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Extended Valuation of Coral Reef Ecosystem Services (2017–2025): Model and Policy Insight

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ABSTRACT

The coral reefs are the most commercially and ecologically significant coastal ecosystems, yet human activity, especially vessel-grounded operations and environmental stresses are posing a growing threat to their survival. To assess the effectiveness of linear and nonlinear models in valuing coral reef ecosystem services, this study builds on earlier research by combining data (2017-2025) from the Ministry of Environment, Ministry of Maritime Affairs and Fisheries, Ministry of Forestry, and associated agencies. The dependent variable is the ecosystem services value (V, millions of Rupiah/m²/year), whereas the independent variables are the year of observation (t), coral reef quality (Q, %), and distance from the shore (D, km). According to the analysis's findings, the linear model yielded an R-square value of 0.2193 (Significance F= 0.0230), and the value of ecosystem services was strongly influenced by coral reef quality (*P*= 0.01998) and distance from the coast (*P*= 0.04918). The non-linear model, on the other hand, did worse, with no factors significant at the 95% confidence level and an R-square of 0.1007 (Significance F= 0.2523). Model performance decreased as temporal scope increased in comparison with the 2019 study, highlighting the shortcomings of simple regression in long-term valuation. To increase forecast accuracy, this study suggests applying more complex non-linear techniques, developing spatiotemporal models, and integrating external variables (such as human activity and environmental dynamics). These results highlight how crucial an adaptive valuation framework is to bolstering coral reef management and promoting evidence-based conservation policy.

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INTRODUCTION

Coral reefs have significant strategic importance from an ecological, economic, and social standpoint. It is one of the most productive coastal ecosystems. Coral reefs enhance the viability of the fisheries and marine tourism industries, act as habitats for marine species, and provide natural coastal protection from abrasion **(Costanza *et al.*, 1997; de Groot *et al.*, 2002; de Groot *et al.*, 2012; Costanza *et al.*, 2014; Wahyudin *et al.*, 2016; Barton *et al.*, 2017; Spalding *et al.*, 2017; Wahyudin *et al.*, 2018; Wahyudin *et al.*, 2023; Wahyudin *et al.*, 2025)**. Given that Indonesia is a mega-biodiversity country with thousands of islands and sizable coral reef areas, this function is especially important there **(Adrianto *et al.*, 2016; Wahyudin *et al.*, 2019; Arkham *et al.*, 2020; Wahyudin, 2020; Arkham *et al.*, 2021; Wahyudin *et al.*, 2022)**.

However, a few local and international forces have put significant strain on Indonesia's coral reefs over the last 20 years **(Mahipal *et al.*, 2025)**. Reef destruction has been caused by bleaching brought on by ocean warming and climate change, and ecological degradation has been made worse by pollution, destructive fishing, and human activities like shipwrecks and excessive tourism **(Gann *et al.*, 2019; Hein *et al.*, 2021)**. The reduction of ecosystem services, including provisioning, regulatory, and cultural services, which have historically made significant contributions to coastal communities and national economies, is a concern raised by these challenges **(Costanza *et al.*, 1997; de Groot *et al.*, 2002; de Groot *et al.*, 2012; Costanza *et al.*, 2014)**.

An essential instrument for calculating the financial gains and the magnitude of losses brought on by environmental harm is the valuation of ecosystem services **(Mahipal & Wahyudin, 2019)**. Additionally, conservation regulations, the settlement of environmental disputes, and the calculation of just compensation are all based on this assessment **(Serkin, 2004; Jones & Pease, 2007; Mahipal & Wahyudin, 2019; Wahyudin & Mahipal, 2020; Mahipal *et al.*, 2025)**. Using data from 2017 to 2018, a prior study evaluated the value of ecosystem services coming from shipwrecks using both linear and nonlinear models **(Wahyudin & Mahipal, 2020)**. Both models did well, according to the results, with the nonlinear model performing somewhat better.

However, the study's restricted temporal span made it difficult to fully capture long-term changes. Following 2018, shipwrecks kept appearing and were documented by the Ministry of Maritime Affairs and Fisheries and the Ministry of Environment and Forestry (which was split off into the Ministry of Environment and Forestry). This made the data collection more comprehensive in terms of location, ecological conditions, and time **(Arkham *et al.*, 2018; Paulangan *et al.*, 2018; Wahyudin *et al.*, 2019; Arkham *et al.*, 2020; Paulangan *et al.*, 2020; Wahyudin, *et al.*, 2022; Wahyudin *et al.*, 2023; Suharyanto *et al.*, 2024)**. As a result, our study used both new and old data from multiple official sources, extending the data coverage to 2017-2025. It is anticipated that this method would offer a more thorough view of the correlation between the value of coral reef ecosystem services (V) and important variables including observation year (t), coral cover quality (Q), and distance to the shoreline (D).

