic threshold for wetland recovery, beyond which the most substantial benefits of ecosystem services are realised.

The initial settings of the simulation are based on a few assumptions. Nonlinear model: With moderate responsiveness ($\lambda = 0.05$), carbon sequestration/species richness starts increasing gradually and continues to rise toward the maximum potential value ($V_{\max} = 100$), but with some random fluctuations added by the noise ($\sigma = 5$). Logistic Model: the growth in carbon sequestration/species richness begins slowly because of the small steepness ($\kappa = 0.1$) but then increases as time approaches the threshold ($\theta = 20$), eventually levelling off as it nears the maximum value ($V_{\max} = 100$).

3. Results and discussion

3.1. Simulated benefit trends

The simulation results illustrate the temporal evolution of benefits derived from wetland restoration, accounting for uncertainty in the ecosystem recovery process. Two models were employed to capture this relationship: a nonlinear value function and a logistic growth model. Figure 3 represents the temporal dynamics of the benefits of climate regulation services derived from mangrove restoration across different countries. Figure 4 represents the restoration benefits in terms of biodiversity, with a specific focus on species richness and invertebrate density based on saltmarsh restoration data from the North Carolina coast. Each graph illustrates the comparison between the nonlinear model (red solid line) and the logistic model (blue dashed line) in estimating the value of ecosystem services over time for nine different countries or regions. The shaded areas represent the uncertainty or variability in the estimates, with the purple and light blue shading indicating a confidence range.

As shown in the set of graphs in Figure 3, in most cases, the nonlinear model predicts a rapid increase in climate regulation benefits, which then stabilises over time for all spatial sites (except India). The logistic model, on the other hand, shows a slower initial increase but eventually converges to the same or slightly lower value than the nonlinear model. In addition, the benefit trends for carbon sequestration across various countries and spatial sites reveal notable differences in both the magnitude and growth patterns of values over time.

Vietnam, Indonesia (Bali), French Guiana, Indonesia (Papua), the Philippines and Malaysia: The nonlinear and logistic models produce very similar results with minor differences, which are primarily observed at the beginning of the time series. Both models reach the maximum value rapidly, showing high initial responsiveness to the restoration efforts, and then stabilise. The shaded areas (uncertainty) are minimal, indicating that both models provide consistent estimates with low variability.

India: A divergence occurs between the two models early in the time series. The nonlinear model reaches the maximum value much faster than the logistic model, which shows a more gradual increase. The uncertainty range (shaded area) is wider in this region, indicating a greater variability in the predicted benefits.

Australia (NSW) and Australia (SA): Similar to India, there is a divergence between the models, but the gap persists throughout the time series. The shaded area indicating variability is larger, particularly in the early stages, indicating greater uncertainty in the estimates. This might reflect regional differences in ecosystem recovery dynamics, where the logistic model is slower at reflecting full restoration benefits than the nonlinear model is.

Overall, the trends reveal key regional differences in the effectiveness and speed of restoration efforts, as well as in the reliability of predictions. In most regions (e.g., Vietnam and Indonesia), restoration benefits stabilise quickly and show minimal uncertainty, suggesting that both models offer consistent and reliable estimates. However, in India and Australia, the larger gaps between models and greater uncertainty indicate that restoration processes may be more variable, requiring careful consideration in policy and management decisions. In these regions, the nonlinear model captures rapid early gains, which could be important for short-term policies, whereas the logistic model suggests a more conservative long-term growth.

As shown in Figure 4, the simulation results of the two ecological indicators for biodiversity, i.e., species richness and invertebrate density, show similar benefit trends. For species richness, both models produce nearly identical results, with the logistic model being slightly more responsive at the beginning, but both reach the maximum value very quickly. The close alignment of the two models and the narrow-shaded area indicate that the models agree well in estimating species richness benefits, with low variability. Similar to species richness, the models for invertebrate density show a high degree of similarity, with minor differences in the early stages. Both models indicate a rapid increase in biodiversity benefit, quickly reaching the maximum value, with minimal uncertainty.

