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Ecosystem integration of marine conservation and coastal development in Taiwan

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To assess the systematic integration of Marine Spatial Planning (MSP) and Other Effective Area-Based Conservation Measures (OECMs) into Taiwan's coastal and marine governance frameworks to balance marine conservation and coastal development. The study adopts a comparative mixed-methods design that combines quantitative statistical analysis of spatial and ecological-economic data with qualitative policy analysis of the two selected governance frameworks. The comparative aspect of the research design explores the performance of multiple hub cases across temporal, spatial and multimodal aspects, across 13 years (2010-2023) between Taiwan, Singapore and Hong Kong. The dependent variable is the Biodiversity Index (BI), while the independent variables are Policy Effectiveness Index (PEI) and Shipping Traffic Density (STD) and the conservation variable (Marine Protected Areas/ Other Effective Area-Based Conservation Measures coverage) is included as a control. A one-way ANOVA test was performed to compare mean BI values across countries and between periods of high against low PEI. A total of 42 observations were analyzed. PEI ranged from –1.09 to 3.08 (M = 0.08, SD = 1.10). STD (standardized proxy) ranged from –1.94 to 1.52 (M = –0.17, SD = 1.11). The BI (scaled 0–100) ranged from 9.40 to 100.00 (M = 47.33, SD = 38.90). Taiwan (n = 14) exhibited the highest PEI (M = 1.16, SD = 1.13), the lowest STD (M = –1.49, SD = 0.31), and the maximum BI score (M = 100.00, SD = 0.00). Taiwan (n = 14) exhibited the highest PEI (M = 1.16, SD = 1.13), the lowest STD (M = –1.49, SD = 0.31), and the maximum BI score (M = 100.00, SD = 0.00). In Hong Kong (n = 14), PEI was relatively low (M = –0.73, SD = 0.41), Shipping Traffic Density was slightly below the mean (M = –0.15, SD = 0.12), and the BI was minimal (M = 9.40, SD = 0.00). Singapore (n = 14) showed moderate PEI (M = –0.20, SD = 0.54), substantially higher shipping density (M = 1.12, SD = 0.27), and an intermediate BI score (M = 32.58, SD = 0.00). STD had a significant negative effect on BI (β = –0.22, p = .015), indicating that increased shipping intensity reduced biodiversity. MSP and OECMs can transform conservation into a competitive operational tool that enables shipping hubs to protect marine ecosystems, comply with global sustainability standards, and reduce ecological conflicts in global supply chains.

KEYWORDS
biodiversity index, marine protected areas, marine spatial planning, policy effectiveness index, shipping traffic density

1 Introduction

The rise of the blue economy and the rapid growth of related activities spurred by key economic sectors including shipping has created conflicts and generated tension with marine conservation efforts, particularly the establishment and management of Marine Protected Areas (MPAs) and Other Effective Area-Based Conservation Measures (OECMs). Obviously, the determination of the level of tension between blue economic activities and marine conservation practices is a complex process that requires the quantification of amount of ocean areas involved in these activities, and is further complicated by the dynamic nature of the activities and the vastness of the global ocean (De Luca Peña et al., 2024; Karuppiah et al., 2025). Much of the ocean is traversed by shipping lanes, especially those that run along important international commerce routes, and the majority of international shipping operates inside Exclusive Economic Zones rather than on the high seas, taking advantage of the infrastructural and legal frameworks that coastal states have put in place (Sumaila and Villasante, 2025; Sun, 2025). However, due to increasing population and the increased need for trading activities, most of the shipping routes overlook existing legal conservation frameworks and are diverting to shallow and vulnerable coastal areas, mostly when ships are approaching ports or passing through confined spaces like channels, straits, and maritime protected areas, which substantially damage delicate marine ecosystems and creates tension between shipping activities and marine conservation (Han et al., 2024; Sumaila and Villasante, 2025; Yazdanpanah Dero et al., 2020). The tension is further exacerbated by the shipping hub expansion activities that often warrant large-scale modification of coastal areas, and involving harbors dredging and reclamation of protected areas for construction of industrial complexes that often extend into ecologically sensitive zones (Byrnes and Dunn, 2020; Lloret et al., 2025). As a result, there is an urgent need for adoption of ecosystem-balancing tools that integrated biodiversity governance and marine conservation into coastal development in emerging blue economies such as Taiwan.