To determine the model's long-term reliability, this study compared the results from earlier periods with the performance of linear and nonlinear models in forecasting ecosystem service values. A longitudinal analysis of model performance, data integration across agencies like the Ministry of Environment (MoE), the Ministry of Marine Affairs and Fisheries (MoMAF), the Ministry of Forestry (MoF), and other pertinent institutions, extending data coverage to nine years (2017-2025), and offering an empirical foundation for creating more adaptive predictive models, including hybrid methods, external environmental variables, and spatiotemporal approaches, are the first and second novel aspects of this research **(Amato *et al.*, 2020; Slater *et al.*, 2023; Kumar *et al.*, 2024; Warne *et al.*, 2024)**.

It is anticipated that these innovations will contribute significantly to the creation of evidence-based conservation policies and will enhance the body of knowledge on the valuation of coral reef ecosystems. It is anticipated that these findings will also contribute to raising stakeholder and public understanding of the significance and economic worth of sustainable coral reef protection.

MATERIALS AND METHODS

This study employed a quantitative methodology, using data from shipwreck-related coral reef damage incidents in Indonesia. In order to assess the link between the value of ecosystem services (V) and the observation year (t), coral reef quality (Q), and the reef's distance to the shoreline (D), linear and nonlinear regression models were constructed. The research period spanned from 2017 to 2025, combining fresh data from 2018 to 2025 with historical data from earlier investigations (2017-2018). As suggested by earlier ecosystem valuation research, this investigation should identify long-term trends in coral reef ecosystem value due to its larger temporal scope **(Costanza *et al.*, 1997; de Groot *et al.*, 2002; Adrianto *et al.*, 2004; de Groot *et al.*, 2012; Costanza *et al.*, 2014; Wahyudin, 2019; Wahyudin, 2020; Wahyudin & Mahipal, 2020)**.

Official documents from the Ministry of Forestry, the Ministry of Maritime Affairs and Fisheries, and the Ministry of Environment provided the research data. The same data and information are provided by the three ministries about shipwreck-related coral reef damage, including ecosystem quality (% of live coral cover), economic worth (in millions of Rupiah/m2/year), and spatial information (the distance to the shoreline) on the incident's location (km). To ensure uniform and complementary data, the only variances are in the administrative and publication channels **(Arkham *et al.*, 2020; Wahyudin & Mahipal, 2020; Wahyudin *et al.*, 2022; Wahyudin *et al.*, 2023)**.

Three independent variables and one dependent variable make up the research variables. The value of coral reef ecosystem services (V), which is measured in millions of rupiah per square meter annually (IDR million/m²/year), is the dependent variable. The coral reef quality (Q, % live cover), the distance of the reef to the shoreline (D, km), and the observation year (t) are the independent variables. These variables were chosen in accordance with other research on the economic worth of coastal ecosystems and the factors that influence that value **(Costanza *et al.*, 1997; de Groot *et al.*, 2002; Wahyudin & Mahipal, 2020; Hein *et al.*, 2021)**.

Two equations make up the analysis model in use **(Wahyudin & Mahipal, 2020)**. The formula for the linear model is:

$$V = \beta_0 + \beta_1 t + \beta_2 Q + \beta_3 D$$

In the meantime, the equation:

$$V = \beta_0 t^{\beta_1} Q^{\beta_2} D^{\beta_3}$$

expresses the nonlinear model.

The same dataset was used to evaluate both models to compare the contributions of each variable (t-test), the overall model significance (F-test), and the level of fit (R^2). In ecosystem valuation research, linear and nonlinear regression techniques have been widely utilized to examine how well simple models explain complex events **(Costanza *et al.*, 1997; de Groot *et al.*, 2002; Wahyudin & Mahipal, 2020; Hein *et al.*, 2021)**.

Statistical software like Microsoft Excel or a comparable data analysis program was used to do the analysis. Prior to the estimate, the model was examined using tests for heteroscedasticity, multicollinearity, and normality, among other traditional regression assumptions **(Gujarati & Porter, 2009)**. The model parameters were then computed, and their importance was examined. If the *P*-value was less than 0.05, the results were deemed significant; factors with a *P*-value greater than 0.05 were still examined to determine their possible significance. The R-squares value and the statistical significance of each variable were then used to compare the performance of the linear and nonlinear models.