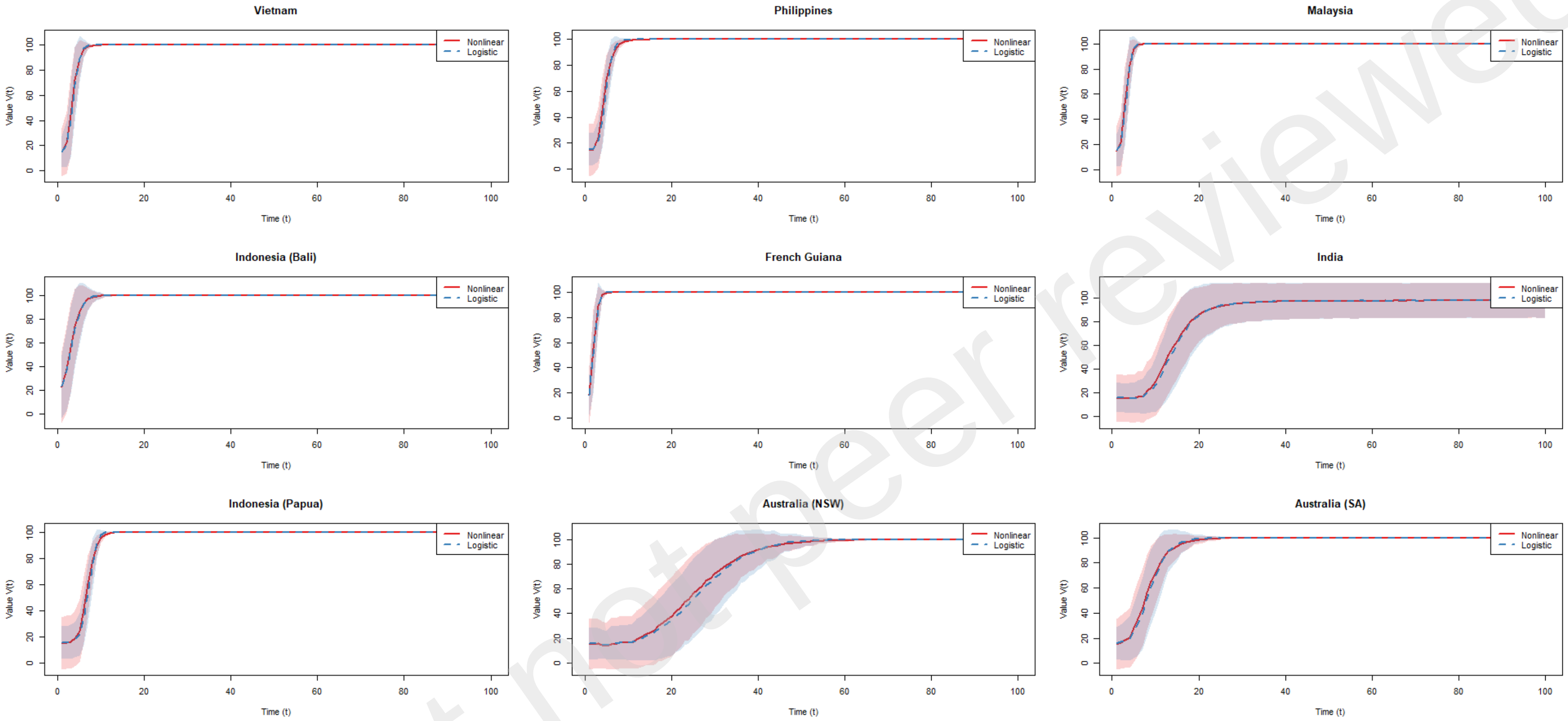


Figure 3. Simulated benefit trends of restored wetlands as NBSs to provide climate regulation services over time.

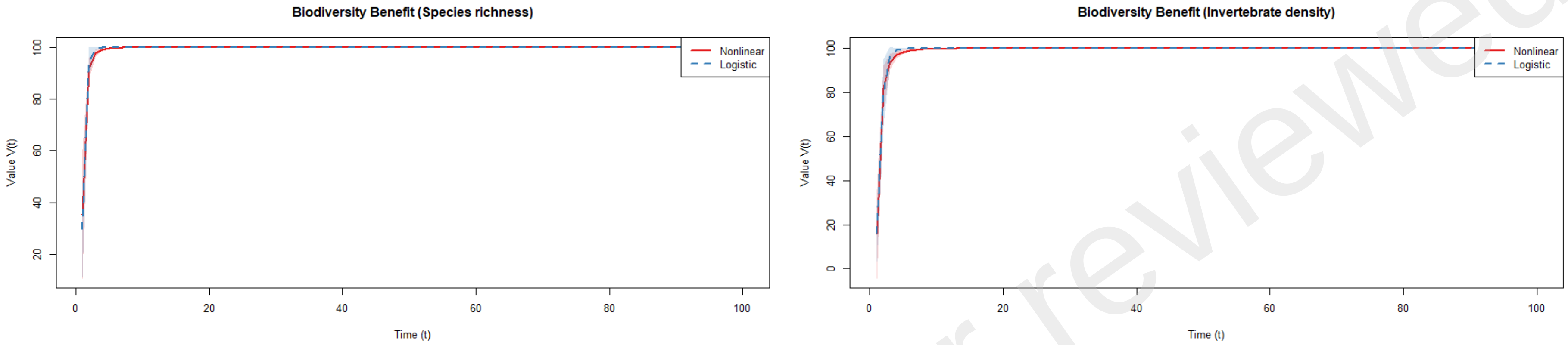


Figure 4. Simulated benefit trends of restored wetlands as NBSs to provide biodiversity protection (fish habitat nurseries) over time.