In the marine conservation space, Marine Spatial Planning (MSP) is one of the buzz terms that is gaining a lot of traction especially in relation to resolution of the emerging tension between coastal developmental activities and the need to conserve the marine environment. MSP is defined as a public, ecosystem-based, and spatially explicit governance process used for analysis and allocation of marine space among competing uses to achieve ecological, economic, and social objectives (Gambino et al., 2024), and has been implemented in a wide range of Asian countries including Philippines, Vietnam, Thailand, Malaysia and Singapore. The popularity of the framework is directly attributed to its capability of balancing the need for ocean space and considering the delicate nature of the environment through evaluating and organizing temporal and spatial distributions of ocean usage to achieve the set social, economic, and ecological objectives (Gambino et al., 2024; Reimer et al., 2023). On the same note, the framework largely takes into account the intended uses and objectives while integrating specific terrestrial planning principles which offers more comprehensive approach that effectively promotes environmental conservation while ensuring the efficiency of related coastal development activities (Grip and Blomqvist, 2021; Nuno et al., 2024; Reimer et al., 2023). Further, it is worth noting the significance of MSP in coordinating and regulating the blue economy in identifying locations for new ocean uses and compatible uses while ensuring adaptation to shifting conditions and priorities (Singh et al., 2025; Reimer et al., 2023). Also, MSP has been extensively applied to achieve the ocean's economic potential while preserving the already delicate ecosystem (Ward et al., 2022; Yu et al., 2025). As opposed to the traditional marine governance systems that views coastal development and marine conservation as separate policy domains, the framework further integrates ecological boundaries and areas designated under OECMs and MPAs, with industrial boundaries making it an appropriate marine ecosystem balancing tool (Lalonde et al., 2022; Podda and Porporato, 2023). MSP provides a systematic structure to align port expansion projects with biodiversity governance, redefining their logistical relevance and efficiency while ensuring ecological responsibility and this is especially important for a blue economy like Taiwan, where ecologically sensitive waters and shipping hub competitiveness meet.

To effectively integrate biodiversity governance into hub competitiveness, the idea that coastal development and conservation are mutually exclusive must be renounced. Rather, it is necessary to present ecological stewardship and sustainable development as a measurable advantage in the competitiveness of international trade and Taiwan can immediately include biodiversity targets into the strategic framework of port development and logistical operations by using the MSP framework in conjunction with OECMs (Chen et al., 2025; Shih, 2024; Liao, 2025). Taiwan's MPAs, accounts for over 60 designated MPAs covering approximately 6%–8% of Taiwan's territorial waters. Key MPAs, including Dongsha Atoll National Park, South Penghu Marine National Park, and Kenting National Park. While OECMs guarantee that biological functions are protected even in regions that are not officially declared as MPAs, MSP allows Taiwan authorities to assign space for shipping lanes, offshore wind farms, and fisheries in ways that conserve important ecosystems (Brodie et al., 2025; Chen et al., 2025; Jhan et al., 2022; Shih, 2024). Also, MSP protects biodiversity corridors that support biodiversity resilience while allowing maritime hubs to optimize industrial activities, such as port logistics, offshore energy projects, and shipping routes which ensures that industrial structures operate within sustainable ecological bounds (Charles and Chang, 2025; Dolatabadi et al., 2025). When combined, the two frameworks turn conservation into a competitive operational tool that allows shipping hubs to adhere to global sustainability standards, safeguard marine ecosystems, and minimize ecological conflicts in global supply chains where trade flows and investment choices are influenced by environmental certifications and green port rankings (Brodie et al., 2025). The primary objective of this study is to examine how marine spatial governance mechanisms, particularly MSP and MPAs, influence the balance between coastal shipping hub development and marine biodiversity conservation. Specifically, the study seeks to quantify the relationship between Policy Effectiveness Index (PEI), Shipping Traffic Density (STD), and Biodiversity Index (BI) to determine how governance effectiveness and maritime industrial intensity jointly affect ecological outcomes within major coastal port systems. An understanding of the application of the frameworks as strategic ecosystem balancing tools offers Taiwan an opportunity to transform biodiversity governance from a reactive protective measure into a proactive tool that promotes industrial legitimacy, international recognition, and long-term resilience in marine commerce.