There were various restrictions on this investigation. Analysis of other unrecorded examples of coral reef damage from shipwrecks was not possible because the data used was restricted to officially documented incidents. The consistency of the estimation results could be impacted by differences in reporting details between locations and years, even though the data collected from the three ministries was consistent. Fig. (1) below presents a conceptual mind-mapping of the research framework. Additionally, only three main variables were taken into account in this study; other outside variables like the level of human activity, the demand from tourists, or oceanographic data were not methodically included. By adding more variables or using more advanced spatiotemporal techniques, this restriction also creates room for future research **(Amato *et al.*, 2020; Slater *et al.*, 2023; Kumar *et al.*, 2024; Warne *et al.*, 2024)**.

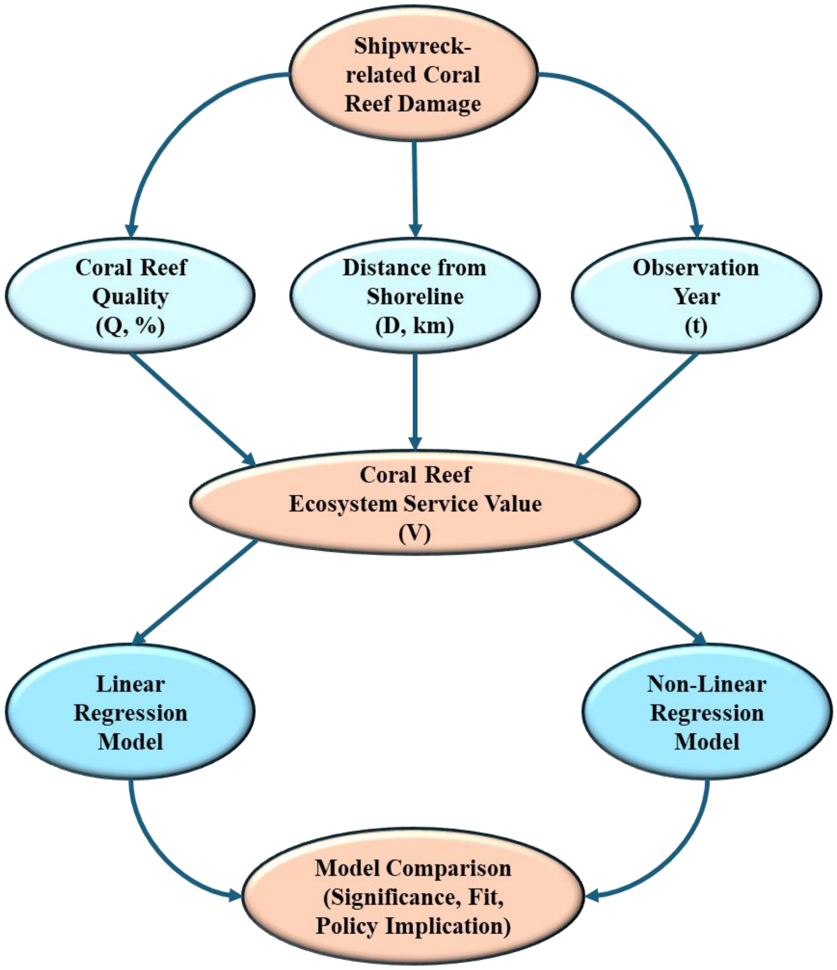

Fig. 1. Conceptual mind-mapping of the research framework

RESULTS

1. Descriptive statistics of data (2017–2025)

A number of 42 observations of shipwreck-related coral reef damage cases in different Indonesian coastal regions are included in the research dataset. The average coral quality was about 38%, with a range of 1 to 64%. A median of IDR 0.49 million/m²/year and a standard error of around 0.03 were found for the estimated value of ecosystem services, which varied from IDR 0.12 million to IDR 0.83 million/m²/year. In contrast, the distance to the shoreline was 8 km with a standard error of 3.36 and the median coral reef quality was 38% with a standard error of 2.59. The Ministry of Environment, the Ministry of Maritime Affairs and Fisheries, and the Ministry of Forestry provided all the information used in this study through their official publications. Table (1) below provides an overview of the descriptive statistics of the dataset used as the foundation for the multiple linear regression analysis in this study.