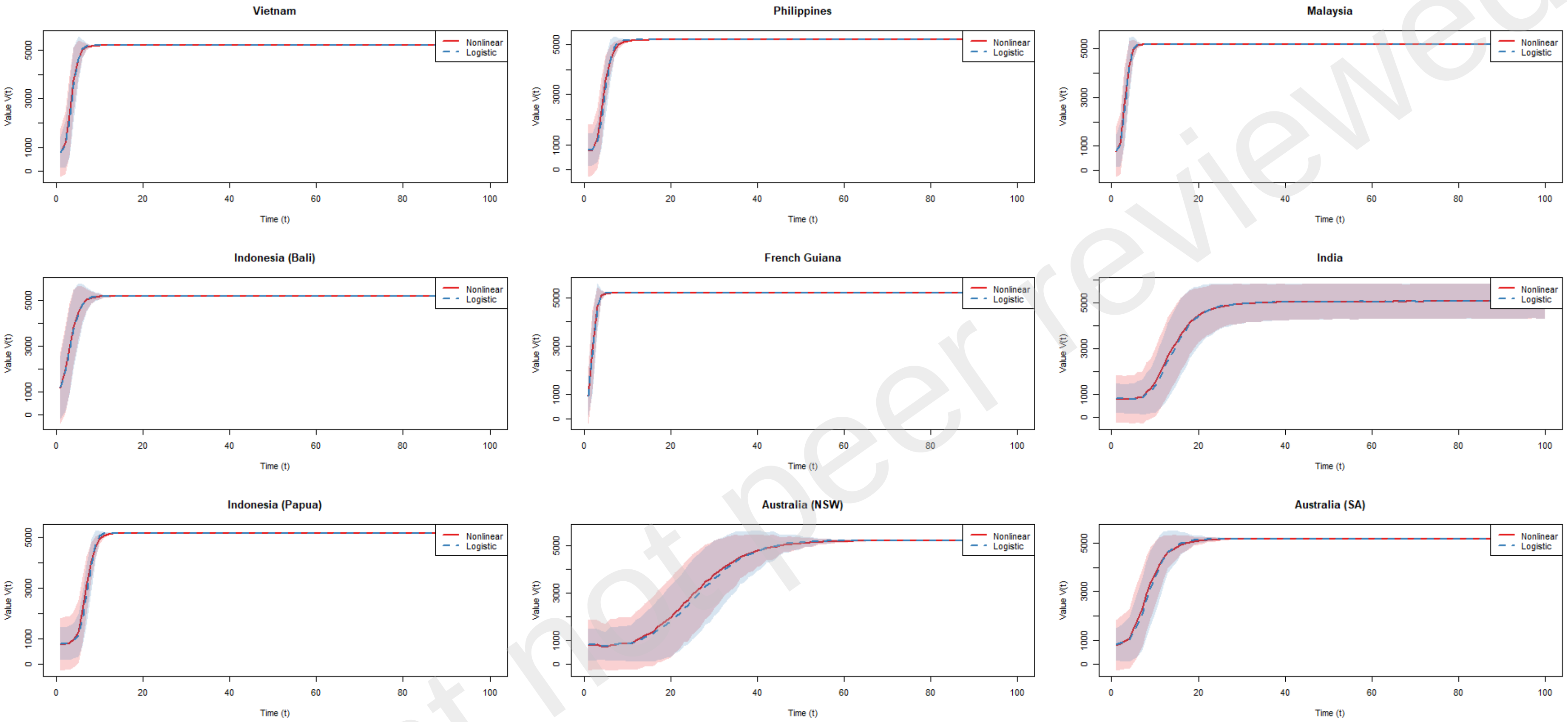


Figure 5. Simulated benefit trends of restored wetlands as NBSs to provide climate regulation services over time, V_{max} = \$5,192 USD per hectare per year.

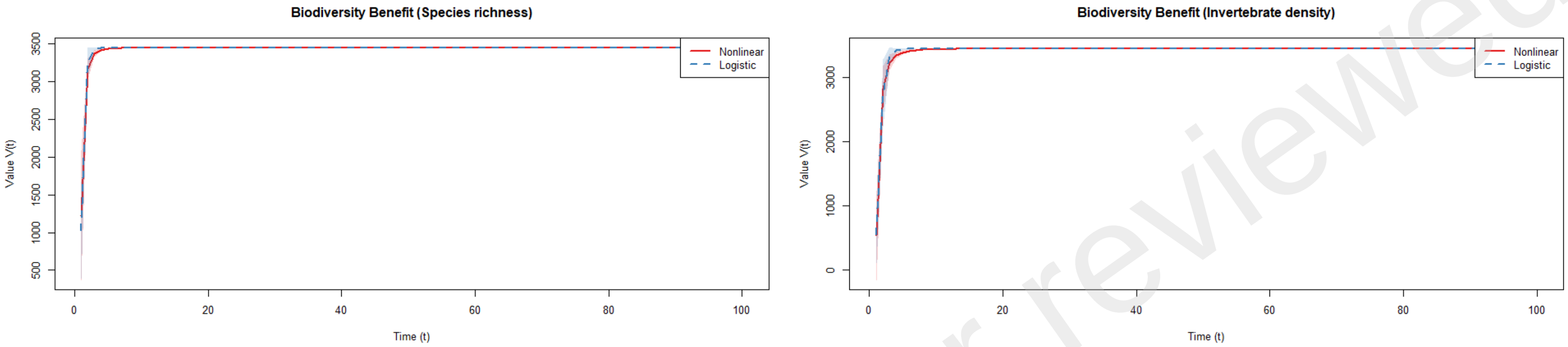


Figure 6. Simulated benefit trends of restored wetlands as NBSs to provide biodiversity protection (fish habitat nurseries) over time, V_{max} = \$3,448 USD per hectare per year.

3.2. Scenario analysis results

3.2.1. The maximum value of ecosystem services

Besides using hypothetical values for the valuation of ecosystem services described above ($\mathrm{V}_{\max} = 100$), we also referred to the Ecosystem Services Valuation Database (ESVD) to draw values for both mangroves and saltmarshes on the ecosystem services of climate regulation and biodiversity (Brander et al., 2024). The benefit value of climate regulation services (mangrove), including erosion prevention and moderation of extreme climate events, is estimated to be USD 5,192 per hectare per year (adjusted to 2024 dollars), and the value of biodiversity services (saltmarsh) is estimated to be USD $3,448 per hectare per year (adjusted to 2024 dollars)[2]. Detailed information about the data collection and valuation is provided in the Appendix. The sets of graphs shown in Figure 5 and Figure 6 present similar benefit trends as those shown in Figure 3 and Figure 4; the timings of convergence and stabilisation are also similar. The results indicate that our models are robust regardless of the maximum values of ecosystem services.

3.2.2. Varying responsiveness (λ), steepness (κ), and threshold (θ)

We changed the values of the key parameters that are relevant to the responsiveness of benefit values to ecosystem response functions: examining how the simulation results respond to high and low responsiveness and steepness in the nonlinear model and logistic model, respectively. As shown in Figure 7a, both models align closely, indicating that under these conditions (i.e., high responsiveness and steepness), the process of climate regulation services and its economic valuation are well captured by either model with minimal uncertainty. In a low-responsiveness and steepness scenario (Figure 7b), the models diverge slightly, with the nonlinear model showing a more cautious growth trajectory, leading to discrepancies in the timing and magnitude of the value stabilisation. The increased uncertainty reflects a more complex and less predictable recovery process. These results suggest that when the valuing system is highly responsive to changes, simpler models such as the logistic model can perform just as well as more complex nonlinear models. However, under less responsive conditions, the nonlinear model might offer a more realistic representation of gradual improvements, although at the cost of increased uncertainty and complexity. We constructed the same scenario analysis for the ecosystem response function of biodiversity protection, and the results (in Figure 8) show trends similar to those in Figure 7, indicating that, regardless of different types of ecosystem responses, our modelling framework provides robust and consistent simulation results for the evaluation of ecosystem services.

Notably, the nonlinear model shows greater responsiveness at low values of the responsiveness parameter (e.g., low λ), suggesting that even small changes in the ecosystem's recovery rate or initial conditions may lead to relatively large changes in the estimated value of ecosystem services early on (shown in Figure 7b and 8b). This implies that in the early stages of restoration, the model is more sensitive to small improvements in wetland functions,

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[2] The original values drawn from the ESVD were 2020 USD and we adjusted to the 2024 USD, considering inflation etc.

making it highly reactive to early changes. The nonlinear model better reflects ecosystem recovery processes that respond rapidly at the beginning but may not sustain high growth over time. Early-stage sensitivity in restoration processes has been noted by studies emphasizing rapid recovery in certain ecological functions. For instance, Zedler & Callaway, (1999) discuss how wetlands and other ecosystems often exhibit a phase of rapid functional recovery, particularly in processes like sediment trapping and nutrient cycling, during early restoration. In these early stages, even small ecological improvements can yield substantial benefits, as seen in the rapid increase predicted by the nonlinear model. This model effectively captures the dynamic, nonlinear nature of such processes, where early gains can be disproportionately large compared to later stages, a feature noted by Mitsch & Gosselink (2015) in their comprehensive work on wetland ecosystems. Moreover, the notion that early interventions yield disproportionately higher economic returns has been discussed in the context of cost-benefit analysis of restoration projects. For example, Hanley et al. (2012) emphasize that prioritizing early investments in ecosystem services can result in greater initial returns, particularly for services like carbon sequestration and water quality improvement. This supports the idea that restoration projects targeting wetland services may be economically more viable in their early phases, as indicated by the rapid gains seen in the nonlinear model.