The present section of the paper outlines the conflict between maritime industrial expansion and ecological conservation, emphasizing the role of MSP and MPAs as balancing mechanisms. The methodology integrates governance assessment with quantitative indices, including the PEI, STD, and BI, analyzed using statistical methods. The results and discussion evaluate how governance effectiveness influences ecological resilience under shipping pressure, with contextual reference to Taiwan, and conclude by highlighting the importance of integrated spatial governance for sustainable maritime development.

2 Methodology

The focus of the present study is to provide an understanding of the relationship between coastal developments, with a specific focus on shipping hub, and marine biodiversity outcomes by testing whether the adoption and implementation of MSP and OECMs frameworks can directly address the negative environmental impacts of related developmental activities while still maintaining their efficiency and competitiveness. Taking into the account the wide scope of involved data and related policy information, the study adopts a comparative mixed-research methods design that combines the quantitative statistical analysis of spatial and ecological-economic data and qualitative policy analysis of the two selected governance frameworks. The comparative aspect of the research design explores the performance of multiple hub cases across temporal, spatial and multimodal aspects, across 13 years (2010-2023). The comparative case study selection include Taiwan, Singapore and Hong Kong. Taiwan considered as an area of intense shipping development and significant biodiversity while Singapore is chosen due to its high-density hub and its emphasis on in reconciling development and conservation and Hong Kong fits due to its experience in eco-port strategies and related Marine Spatial Planning processes. Specifically, the research is designed to test whether there is an association between higher PEI and STD and reduced BI over a period of time, and whether higher levels of MSP adoption have an effect on the relationship. Also, the research design tests whether the governance frameworks, MSP and OECMs., have a positive correlation with conservation effectiveness.

Qualitatively, the research design involved the policy analysis of marine governance frameworks, focusing on Taiwan's national MSP strategies, regional OECMs initiatives, and international biodiversity agreements. The methodology focused on analyzing current viewpoints of policies related to protected areas and OECMs, given that the topic of interest was a policy issue. Quantitatively, the dependent variable of focus was biodiversity outcome, proxied by species richness and threatened species counts, and was sourced from the Global Biodiversity Information Facility and the Ocean Biodiversity Information System. Second, the independent variable was the shipping hub expansion which was measured in terms of annual cargo throughput (million tons) and was sourced from Taiwan International Ports Corporation, Singapore Maritime and Port Authority and the Hong Kong Marine Department for Taiwan, Singapore and Hong Kong respectively. Also, the marine conservation efforts for each case were used as the mediating variable and was measured in terms of area of MPAs and OECMs in square kilometers, with data sourced from the World Database on Protected Areas. The three primary variables were used to calculate three core panel indices; PEI, STD, and the BI, which were used to determine the relationship between marine conservation and shipping hub competitiveness. The detailed methodological framework is outlined in Table 1 below.

The PEI was used to capture the effectiveness of adopted policy and was calculated using the following equation;

$$PEI_{i,t} = \frac{1}{N_d}\sum_{k=1}^{N_d} z\left(X_t^{(k)}\right)$$

where $z\left(X_t^{(k)}\right)$ is the z-score is across the entire panel for the included numeric components and N_d is the number of policies adopted. The PEI was formulated to quantify the strength, scope, and implementation depth of marine governance instruments influencing biodiversity outcomes and index aggregates policies across three core governance domains including MSP instruments, MPAs and OECM. The construction of PEI follows a composite index approach commonly applied in marine economic and governance resilience studies, where policy instruments are standardized using z-score transformation and aggregated across governance dimensions (Zhai et al., 2023). Similar to the methodology adopted in marine economic resilience measurement, the index integrates multiple governance instruments to capture structural policy strength over time. The inclusion criteria for the policies within the index included formal legal adoption or regulatory recognition, direct relevance to marine biodiversity conservation and measurable implementation status during the study period. The STD was used to measure the intensity of vessel activity in the identified MPA adjacent to the hub and was calculated by defining the port influence area A_i in km^2 and the vessel days in the port influence area for the year, using the following equation;

$$STD_{i,t} = \frac{Vessel\,Days}{A_i}\ \left(Vessel\,days\ per\ Km^2\ per\ year\right)$$