Table 1. Research dataset descriptive statistics summary

No	Variable	Median	Standard Error
1	Distance to the shore (km)	8	3.36
2	Coral quality (%)	38	2.59
3	Value (million IDR/m²/year)	0.49	0.03

Source: Information extracted from the Ministry of Environment, the Ministry of Maritime Affairs and Fisheries, and the Ministry of Forestry (2017-2025).

2. Linear model estimation results

With an R2 of 0.2193 from the linear regression analysis, the model can account for about 21.9% of the variation in ecosystem service values. Overall model significance at the 95% confidence level was shown by the model significance test, which yielded a Significance F of 0.0230.

In particular, the estimation results demonstrate that the value of ecosystem services is positively and significantly impacted by coral reef quality. The value of ecosystem services increases by around IDR 0.00435 million per square meter annually for every 1% improvement in coral reef quality (β = 0.00435; *P*= 0.01998). The value of the resulting ecosystem services, on the other hand, decreases with increasing distance to the shore (β = -0.00288; *P* = 0.04918), indicating a substantial negative influence. The value of ecosystem services is positively impacted by the observation year variable, although this effect is not statistically significant (β = 0.01614; *P* = 0.1884). Table (2) provides a clearer view of these estimation results.

Table 2. Linear model estimation results

No	Variable	Coefficient (β)	*P*-value	Note
1	Intercept	-32,2323	0,194	Not significant
2	Year (t)	+0,0161	0,188	Not significant
3	Coral quality (%)	+0,00435	0,020	Significant (+)
4	Distance to the shore (km)	-0,00288	0,049	Significant (–)

Source: **Regression results (2025)**.

The main interpretation of Table (2) above is that the value of ecosystem services is strongly influenced by biophysical conditions (coral quality and spatial location), not by the temporal dimension (year). Plot of residual of year, coral quality and distance to the shore are shown in Fig. (2), meanwhile line fit plots are shown in Fig. (3), and the normal probability plot of linear model is hown in Fig. (4).