In contrast, the logistic model's slower initial growth due to its sigmoid shape may indicate that improvements in ecosystem services are more gradual and less responsive to early changes. The logistic model typically has a lag phase before reaching a point of rapid growth, which suggests that it is less sensitive to early restoration efforts but more stable over time. Hence, the logistic model is more appropriate for processes with gradual accumulation, such as biodiversity restoration or organic detritus buildup, where slow initial growth is followed by a phase of rapid improvement before levelling off. Dobson et al. (1997) and Tilman et al. (2001) highlight that biodiversity recovery is often a slow process, characterized by initial lags before accelerating as species richness and ecosystem complexity increase. This is particularly relevant for services tied to long-term ecological processes, such as soil organic matter accumulation and the rebuilding of ecosystem structure, which accumulate benefits gradually but ultimately stabilise at higher levels, as observed in the logistic model. This reflects the gradual development of ecosystems, as described by (Connell & Slatyer, 1977) in their work on succession models. For long-term projects focused on services that require prolonged ecological maturation (e.g., biodiversity recovery), this model demonstrates the importance of sustained investment, as it accounts for delayed but significant improvements. This finding is consistent with research by Bullock et al. (2011) who suggests that long-term funding is crucial for ecosystem services like biodiversity recovery that may show limited progress in the early years but provide substantial long-term benefits once key thresholds are reached.

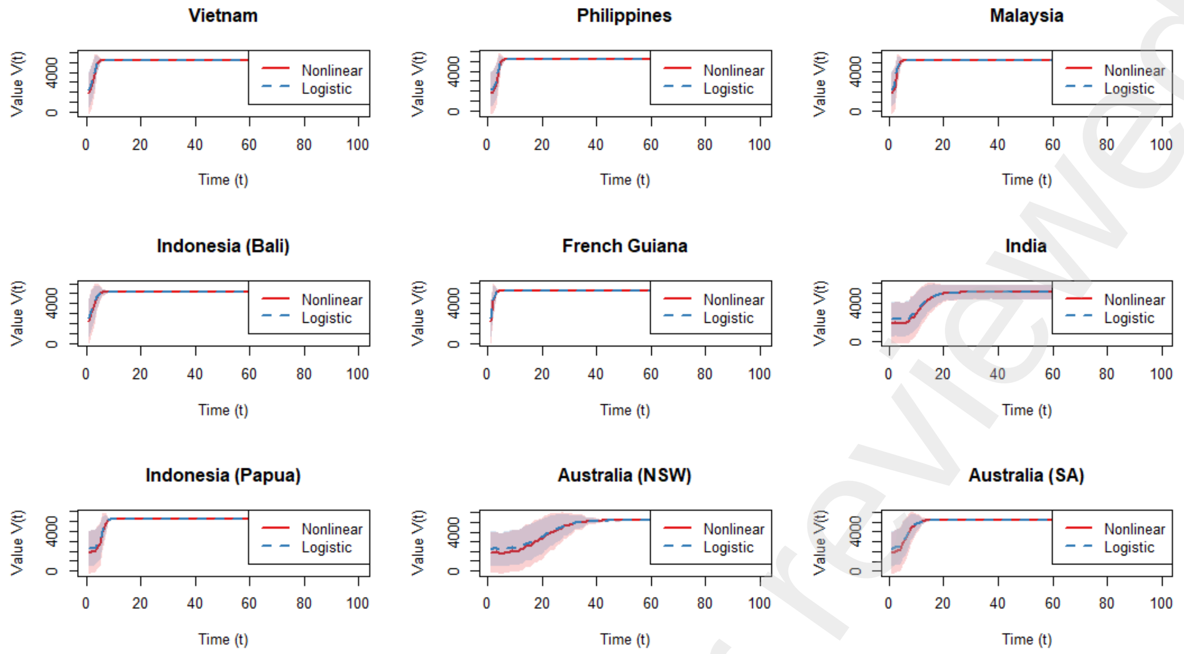

Figure 7a. high responsiveness, steepness, and threshold ($\lambda = 0.5$, $\kappa = 0.5$, $\theta = 1$)

