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Spatiotemporal distribution and influencing factors of Chinese marine protected areas under a social-ecological system framework

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Introduction: Despite China's devotion to marine biodiversity by conserving 12.98% of its seas, recent years saw the more flattened growth of marine protected area (MPA) establishment. Understanding the establishment mechanisms of MPAs is crucial for protecting marine wildlife and achieving balanced conservation and development. However, traditional linear or generalized linear models are insufficient to capture complex nonlinear effects between marine ecosystems and society.

Methods: Adapting the social-ecological system (SES) framework, from the perspective of public goods decision-making, this paper uses overdispersion-robust Poisson pseudo-maximum likelihood (PPML) regressions with high-dimensional fixed effects to study the distribution pattern and factors influencing MPA establishment in 49 Chinese coastal cities that built MPAs during 1998-2020. It also developed a mathematically based algorithm to locate thresholds where effects change.

Results: Results show GDP over ¥55 billion (1998-based, equal to ¥106.5 billion in 2020) to be conducive to MPA establishment, while built-up areas over 63 km² are antagonistic to MPA development. Illustrated by an N-shaped curve, the article supplements previous studies of the U-shaped environmental Kuznets curve in MPA establishment, providing new theoretical insights from a complex system perspective.

Discussion: Drawing on the results, practical implications were given for balance between conservation and development, spatial-ecological and socioeconomic alignment and top-down adaptive governance, with a list of prioritized coastal cities to receive conservation fund as 2030 looms. The conclusions also pertain to global nonlinear MPA development and merit future studies to deepen MPA establishment research with higher-order interactions and complex dynamics.

KEYWORDS

influencing factors, marine protected area, public good, social-ecological system, spatiotemporal distribution

1 Introduction

China has made substantial efforts to establish marine protected areas (MPAs) for 12.98% of its seas (Bohorquez et al., 2021; Zeng et al., 2022; Chen and Xu, 2024c). However, after achieving the Aichi Target of protecting at least 10% of coastal and marine areas by 2020, there has been a flattening in MPA area and number growth (Hu et al., 2020) (Figure 1). As the ends of the 14th Five-Year Plan (2021-2025) and the 2030 Agenda near (Chen and Xu, 2024d; Warchold and Pradhan, 2025), research on the establishment mechanisms and retrospect of past MPA success once again gains momentum. Although the Central Marine Ecological Protection and Restoration Fund since 2021 (Ma et al., 2022) has provided precious opportunities for local governments to conserve their seas, it is vital to prioritize cities with the largest needs to balance conservation and development (Suryawan et al., 2025) as China turns to high-quality instead of GDP-oriented development (Pan et al., 2021). Besides, the underlying first principles of MPA establishment dynamics could be instructive for marine conservation and Sustainable Development Goals (SDGs) around the world (Chen et al., 2023; Chen and Xu, 2024d).

The establishment of MPAs can be understood from a public goods perspective under the social-ecological system (SES) framework (Ostrom, 1990; 2007; 2009; 2010a; b), where the resource-governance systems and units' capabilities are weighed against shared benefits. Despite the scarcity of research on the determinants of MPA establishment in China, global scholars have applied generalized linear models to study cross-national factors such as space, economy and governance in building MPAs (Fox et al., 2012; Fouqueray and Papyrakis, 2019). Yet, these studies only focused on linear effects, often not involving ecological variables, nonlinear relationships and threshold effects, which are ubiquitous in socio-oceanographic systems (Popova et al., 2023; Chen et al., 2024; Chen and Xu, 2024b). These empirical, methodological and topical curiosities deserve more sophisticated framework, method and interpretations to advance the current understanding.

This article intends to address these issues by adaptively developing an SES-based theoretical framework of decisionmaking and extensively reviewing potential influencing factors of MPA establishment in spatial ecology and socioeconomics. Since most non-national-level MPAs in China are applied for and administered by municipal governments (Food and Agriculture Organization, 2024), data of 49 Chinese coastal cities that built MPAs during 1998-2020 were used for empirical verification. To overcome data issues, overdispersion-robust Poisson pseudomaximum likelihood (PPML) regression with high-dimensional fixed effects (Correia et al., 2020) was adopted, with a mathematically based threshold algorithm to find the critical points where effects change. Among the determinants examined by the models, the effect of GDP revealed an N-shaped curve, supplementary to previous studies in the U-shaped environmental Kuznets curve, offering new insights of MPA establishment as a complex system.

Section 2 describes the theoretical framework and empirical methods used in this study, including spatial-ecological and socioeconomic foundations, empirical model specification and the threshold algorithm. It also describes the theoretical and empirical rationale for selecting specific indicators based on plentiful previous literature. Section 3 presents results of the full regression, threshold calculation and threshold regressions using the calculated tipping points. Section 4 discusses theoretical inference on the determinants, the N-shaped environmental Kuznets curve and threshold algorithm. Practical implications were drafted for balance between conservation and development, spatial-ecological and socioeconomic alignment and top-down adaptive governance. Section 5 draws the conclusions.