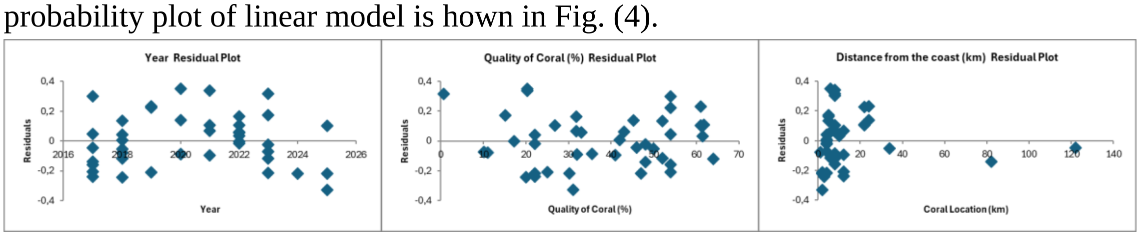

Fig. 2. Residual plots of year, coral quality, and distance from the coast

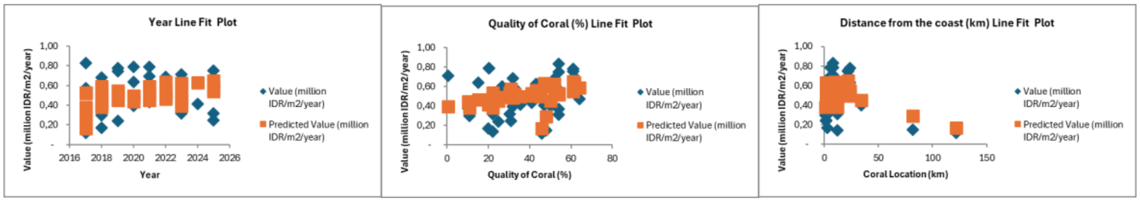

Fig. 3. Lines fit plots of year, coral quality, and distance from the coast

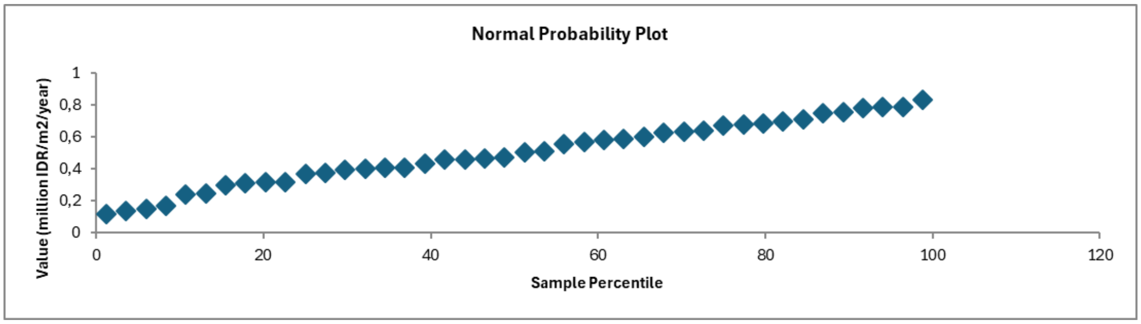

Fig. 4. Plot of normal probability of lienar model

3. Results of non-linear model estimation

Compared to the linear model, estimation using a log-log non-linear model performed comparatively worse. The model's predictive capacity is modest, as evidenced by its R2 value of 0.1007, which shows that it can only account for around 10% of the variation in ecosystem service levels. Additionally, the model was not significant overall, according to the simultaneous test (Significance F = 0.2523).

The variable ln (Year) has a strong positive coefficient (β = 132.64) and is close to significance (*P*= 0.0511), according to the log-log regression estimation results. Although the level of significance is still low, this shows a tendency toward rising ecosystem service values as the number of observation years increases. In contrast, the variable ln (Coral Quality) did not significantly affect the non-linear model (β = 0.0617; *P*= 0.554), suggesting that changes in coral condition had no discernible impact. The distance of the damage location from the shoreline did not significantly affect the estimated value of ecosystem services, as indicated by the negligible value of the variable ln (Distance to shore) (β = 0.0197; *P*= 0.823). Table (3) provides a thorough synopsis of the estimation results.

Table 3. Non-linear model estimation results

No	Variable	Coefficient (β)	*P*-value	Note
1	Intercept	-1010,59	0,051	Marginal (Close to significant, -)
2	ln (Year)	+132,64	0,051	Marginal (Close to significant, +)
3	ln (Coral quality)	+0,0617	0,554	Not significant (+)
4	ln (Distance to shore)	+0,0197	0,823	Not significant (+)

Source: Regression results (2025).

The results as seen in Table (3) indicate that the non-linear model does not provide good predictive power, especially after the integration of additional data from 2019-2025. Plot of residual of year, coral quality and distance from the coast are shown in Fig. (5), meanwhile line fit plots are shown in Fig. (6), and the normal probability plot of linear model is shown in Fig. (7).