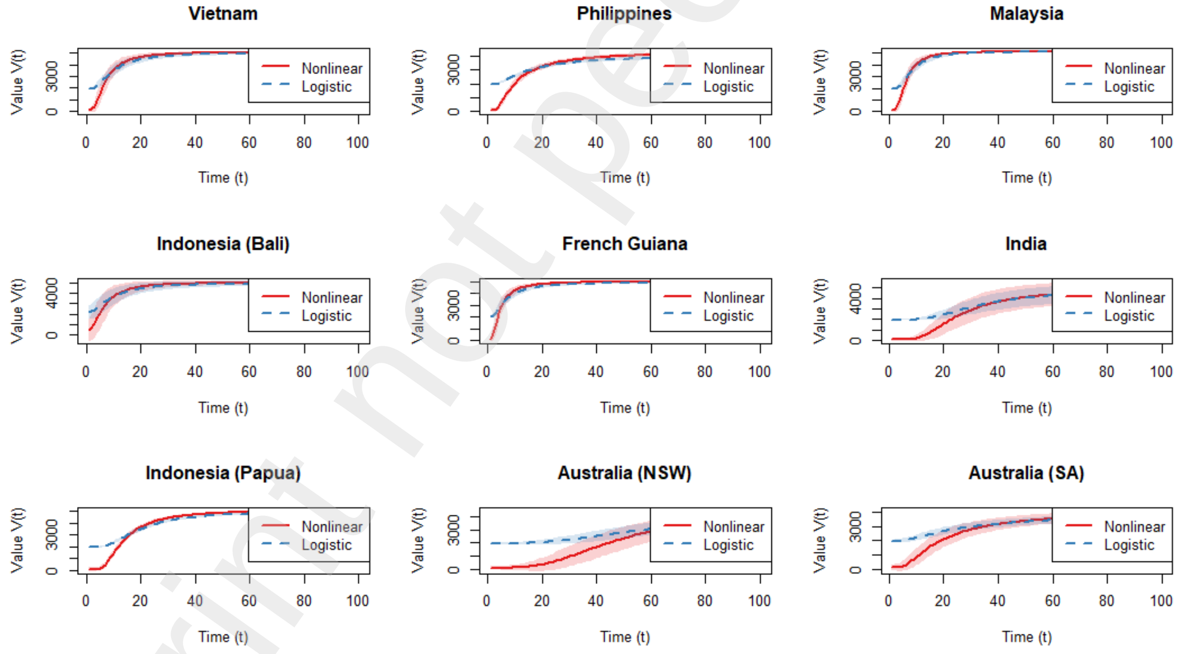

Figure 7b. low responsiveness & steepness ($\lambda = 0.01$, $\kappa = 0.01, \theta = 50$)

Figure 7. Simulated benefit trends of restored wetlands as NBSs to provide climate regulation services over time, with high and low responsiveness and steepness, $V_{max} = \$5{,}192$ per hectare per year.

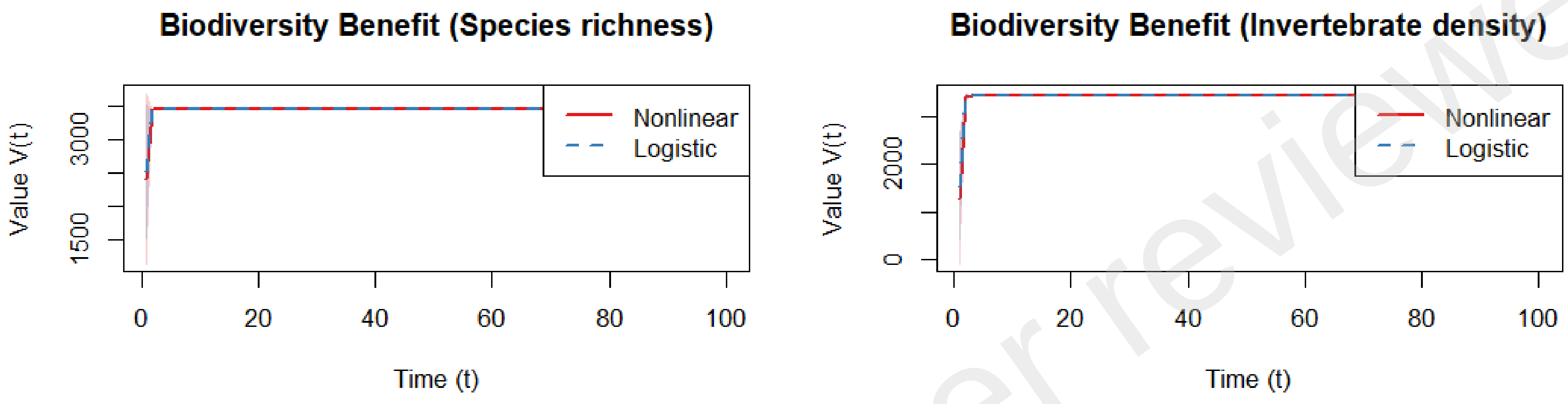

Figure 8a. high responsiveness, steepness, and threshold (λ = 0.5, κ = 0.5, θ = 1)

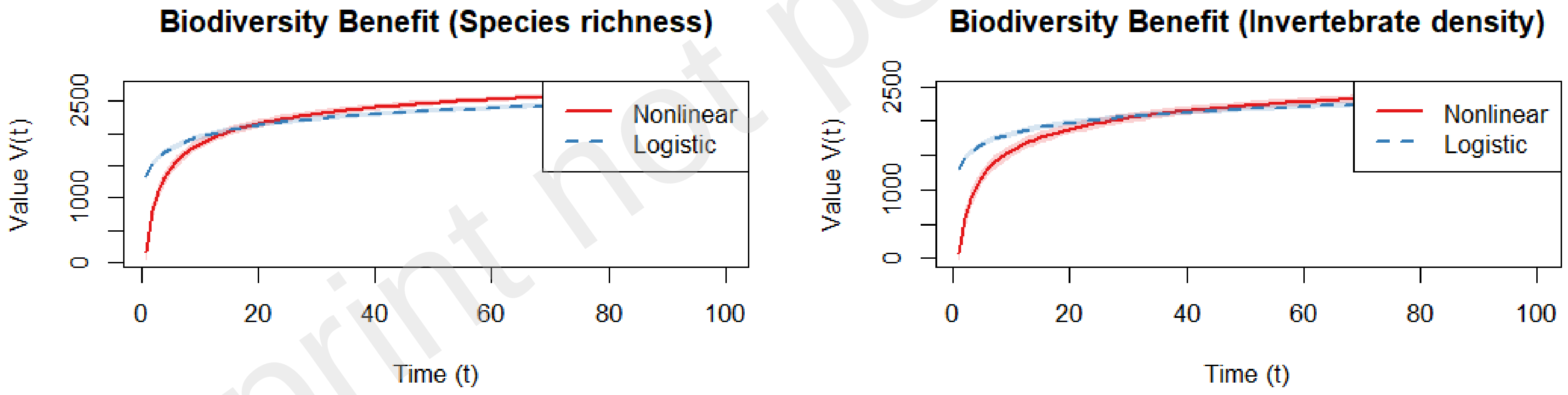

Figure 8b. low responsiveness & steepness (λ = 0.01, κ = 0.01,θ = 50)

Figure 8. Simulated benefit trends of restored wetlands as NBSs to provide biodiversity protection (fish habitat nurseries) over time, with high responsiveness and steepness, $V_{max} = \$3{,}448$ per hectare per year.