2 Framework and methods

2.1 Framework

Assuming that the region's total MPA area is *A*, the species richness (number of species) within the area is *S*. The classical species-area relationship in ecology postulates $S = cA^z$ or $\ln S = \ln c + z \ln A$ (Matthews et al., 2019), where *c* is the number of species for one square unit and *z* is the rate of growth and usually *z* < 1. This relationship applies to marine ecosystems (McDermott, 2021) and has been widely used to design MPAs (Terui et al., 2021). MPA benefits can be considered public goods shared by the total population *P* (Ban et al., 2015; Choi et al., 2020), where the total willingness to pay (*W_i*) for these benefits is:

$$\sum_{i \in P} W_i = PS = PcA^z$$

According to the SES theory (Ostrom, 1990; 2007; 2009; 2010a; b), the establishment of MPAs is subject to both resource and governance capacities. Suppose the MPA is fully planned and the number of spatial-ecological resources distributable to one species is *R*. Applying the concept of ecological connectivity, with every *j*-th new species introduced to the MPA, it can acquire resources from the former *j* – 1 species through *j* – 1 links. Therefore, the required new resource input is *R*/*j*. Summing over all species yields the total ecological resource requirement of $\sum_{j=1}^{S} R/j \approx R(\ln S + \gamma)$, the harmonic series with γ being the Euler–Mascheroni constant. The logarithmic cost of dispersal is supported by literature in small species (Burkhalter et al., 2015), which is the case of many MPAs in China (Jiang and Jiang, 2023). Besides, the population *P* also demands spatial-ecological resources for sustainment, which is proportional to itself: *bP*. Substituting ln *S* with ln *c* + *z* ln *A* yields:

$$a(\ln c + z\ln A + \gamma) + bP = N + M$$

where *N* is the amount of natural conditions (resource system) including water, nutrition, connectivity, and *M* is the land-sea space (resource unit). Although previous research found the establishment and operating costs of MPAs to be exponentially related to size (Balmford et al., 2004; Brander et al., 2020), the overall socioeconomic cost during resource allocation is logarithmic from a network and system perspective (Herald and Ramirez-Marquez, 2012; von Falkenhausen and Harks, 2013). According to the economies of scale, suppose the cost of building one unit area of MPA is *C*. When building the *k*-th unit area of MPA, due to the ability to use existing infrastructure and personnel from previous areas, the marginal cost is C/k. Therefore, the total socioeconomic cost of building *A* units of MPAs is $\sum_{k=1}^{A} C/k \approx C(\ln A + \gamma)$. Also considering the socioeconomic cost of periods and the population dP, the equation for economic resource allocation becomes:

$c(\ln A + \gamma) + dP = G + E$

where c and d are parameters, G represents policy factors and E is the economy size, both rendered in comparable units. The ideal amount of A maximizes total willingness to pay while minimizes resource and governance costs, formulated by the Lagrange

multiplier (\mathcal{L}) :

$$\begin{aligned} \mathcal{L}(A,\lambda_1,\lambda_2) &= PcA^z + \lambda_1 [a(\ln c + z \ln A + \gamma) + bP - N - M] \\ &+ \lambda_2 [c(\ln A + \gamma) + dP - G - E] \end{aligned}$$

whose first-order derivative equations are:

$$\begin{cases} \frac{\partial \mathcal{L}}{\partial A} = PczA^{z-1} + \frac{1}{A}(\lambda_1 az + \lambda_2 c) = 0\\ \frac{\partial \mathcal{L}}{\partial \lambda_1} = a(\ln c + z \ln A + \gamma) + bP - N - M = 0\\ \frac{\partial \mathcal{L}}{\partial \lambda_2} = c(\ln A + \gamma) + dP - G - E = 0 \end{cases}$$

Solving the equations yields:

$$\ln A = \frac{1}{adz - bc} \left[d(N+M) - b(G+E) - ad \ln c - (ad - bc)\gamma \right]$$

which means the logarithm of the total area (*A*) of MPAs is a linear combination (additive result) of spatial-ecological capacity (N + M) and socioeconomic capacity (G + E) (Figure 2). However, these relationships are not guaranteed to be always linear. The environmental Kuznets curve (EKC) implies that development-related variables may first inhibit environmental protection, then promote it when some threshold is crossed, while other variables could be the opposite (Wang et al., 2024c). Empirical methods are needed to address these threshold effects.

2.2 Methods

2.2.1 Empirical model

Although ecological studies suggest that species richness S in MPAs could be modeled using the Poisson distribution (Davies et al., 2022; Hoeksema et al., 2022; Espinoza et al., 2024), the area A of MPAs is usually not Poisson-distributed. Since ln A implies an additive relationship with spatial-ecological capacity (N + M) and socioeconomic capacity (G + E), its exponential form $A = e^{x\beta}$ suggests a multiplicative relationship with $x = [1, N, M, G, E]^{T}$ and β being undetermined coefficients. To estimate the coefficients, the Poisson pseudo-maximum likelihood (PPML) regression with highdimensional fixed effects (HDFEs) is adopted (Santos Silva and Tenreyro, 2006; Correia et al., 2020), which can pertain to any nonnegative data (including non-count data with zeros) without needing to assume a specific distribution (e.g., Poisson). The method is robust to distributional misspecification such as overdispersion, zero-inflation, heterogeneity and heteroskedasticity. Since the method relies on pseudo-maximum likelihood (PML) principles, consistent and unbiased estimates only require correct specification of the conditional mean structure: $E(y_i|x_i) = \mu_i = e^{x_i\beta}$, which is ensured by the theoretical deduction.