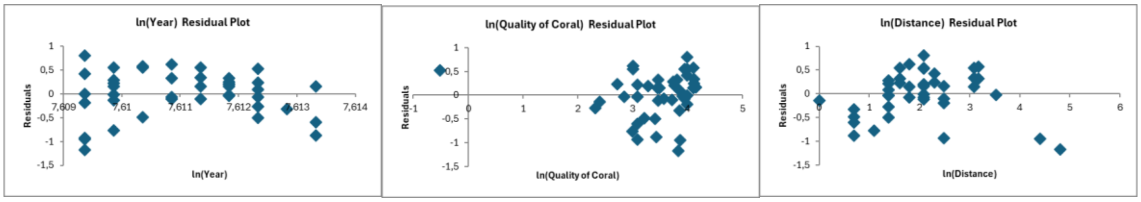

Fig. 5. Residual plots of year, coral quality, and distance from the coast

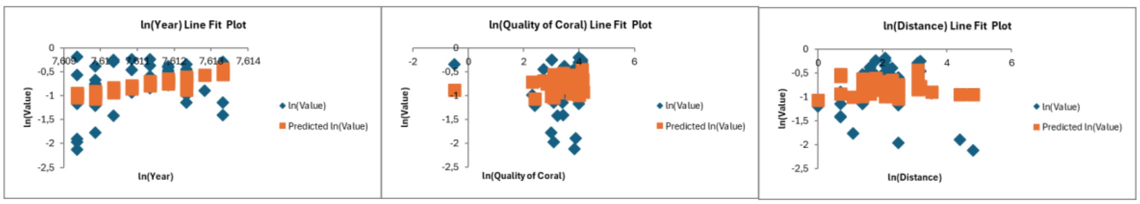

Fig. 6. Lines fit plots of year, coral quality, and distance from the coast

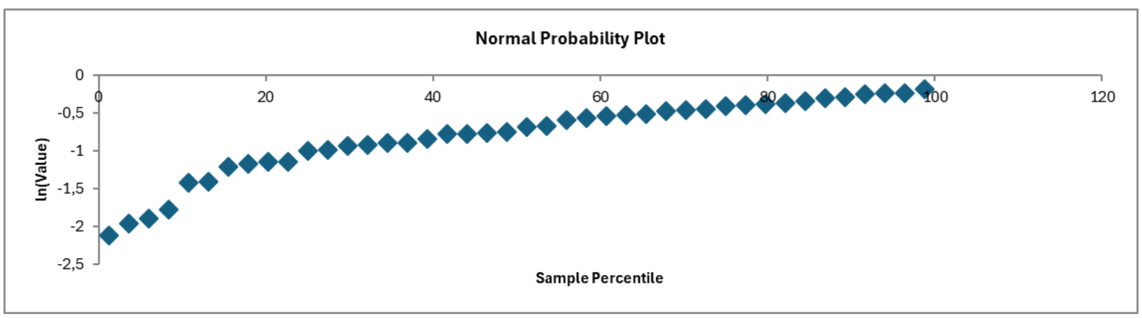

Fig. 7. Plot of normal probability of non-lienar model

4. Comparison of linear and non-linear models

To determine which approach is more appropriate in explaining the relationship between biophysical variables and ecosystem service values, a comparison was conducted between linear and non-linear models. The summary results of the performance comparison of the two models are presented in Table (4).

Table 4. Comparison of linear and non-linear model performance

No	Aspect	Linear Model	Non-Linear Model
1	R^2	0.219	0.101
2	Significance F	0.023 (significant)	0.252 (not significant)
3	Significant variables	Coral quality (+), Distance to the shore (-)	None
4	Relative performance	Better	Weaker

Source: **Regression results (2025)**.

Table (4) shows that the linear model performs better than the non-linear model. The linear model yielded a R^2 of 0.219 with a significance F of 0.023, indicating statistical significance. Furthermore, two variables proved significant: coral quality (positively affected) and distance to the shore (negatively affected). These results indicate that improved coral quality increases the value of ecosystem services, while the greater the distance to the shore, the value of ecosystem services tends to decrease.

Conversely, the nonlinear model yielded only a R^2 of 0.101 with a significance F of 0.252, indicating that the model was insignificant and no variables had a significant effect. This indicates that the nonlinear model is less able to explain variations in the value of ecosystem services. Therefore, it can be concluded that linear regression is more reliable for modeling the relationship between biophysical variables and the value of ecosystem services than nonlinear regression.

5. Evaluation in relation to previous studies

There is a clear change in the estimation pattern when compared to the 2019 analysis, which only contained data from 2017-2018 **(Wahyudin & Mahipal, 2020)**. In fact, the nonlinear model outperformed the linear model in the earlier investigation. The situation changed in the most recent analysis, though, with a longer data span (2017-2025) that the linear model grew more significant and resilient, while the nonlinear model significantly diminished. This suggests that the nonlinear model is extremely sensitive to unmeasured external dynamics in the study variables, whereas the basic (linear) model is more robust to fluctuation across an expanding temporal range.

With R-squared values of 0.6586 and 0.7296, respectively, and substantial significance (F= 0.0285 for the linear and 0.0116 for the nonlinear), the 2019 study showed that both the linear and nonlinear models performed well. The brief data period was actually outperformed by the nonlinear model. The R-square values for both models, however, sharply declined in the 2025 research, falling to just 0.219 for the linear model and 0.101 for the nonlinear model. The nonlinear model lost significance (F= 0.2523), but the linear model remained significant (F= 0.0230). This shift demonstrates that interactions between variables become more complicated with a wider temporal scope, allowing simpler models to better represent broad trends than nonlinear models that depend on short-term patterns. Table (5) provides a thorough comparison of the findings from the 2019 and 2025 studies.

Table 5. Comparison of the 2019 and 2025 studies' regression results

No	Parameter	Linear Model		Non-Linear Model	
		2019	2025	2019	2025
1	R-square	0.6586	0.2194	0.7296	0.1007
2	Significance F	0.0285	0.0230	0.0116	0.2523
3	Intercept	-437.8932	-32.2323	-8171.2724	-1010.5862
4	Year (t)	+0,217	+0.0161	+1073.1471	+132.6404

5	Quality of Coral (%)	+0,0076	+0.0044	+585.2942	+0.0617
6	Distance to the shore (km)	-0,0011	-0.0029	-0.2323	+0.0197

Source: **Wahyudin & Mahipal (2020)** and **Regression results (2025)**.