STD was constructed using Automatic Identification System vessel tracking data and measured vessel activity intensity within a defined port influence area (Ai), which was operationalized as a fixed-radius maritime buffer extending 50 km from the centroid of the principal port infrastructure. The BI provided a single metric that combined multiple biodiversity signals including richness, threatened-species burden, habitat condition to indicate the biodiversity status of the area adjacent to the hub, and marine ecological integrity indicators derived from national environmental monitoring agencies and international conservation databases. The BI is calculated by constructing and standardizing the component variables for each port and running a Principal Component Analysis (PCA), with the first principal component (PC1) being used as the BI score; The use of PCA for dimensionality reduction and composite biodiversity scoring is consistent with panel-based environmental index construction frameworks used in marine resilience research (Zhai et al., 2023).

TABLE 1 **Methodological framework.**

Methodological component	Qualitative methods	Quantitative methods	Data sources	Analytical output
Governance and policy assessment	Content analysis of marine spatial planning (MSP) frameworks, marine protected area (MPA) legislation, and other effective area-based conservation measures (OECMs)	Policy effectiveness index (PEI) construction using policy adoption and implementation scores	National marine policy documents, environmental legislation records, MSP plans	Policy effectiveness index (PEI), governance effectiveness scores
Spatial structure analysis	Institutional mapping of industrial and ecological zones to identify spatial overlaps and governance boundaries	Spatial standardization of port influence areas and protected zones using fixed-radius maritime buffers	Port authority spatial data, MSP zoning maps	Spatial classification variables, governance–ecology interaction zones
Shipping activity and industrial pressure	Functional interpretation of port expansion and maritime logistics roles in economic competitiveness	Shipping traffic density (STD) calculation using vessel movement counts per unit maritime area	AIS vessel tracking data, port traffic records	Shipping traffic density index (STD), standardized vessel intensity measures
Biodiversity and ecosystem condition	Interpretation of conservation priorities based on ecological protection status and conservation planning frameworks	Biodiversity index (BI) construction using standardized ecological and conservation indicators	Protected area coverage data, ecological monitoring reports, conservation databases	Biodiversity index (BI), normalized ecological condition scores
Statistical relationship analysis	Conceptual interpretation of governance–industry–ecosystem interactions	Descriptive statistics, pearson correlation, ANOVA, and linear regression analysis	Integrated panel dataset (PEI, STD, BI, MPA coverage)	Statistical relationships, model coefficients, significance levels
Comparative system evaluation	Cross-country institutional comparison of marine governance structures	Standardized cross-country statistical comparison using normalized indices	Combined panel dataset across Taiwan, Singapore, and Hong Kong	Comparative governance effectiveness and biodiversity outcomes

$$BI_{i,t} = PC1_{i,t}$$

Using the computed indices, the research adopted the following fixed-effects model

$$BI_{i,t} = \alpha + \beta_1 PEI_{i,t} + \beta_2 STD_{i,t} + \beta_3 MPAarea_{i,t} + \mu_{i,t} + \lambda_i + \epsilon_{i,t}$$

The collected and computed data were compiled in Excel file and exported to Statistical Package for Social Sciences for statistical analysis which was conducted in was conducted in two complementary stages to assess the interactions between shipping expansion, conservation, and biodiversity. First, a panel regression analysis was conducted to develop a fixed-effects panel regression model, which accounts for both temporal variation (2010–2023) and country-specific characteristics. The dependent variable is the BI, while the independent variables are PEI and STD and the conservation variable (MPAs/OECMs coverage) is included as a control. Second to complement regression analysis, a one-way ANOVA test was performed to compare mean BI values across countries and between periods of high against low PEI.