4. Conclusion

This study highlights the significant economic benefits of wetland restoration as a nature-based solution for addressing critical environmental challenges such as climate regulation and biodiversity protection. Using both nonlinear and logistic models, our analysis captures the temporal dynamics of ecosystem service valuation across diverse geographical regions, providing valuable insights for policy formulation and investment strategies. The nonlinear model's prediction of rapid early-stage benefits suggests that restoration efforts can yield immediate returns, particularly in regions where short-term economic gains are a priority. This responsiveness to initial restoration efforts is critical for decision-makers looking to justify upfront investments in ecosystem recovery. Conversely, the logistic model's slower, more gradual growth trajectory reflects the need for sustained, long-term strategies, especially in regions where ecosystem recovery and associated services take time to fully materialise. Our scenario analysis demonstrates that both models can provide robust and reliable estimates under varying conditions of ecosystem responsiveness and recovery steepness, with minimal uncertainty in high-responsiveness scenarios. However, the divergence between the two models in low-responsiveness scenarios underscores the complexity of accurately valuing ecosystem services in regions with unpredictable recovery patterns, such as India and Australia. This finding reinforces the importance of tailoring restoration policies and investments to local ecological and socio-economic conditions. The integration of maximum ecosystem service values from the ESVD further supports the validity of the models across different ecosystems.

The findings of this study underscore the critical role of coastal wetland restoration as an NBS to address climate change, biodiversity loss, and ecosystem degradation. As policymakers and environmental managers seek to mobilise climate finance and implement effective strategies, several key implications emerge. First, policymakers need to integrate dynamic valuations into policy frameworks. Traditional cost-benefit analyses and valuation methods often overlook the temporal dynamics of ecosystem recovery and the delayed realisation of economic benefits, leading to inaccurate estimations of the benefits of wetland restoration. Policies should incorporate models that account for the nonlinear recovery of ecosystem services over time. By doing so, funding and resource allocation can be better aligned with the actual timelines of ecosystem recovery, ensuring that investments in wetland restoration yield maximum long-term returns. In addition, given the variable rates at which different ecosystem services recover, adaptive management is essential. Policymakers should promote flexible, iterative management frameworks, such as dynamic adaptive pathway planning (DAPP), which allow for adjustments as ecosystems evolve. Monitoring and evaluation protocols should be established to track the recovery of key indicators, such as carbon sequestration, biodiversity, and nutrient retention, enabling timely interventions to optimise restoration outcomes along adaptive pathways. Second, the results and findings provide more accurate estimations to guide investment in NBSs within climate finance. The long-term economic benefits of wetland restoration demonstrate the need for more targeted and informed investments in NBSs, ensuring that resources are allocated efficiently. Policymakers should advocate for the inclusion of precise, data-driven approaches in national and international climate finance mechanisms, such as the Green Climate Fund and carbon offset markets. Emphasising the co-benefits of NBSs, including disaster risk reduction, biodiversity conservation, and local livelihoods, can attract diverse funding streams and promote broader adoption. Additionally, the economic value of nonmarket benefits, such as flood protection, carbon storage, and habitat provision, needs to be recognised and integrated into policy decisions. While challenging, efforts to monetise these benefits can support more informed decision-making and justify public and private investments in restoration projects. The development of standardised methodologies for nonmarket valuation that consider the dynamics of ecosystem recovery will increase the robustness of economic assessments. Finally, the modelling framework proposed in the paper addresses the need for further research to better understand the complex interactions between ecological restoration and economic outcomes. Policymakers should support research initiatives that explore the thresholds and tipping points in wetland restoration, as well as the socioeconomic impacts of these projects. Building a robust evidence base will improve the effectiveness of policies and management practices, leading to more resilient and sustainable coastal ecosystems.

Despite these insights, the study has certain limitations. First, the models are based on simplified assumptions about ecosystem recovery processes and may not fully capture the complex, context-dependent interactions between ecological factors and socioeconomic conditions. Additionally, the temporal resolution of the simulation may overlook short-term fluctuations or delays in ecosystem responses that could affect the accuracy of service valuations. Data limitations also constrain the generalisability of our results, particularly in regions with insufficient or inconsistent data on wetland ecosystems. Future research should focus on refining these models by incorporating additional ecosystem services, such as nutrient cycling and flood protection, as well as ecosystem response functions and data to test for the robustness of the models.

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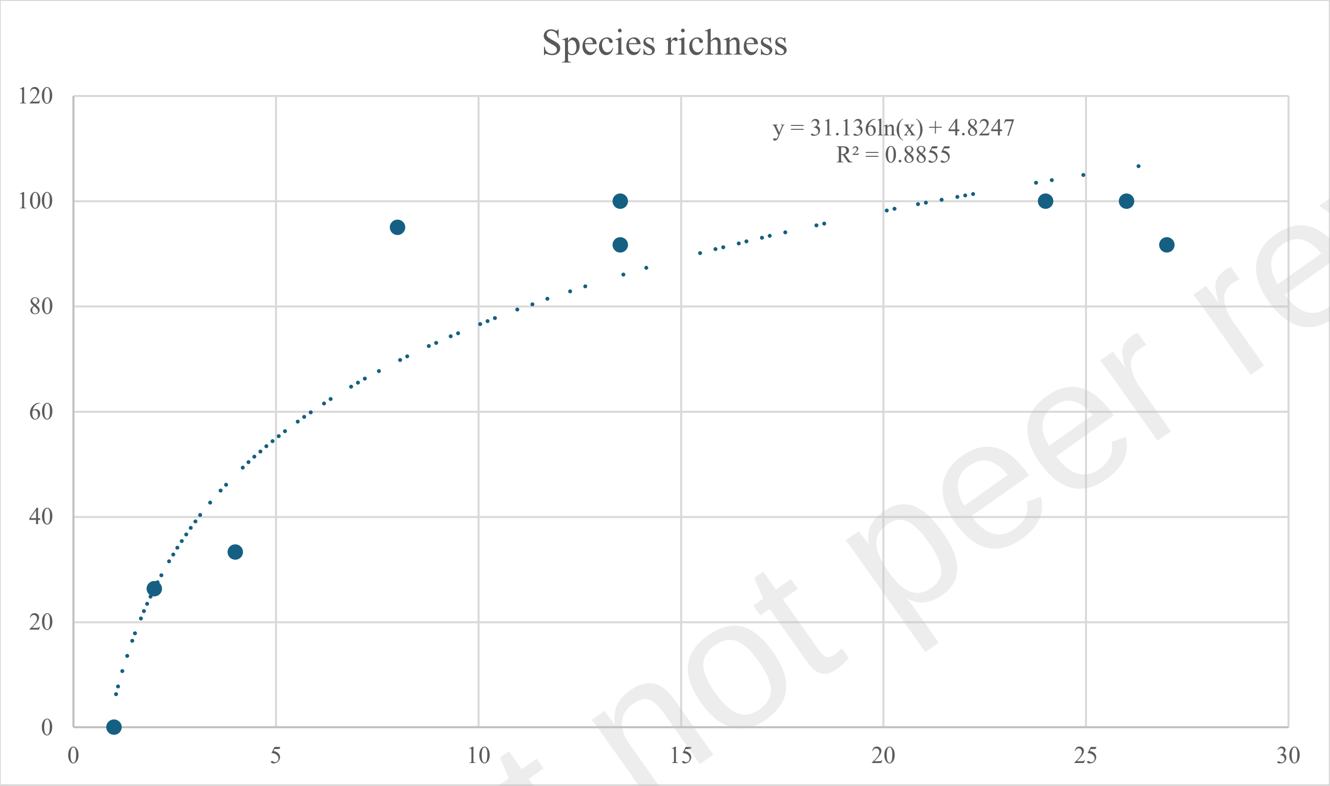
Appendix