Table (5) above demonstrates that the performance of both linear and nonlinear regression models has changed significantly in comparison with earlier research carried out in 2019 **(Wahyudin & Mahipal, 2020)**. Both models fared reasonably well in the prior study, which only included data from 2017 to 2018. The linear model's R-squared values were 0.6586, while the nonlinear models were 0.7296. The models demonstrated a considerable ability to explain differences in ecosystem service values, as both had significant values below the 0.05 threshold. The nonlinear model performed better at the time because it could capture more intricate interactions between the variables under study, especially distance from the coast and coral reef quality, both of which are crucial in determining the value of ecosystem services.

With data coverage extending to 2025, the most recent study's findings, however, reveal a distinct pattern. The linear model's R-squared value dropped sharply to 0.2193, while the non-linear models were much lower, at just 0.1007. This suggests that as the observation duration increases, both models' capacity to explain data variation decreases. The linear model was still valid for use in the analysis, nevertheless, as it showed an adequate level of significance (F= 0.0230). On the other hand, the non-linear model lost significance (F= 0.2523), suggesting that the model is no longer able to appropriately capture the intricacy of the relationship patterns.

A considerable shift was also seen when the coefficient parameters were examined more closely. In the new analysis, the variable "year" which was crucial in elucidating the patterns of ecosystem service values in the 2019 study, was negligible. On the other hand, distance to the shore continued to have a negative impact on ecosystem service values, whilst coral reef quality continually had a favorable influence. These shifts imply that, in the long run, biophysical variables, as opposed to temporal factors, which are typically more dynamic, are more stable in explaining changes in ecosystem service values.

This result emphasizes that when the temporal scope is extended, models that perform better across brief data periods may not necessarily perform similarly. To put it another way, when temporal variance rises, model stability falls. For estimation results to more accurately reflect actual conditions on the ground, more complex and adaptive predictive models must be developed. One way to do this is by integrating external variables that include both environmental factors and human activities, or by using a hybrid approach.

DISCUSSION

According to the study's findings, the efficacy of linear and nonlinear models in describing variations in the value of coral reef ecosystem services changed significantly when the data period was extended from 2017 to 2018 to 2017–2025. With an R-squared value of 0.219 and significance for the variable's coral quality and coastline distance, the linear model remained relevant. The nonlinear model, which had previously performed best in the 2019 research (R-squared value of 0.7296), saw a sharp fall in performance, accounting for only 10% of the variation in the data and not reaching statistical significance. This change suggests that ecological complexity and external pressure unpredictability become more significant as the temporal scope increases, making it more challenging for straightforward mathematical connections to describe the dynamics.

These findings, in contrast to earlier research, support the idea that the services provided by coral reef ecosystems are extremely valuable but susceptible to deterioration and external stresses **(Costanza *et al.*, 1997; Wahyudin, 2005; Costanza *et al.*, 2014; Spalding *et al.*, 2017)**. **de Groot *et al.* (2002)** and **de Groot *et al.* (2012)** highlighted ecosystem health as a key factor influencing economic value. Moreover, they noted that coral reef quality is still a significant variable. On the other hand, the year variable's decline in significance indicates that temporal dynamics are not a reliable predictor on their own and are instead impacted by interactions with outside variables including pollution, climate change, and human activity **(Ives *et al.*, 2003; Pitaru & Ployhart, 2010; Barton *et al.*, 2017; Spalding *et al.*, 2017; Wahyudin *et al.*, 2018; Wahyudin & Mahipal, 2020; Wahyudin, 2023)**.

These findings highlight the methodological shortcomings of basic linear and nonlinear models in describing long-term dynamics. More intricate and comprehensive non-market methods are advised by the ecosystem valuation literature, especially when data show non-linear correlations with threshold effects or substantial uncertainty **(Willis *et al.*, 2000; Carlsson, 2011; Brouwer *et al.*, 2013)**. Thus, there is a pressing need to create prediction models that are more adaptive. Because they are more adept at capturing variable interactions and non-linear patterns, generalized additive models (GAM), random forest regression, and neural networks are some of the possibilities that have emerged from the research **(Rodriguez-Galiano *et al.*, 2015)**.