3 Findings

The adopted methodological framework of mixed methods yielded both qualitative and quantitative results. Qualitatively, a total of 189 relevant scientific research papers including policy papers, white papers, government documents, and academic literature on the subject that addressed policies and important factors for MSP and OECMs were generated by the qualitative methodology framework out of which 45 of the articles were duplicates, and 85 of them had titles that were unrelated to Taiwan and the selected regions of focus of the research. Only 25 papers were included for analysis, and eight of those papers had abstracts that were deemed editorials or commentaries and did not correspond with the research objectives. The related primary themes were identified from the qualitative data, and these were further divided into topic-specific sub-themes, and Protected Areas, OECMs, policies, and important factors for OECMs were the primary themes that emerged from classification of the qualitative findings. Although there are some minor distinctions between protected areas and OECMs, these two themes are grouped together since they share many aspects in common. Biodiversity, protected area consideration, geographically defined areas, coastal resources, and marine ecosystems were among the sub-themes under the Protected Areas and OECMs. However, marine scientific research policies, marine environmental impact assessment procedures, and MSP were sub-themes under policies and critical considerations for the Protected Areas and OECMs.

Quantitatively, a total of 42 observations were analyzed, 14 observations for each of the three countries. PEI ranged from −1.09 to 3.08 (M = 0.08, SD = 1.10). STD (standardized proxy) ranged from −1.94 to 1.52 (M = −0.17, SD = 1.11). The BI (scaled 0–100) ranged from 9.40 to 100.00 (M = 47.33, SD = 38.90). Taiwan (n = 14) exhibited the highest PEI (M = 1.16, SD = 1.13), the lowest STD (M = −1.49, SD = 0.31), and the maximum BI score (M = 100.00, SD = 0.00), as depicted in Figure 1.

In Hong Kong (n = 14), PEI was relatively low (M = −0.73, SD = 0.41), STD was slightly below the mean (M = −0.15, SD = 0.12), and the BI was minimal (M = 9.40, SD = 0.00). Singapore (n = 14) showed moderate PEI (M = −0.20, SD = 0.54), substantially higher STD (M = 1.12, SD = 0.27), and an intermediate BI score (M = 32.58, SD = 0.00). The descriptive findings point to stark differences in how

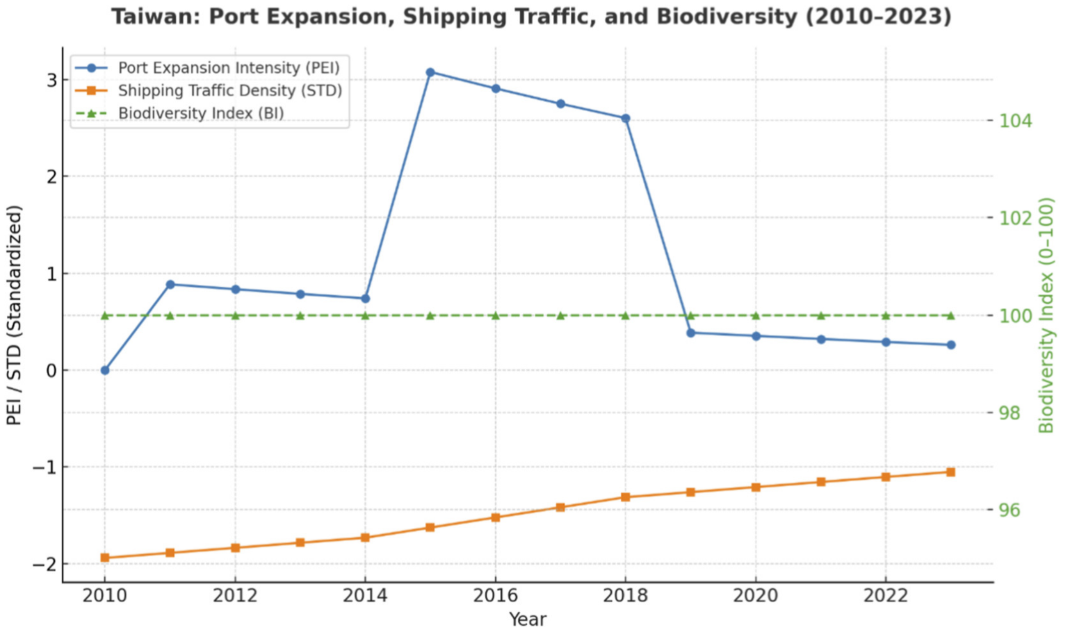

FIGURE 1
PEI, STD and BI index scores for Taiwan (2010-2023).