Appendix A - Tables and Figures

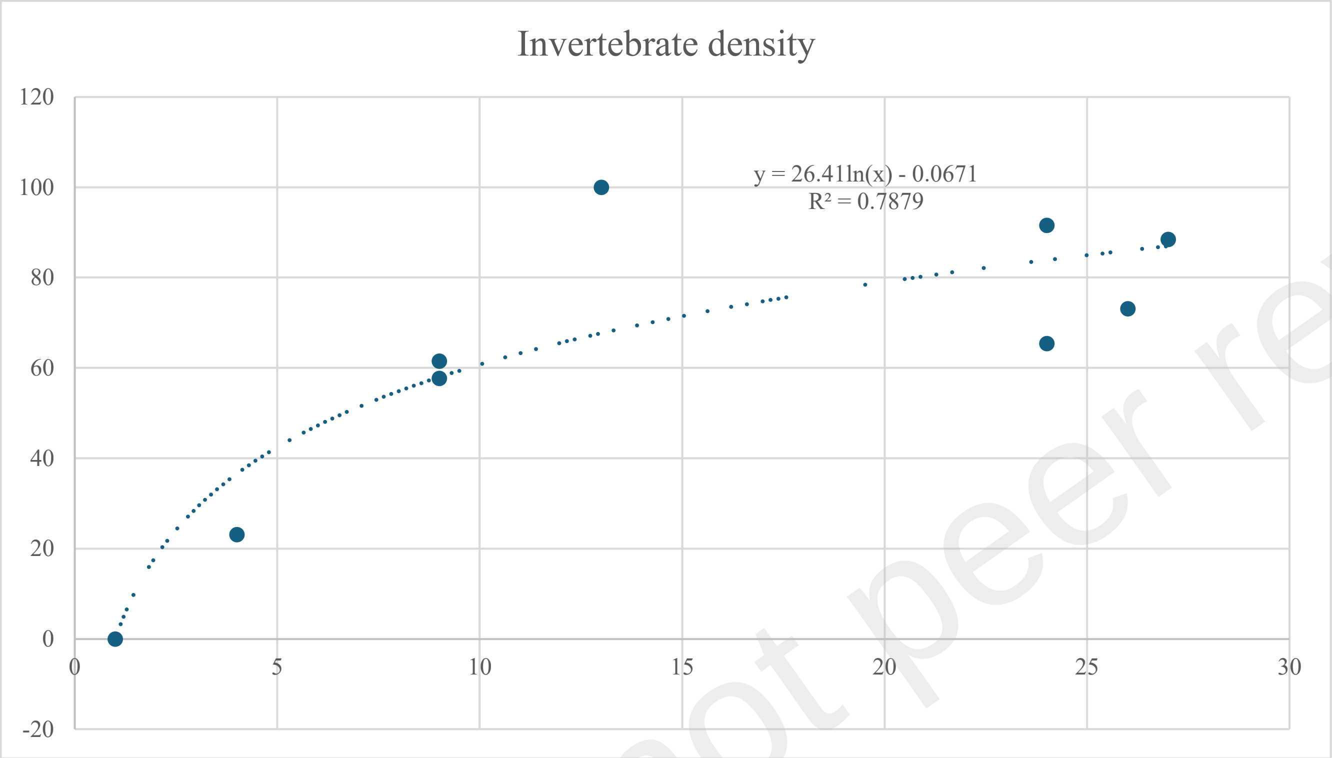
Appendix Table 1. Ecosystem response functions (aboveground biomass carbon) of mangroves across different countries

Location	**Species**	**Activity**	**a**	**k**	**R2**	**Reference**
Vietnam	Rhizophora apiculata	Plantation	467.6 ± 61.5	13.69 ± 3.09	0.632	Phan et al. 2019
Philippines	Rhizophora apiculata	Plantation	193.3 ± 11.9	13.49 ± 1.33	0.895	Salmo et al. 2013
Malaysia	Rhizophora apiculata	Plantation	604.4 ± 53.5	13.12 ± 2.36	0.817	Adame et al. 2018
Indonesia (Bali)	Rhizophora apiculata	Planted shrimp ponds	465.7 ± 111.6	11.99 ± 6.40	0.642	Sidik et al. 2019
French Guiana	Avicennia germinans	Natural regeneration	377.7 ± 27.7	7.61 ± 1.98	0.484	Walcker et al. 2018
India	Avicennia marina	Planting mud flats	621.5 ± 308a	58.1 ± 11.9	0.721	Kandasamy et al. 2021
Indonesia (Papua)	Rhizophora apiculata	Natural regeneration	464.6 ± 26.2	26.4 ± 1.74	0.99	Sillanpaa et al. 2016
Australia (NSW)	Avicennia marina	Natural regeneration	405.7 ± 27.7	97.8 ± 25.6	0.696	Unpublished
Australia (SA)	Avicennia marina	Natural regeneration	171.5 ± 24.9	23.9 ± 6.7	0.383	Unpublished

Source: (Lovelock et al., 2021).