These findings directly align with global frameworks for policy and management, including the Convention on Biological Diversity (CBD) Post-2020 Global Biodiversity Framework and SDG 14 (Life Below Water), which focuses on protecting and using oceans and marine resources sustainably. The observed instability of the model over time horizons indicates that long-term decision-making regarding conservation methods cannot rely on short-term valuation outcomes. Rather, in order to represent variability over time and location, valuation-based policies need to encompass spatial-temporal dimensions, integrate multi-decadal datasets, and guarantee frequent model validation **(Irwin *et al.*, 2009; An *et al.*, 2015; Atluri *et al.*, 2018)**. This is in line with Indonesia's National Coral Reef Action Plan and pledges to increase the number of marine protected areas (MPAs), where careful assessment may help determine which places should be prioritized for preservation, restoration, and sustainable tourism growth **(Wahyudin *et al.*, 2023; Prasetiyo *et al.*, 2025)**.

Realizing that the biggest danger to ecosystem service values is still coral reef destruction is equally important. Therefore, policy initiatives must prioritize reef restoration, more stringent regulation of damaging practices, and improved MPA monitoring **(Mahipal & Wahyudin, 2019; Wahyudin, 2025)**. Ecological advantages can also be converted into concrete incentives for coastal communities by tying ecosystem service value to adaptive policy tools like blue carbon programs or payment for ecosystem services (PES) **(Lau, 2013; Wahyudin, 2024)**. In addition to protecting biodiversity, these actions directly support SDG 14's goals for habitat restoration and resource sustainability, furthering Indonesia's larger blue economy ambition **(Wahyudin, 2016; Nugroho *et al.*, 2019; Sasmito *et al.*, 2023)**.

This study highlights a pressing research need in the creation of long-term predictive valuation models that incorporate socioeconomic, meteorological, and ecological factors. Multidisciplinary strategies integrating big data, machine learning, and ecological-economic modeling are needed to close this gap. In addition to producing insights that are pertinent to policy and robust to uncertainty, such integration would improve the accuracy of economic forecasts. In the age of swift environmental change, improving valuation techniques is no more merely a theoretical endeavor but rather a tactical requirement for setting conservation priorities and maintaining livelihoods that depend on ecosystems.

This paper contributes to the discussion of ecosystem service valuation by highlighting the interaction among data features, model performance, and policy relevance. The results strengthen the empirical and conceptual basis for Indonesia's coral reef management within international sustainability frameworks, in addition to enhancing theoretical understanding. Finally, in accordance with global pledges to ocean sustainability, adaptive, data-driven valuation techniques can guarantee that coral reefs continue to provide essential ecological, economic, and social benefits.

CONCLUSION

Using data from 2017 to 2025, this study evaluated how well linear and nonlinear models performed in valuing coral reef ecosystem services. It also looked at how this study differed from a 2019 study that only looked at the years 2017–2018. Despite a decline in predictive power, the research demonstrated that the linear model remained relevant. The most recent study's linear model's R-square value was 0.219, which was less than the 2019 result (0.6586) but still statistically significant. The primary factors were distance from the beach (P= 0.04918) and coral reef condition (P= 0.01998). With an R-square of just 0.1007 and no other variables being significant, the once-excellent nonlinear model, on the other hand, saw a sharp drop.

This comparison demonstrates how adding long-term data alters the pattern of variable interactions and decreases the initial model's fit. Simple nonlinear models are insufficient due to the increasingly complicated temporal dynamics that are driven by anthropogenic pressures, conservation measures, and ecosystem deterioration. Although their predictive effectiveness has decreased, linear models have shown greater stability in characterizing long-term relationships in this setting. These results highlight the fact that without methodological modifications, ecosystem assessments derived from short-term data cannot be generalized to longer time periods.

Several suggestions can be made considering these findings. To reduce noise and enhance model validity, the priority should be to build the database using regular, ongoing collection and the application of standard techniques. Second, to represent the intricacy of interactions between variables, hybrid modeling approaches or sophisticated statistical techniques like Generalized Additive Models (GAM), Mixed-Effects Models, or even machine learning algorithms must be evaluated. Third, the analysis will be enhanced, and a more complete picture of ecosystem dynamics will be provided by incorporating external factors such as pollution, human activity, sea surface temperature, and wave intensity.

Long-term monitoring that goes beyond the horizon (for example, until 2030) is also essential for identifying recurring patterns and the effects of conservation efforts and extreme weather occurrences. The findings of the 2025 study's linear model are still useful from a policy standpoint for conservation planning, especially when determining priorities for enhancing ecosystem health and overseeing coral reef regions that are farther from the coast. By taking these actions, ecosystem valuation can more successfully support evidence-based, long-term, sustainability-focused coral reef management plans that are adaptive.

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