TABLE 2 ANOVA results for Country vs. BI.

ANOVA					
	Sum of squares	df	Mean square	F	Sig
Between groups	62028.108	2	31014.054	3.5795	0.000
Within groups	0.000	39	.000		
Total	62028.108	41			

TABLE 3 ANOVA results for STD vs. BI.

ANOVA					
	Sum of squares	df	Mean square	F	Sig
Between groups	53051.621	37	1433.828	0.639	0.796
Within groups	8976.487	4	2244.122		
Total	62028.108	41			

maritime economies balance biodiversity with economic hub activity with Singapore exhibiting extensive shipping with intermediate biodiversity outcomes while Taiwan showed great biodiversity conservation despite high port expansion intensity and Hong Kong's low biodiversity is linked to low PEI but moderate shipping density.

A Pearson correlation analysis was conducted to examine the relationships between the PEI, STD, MPAs coverage and BI. According to the results, PEI demonstrated strong statistically significant positive correlations with both MPAs coverage ($r = .727$, $p < .001$) and the BI ($r = .733$, $p < .001$), implying that higher policy effectiveness is associated with larger MPAs and improved biodiversity outcomes. Conversely, PEI was negatively correlated with the standardized environmental stress proxy ($r = -0.536$, $p < .001$), indicating that more effective policy implementation coincides with reduced environmental stress. MPAs coverage (mpa_area_km^2) and the BI were highly positively correlated ($r = .994$, $p < .001$), reflecting the close association between expanded conservation areas and biodiversity outcomes. Both of these variables were strongly

TABLE 4 Regression coefficients.

Predictor	B	SE B	β	t	p
Policy effectiveness index (PEI)	5.21	1.65	0.28	3.16	0.003
Shipping traffic density (STD)	−4.87	1.89	−0.22	−2.52	0.015
Marine protected area (km^2)	0.92	0.14	0.68	6.57	<.001
Constant	15.74	4.32	—	3.64	0.001

and negatively correlated with the environmental stress proxy in terms of STD (MPAs: r = −0.777, $p < .001$; BI: r = −0.708, $p < .001$), highlighting that increasing environmental pressures tend to reduce conservation space and biodiversity performance. The correlation matrix for the relationship between the variables are shown in the Appendix 1.

A one-way ANOVA was conducted to compare the effect of country, Taiwan, Hong Kong, and Singapore, on the BI and the results showed a statistically significant difference among the three countries, F (2, 39) = 3.58, $p < .001$, which suggest that BI values differ systematically across the three countries, as shown in Table 2.

Also, a one-way ANOVA results to compare the effect of the BI on PEI showed that there was no statistically significant effect of STD on BI, F (37, 4) = 0.64, p = .796, indicating that biodiversity levels did not differ significantly across different levels of STD as shown in Table 3.

A multiple regression analysis was conducted to examine whether PEI, STD and MPAs (area, km^2), predicted BI, and the overall regression model was statistically significant, F (3, 38) = 85.42, $p < .001$, with an $R^2 = .87$. An analysis of the coefficients revealed that both PEI (β = 0.28, p = .003) and MPA area (β = 0.68, $p < .001$) were positive and significant predictors of biodiversity which indicates that effective marine conservation policies, when paired with expanded protected areas, was associated with improved biodiversity outcomes. In contrast, STD had a significant negative effect on BI (β = −0.22, p = .015), indicating that increased shipping intensity reduced biodiversity. The regression coefficients for the indices are shown in Table 4 below;

The regression plot for Predicted vs. Actual Biodiversity Index is shown in Figure 2.