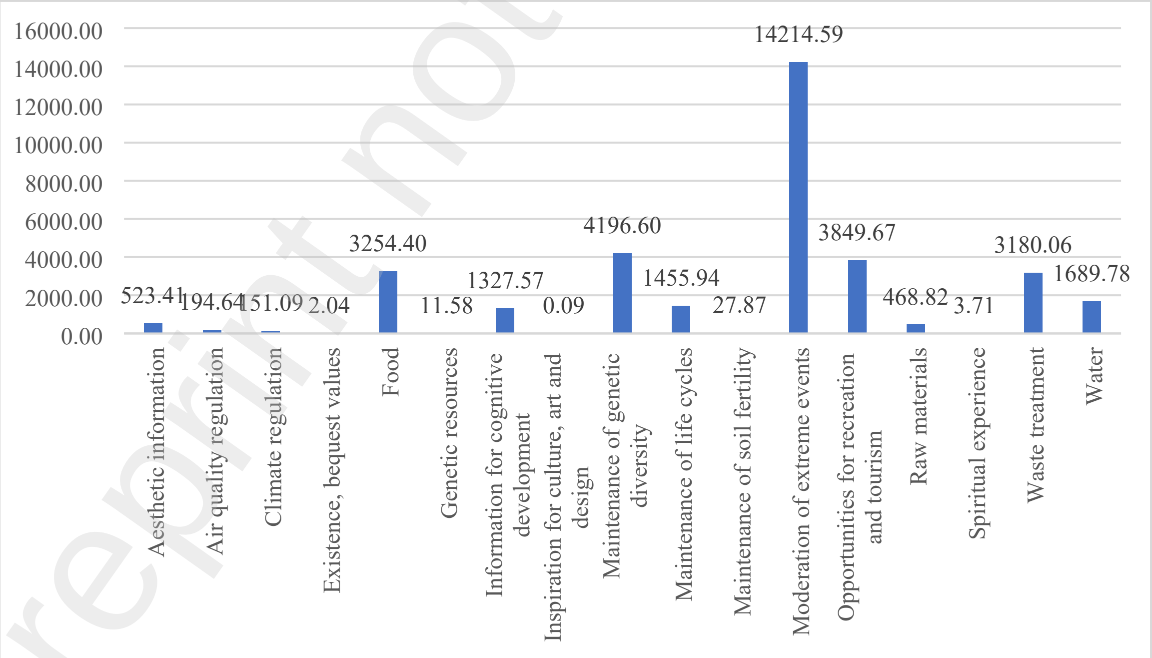
Appendix Figure 1. The fitting of species richness over time (the age of the restored wetland - saltmarshes).



Appendix Figure 2. The fitting of invertebrate density over time (the age of the restored wetland - saltmarshes).

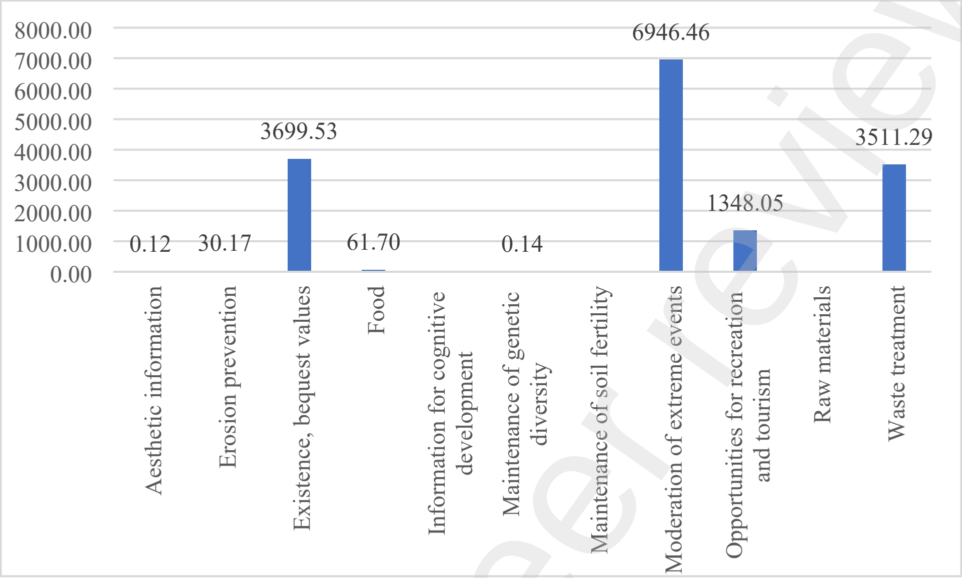
Appendix B – nonmarket values of ecosystem services for mangroves and saltmarshes

This analysis aims to collect economic evaluation data on the value of saltmarshes from various perspectives, such as coastal restoration and evaluation of coastal or marine ecosystems. The data used in the analysis were sourced from the Ecosystem Services Valuation Database (ESVD), which was developed with the long-term goal of providing robust and easily accessible information on the economic benefits of ecosystems and biodiversity and the costs of their loss to support decision making regarding nature conservation, ecosystem restoration and sustainable land management. It is the largest database (now 10,889 value records) with monetary values mapped across different ecosystem services and geographic regions. The search strategy is as follows. First, we used the search filter to include only biomes of marine and coastal systems. Second, we use the keyword "salt marsh" to narrow down the focus to studies on/relevant to salt marshes. This produced 438 value records. We further filtered the ecosystems to include only the categories of "coastal salt marshes and reedbeds", producing a final list of 164 observations. A further breakdown of the values by ecosystem services is shown in the following figure. We used the average values for maintenance of generic diversity and maintenance of the life cycle (including providing refugia for migratory and resident species, such as fish). bird. Mammal and nursery services) to represent the value of biodiversity protection and adjust it to 2024 USD.



Appendix Figure 3. Benefit values across different types of ecosystem services of saltmarsh wetlands.

We conducted the same search and analysis process for nonmarket values of ecosystem services for mangroves, which provided a list of 58 value estimates, and the values were further categorised into different ecosystem services (shown below). We used the values for erosion prevention and moderation of extreme events and adjusted them to 2024 USD.



Appendix Figure 4. Benefit values across different types of ecosystem services of mangrove wetlands.