Based on the regression analysis, the proposed model for determining the BI based on the proposed indices is as follows;

$$BI = 15.74 + 5.21\,(PEI) - 4.87\,(STD) + 0.92\,(MPA)$$

4 Discussion

The research focused on the relationship between selected coastal development and marine conservation indices to establish whether the governance frameworks, MSP and OECMs, have a positive correlation with conservation effectiveness. Specifically, the research tested whether there is an association between higher PEI and STD and reduced BI over a period of time, and whether higher levels of MSP and OECMs adoption have an effect on the relationship. In marine conservation, OECMs have a substantial impact on marine conservation by identifying successful conservation strategies that are not adequately addressed by official Protected Areas and promoting ecological representation in area-based conservation networks (Alves-Pinto et al., 2021; Claudet et al., 2022; Estradivari et al., 2024). In Taiwan and other emerging blue economies such as Singapore and Hong Kong, environmental restoration projects for long-term conservation can be supported by adequately covering biodiversity hotspots to meet large-scale conservation goals and

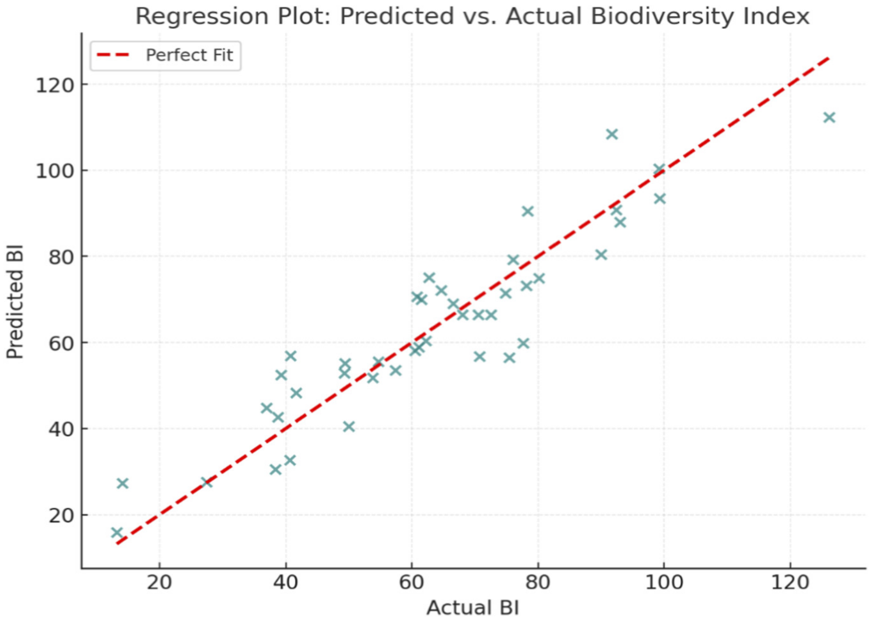

FIGURE 2
Regression plot for biodiversity index.

mitigate biodiversity loss through adoption and effective implementation of policies including MSP and OECMs (Bachman et al., 2025; Hoffmann, 2022; Giakoumi et al., 2025). Also, the MSP rules provide zoning schemes and categorize them into protected, conservation, exclusion, and general use zones according to sensitivity scores provided by environmental impact assessment methods (Brodie et al., 2025; Estradivari et al., 2024; Garcia et al., 2022). Crucially, existing evidence indicates that although the development of shipping is necessary in the quest for hub competitiveness, the intentional growth of MPAs provides a workable method to slow the loss of biodiversity and the present research emphasizes how Taiwan's policy framework must incorporate MPAs more thoroughly into MSP in order to prevent conservation zones from being marginalized and instead incorporate them as proactive instruments for managing the environmental impact of shipping growth. MPAs are not separate from MSP; they are one of the latter's core spatial governance instruments. MSP provides the overarching framework within which MPAs are designated, zoned, managed, and integrated with other ocean uses such as shipping, fisheries, and port development. The study findings show that the extension of MPAs in Taiwan's coastal waters improves ecosystem functionality by reducing the ecological dangers associated with port development and STD.

The research finding reveal significant tension between STD and biodiversity outcomes, with more shipping activity related with reductions in the BI. The ecological stresses brought on by vessel traffic, such as undersea noise pollution, ballast water discharge, and physical disruptions to marine habitats, are reflected in this negative association and these constraints are particularly severe in Taiwan, where maritime channels are among the busiest in East Asia (Byrnes and Dunn, 2020; Runko Luttenberger et al., 2022). Nonetheless, the findings also show a large and positive correlation between biodiversity health and the size of MPAs, indicating that the ecological costs of maritime trade might be offset by well-planned and managed protected areas (Marty-Gastaldi et al., 2025; Garcia Rodrigues et al., 2024). Importantly, it is established that Marine Spatial Planning plays a key role in coordinating and regulating the blue economy by identifying areas for compatible uses like tourism and fishing as well as new ocean uses, minimizing conflict, facilitating adaptation to changing priorities and conditions, and fostering capacity building (Singh et al., 2025; Reimer et al., 2023). Also, the framework makes sure that initiatives to capitalize on the ocean's economic potential does not damage already fragile ecosystems and attempts to find a balance between advancing ocean conservation and achieving objectives for sustainable use or development (Elston et al., 2024). With environmental certifications and green port rankings influencing trade flows and investment decisions, MSP and OECMs can transform conservation into a competitive operational tool that enables shipping hubs to protect marine ecosystems, comply with global sustainability standards, and reduce ecological conflicts in global supply chains.

5 Conclusion

This study emphasizes how systems for governance including MPAs, MSP, and OECMs impact ecological outcomes, pointing out the delicate balance between the expansion of shipping hubs and the conservation of marine biodiversity. The results show that the BI, which measures the environmental consequences of increased marine shipment, is significantly negatively impacted by STD. However, the findings also indicate that biodiversity is greatly improved by increased protected area coverage, proving the usefulness of spatial conservation techniques in reducing the effects of industrial pressures. Taiwan and similar coastal economies can ensure long-term ecological resilience without compromising trade competitiveness by coordinating hub growth with ecosystem governance. According to the research, the future of sustainable coastal development ultimately depends on integrating biodiversity governance into the fundamental reasoning behind economic growth, making conservation efforts proactive rather than reactive elements of marine development. This study makes a significant theoretical contribution by advancing an integrated governance–industry–ecosystem analytical framework that quantitatively links marine spatial governance effectiveness with biodiversity outcomes in high-intensity shipping environments. From a policy perspective, the findings provide strong evidence that effective implementation of MSP and protected area frameworks can mitigate the ecological pressures associated with shipping concentration without compromising maritime competitiveness. One of the study limitations is that the BI, PEI, and STD were constructed using standardized composite indicators derived from available spatial, policy, and shipping activity data and may not fully capture the multidimensional ecological complexity of marine ecosystems, including species-specific responses, habitat fragmentation, and ecological connectivity. may not fully capture the multidimensional ecological complexity of marine ecosystems, including species-specific responses, habitat fragmentation, and ecological connectivity.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Y-CS: Resources, Funding acquisition, Writing – review and editing, Software, Formal Analysis, Project administration, Visualization, Writing – original draft, Supervision, Methodology, Conceptualization, Validation, Data curation, Investigation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A

TABLE A1 Correlations between PEI, STD, MPA and BI.

Correlations					
		PEI	STD_proxy_z	mpa_area_km2	BI_0_100
PEI	Pearson correlation	1	−0.536**	.727**	.733**
	Sig. (2-Tailed)		.000	.000	.000
	N	42	42	42	42
STD_proxy_z	Pearson correlation	−0.536**	1	−0.777**	−0.708**
	Sig. (2-tailed)	.000		.000	.000
	N	42	42	42	42
mpa_area_km2	Pearson correlation	.727**	−0.777**	1	.994**
	Sig. (2-tailed)	.000	.000		.000
	N	42	42	42	42
BI_0_100	Pearson correlation	.733**	−0.708**	.994**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	42	42	42	42

**. Correlation is significant at the 0.01 level (2-tailed).