Despite originating from spatial econometrics of international trade, the PPML method has been widely adopted in many areabased geographic analyses, such as land size (Lay and Nolte, 2017; Anti, 2022; Raimondi and Scoppola, 2022). One of its advantages at addressing spatiotemporal problems is the ability to construct HDFEs to represent latent spatial and network autocorrelation (Gu et al., 2022, 2023, 2024). Additionally, it allows for cluster



robust standard errors to account for autocorrelation in the variables (Anderton and Anderton, 2021; Ding et al., 2025; Long et al., 2025). In environmental planning and management, scholars found PPML to be superior to spatial Durbin models with higher probability of finding significant impacts of climate factors by using more granular data (Ton et al., 2024), providing more information about the mechanisms behind the effects with advanced accuracy of the estimated coefficients. It also performs better than geographically weighted regression (GWR) models in avoiding heteroskedasticity (Ko et al., 2022).

Previous research has noted the potential endogeneity between protected areas and establishment costs in China, such as opportunity costs for local communities or industries (Yang and Wu, 2022). However, the ideal instruments to address MPA endogeneity are difficult to identify, and incorporating instrumental variable estimators with fixed effects in PPML evokes the incidental parameter problem, leading to inconsistent estimates (Santos Silva and Tenreyro, 2022). Following empirical studies in econometrics and ecological economics (Baier and Bergstrand, 2007; Weidner and Zylkin, 2021; Peiró-Palomino et al., 2022), the article adopted three-way fixed effects on province, municipal and temporal levels to absorb time-varying factors like policy changes, economic conditions, or shifts in political power, and time-invariant path-dependence factors such as regional preferences for conservation, institutional capacity, or geographical conditions.

According to Article 12 of the Regulations of the People's Republic of China on Nature Reserves effective during 1994-today (the 1994 Regulations, for short), the province is tasked with applying for national protected areas, while municipal

governments can apply for local ones (Food and Agriculture Organization, 2024). Considering that the establishment of MPAs in China is coordinated by provincial and municipal factors (Wang et al., 2025b) as well as time trends (Bohorquez et al., 2021), the study also incorporates high-dimensional fixed effects for the province (π_i), city (σ_i) and year (τ_t) to absorb the effects of omitted variables due to unobserved provincial, municipal and temporal heterogeneity (Yao et al., 2025).

Previous studies used year t-1 independent variables to explain China's protected areas in year t based on the policy lag premise (Yang and Wu, 2022). However, using lagged independent variables (lagged predictors) in panel data analysis with fixed effects risks potential biases or misleading results (Vaisey and Miles, 2017), even obscuring the true causal mechanisms when the correct lag structure is not properly specified (Leszczensky and Wolbring, 2022). Moreover, studies found China's nature reserves to be subject to ad hoc policy changes or project demands such as the construction of ports, industrial zones, and infrastructure (Ma, 2016; Ma et al., 2019), which are best reflected in socioeconomic indicators of the same year. Besides, climatological predictors are instantaneous (Nordio and Fagherazzi, 2022) and exogenous (Wang et al., 2022) in protected areas. Consequently, no lags were applied to variables in the study, as in other PPML studies on contemporaneous effects (von Laer et al., 2022; Ekanayake et al., 2023; Friedmann and Pedersen, 2024; Giorgi et al., 2025) and studies on determinants of protected areas (Sims, 2010; Fox et al., 2012; Opršal et al., 2018; Fouqueray and Papyrakis, 2019; Mance et al., 2021; Bareille et al., 2023).

Since previous studies found in welfare economics that the odds of building protected areas are linearly tied to the net social benefit

decided by the difference between total benefit and costs (Wu and Liu, 2012; Yang and Wu, 2019), the number of MPAs (*n*) is also used as an alternative to ln *A*. This is equivalent to the identify link function $g(\mu) = \mu = X\beta$ instead of the more often used log link function $g(\mu) = \ln \mu = X\beta$ in general linear models (GLMs), but it is equally effective under nonnegativity constraints and may generate a better fit in biometrics and ecology (Lu et al., 2022; Pinheiro et al., 2022; Heit et al., 2024). The use of the exponentiated number of MPAs is further bolstered by previous research on the log-log linear relationship between MPA number and area (Fox et al., 2012), which is equivalent to exponentiality. As the original dependent variable data, it takes the exponential form. With $y_{i,t} = A_{i,t}$ or $e^{n_{i,t}}$ being the dependent variable, the final empirical model can be written as:

$$\ln y_{i,t} = \beta_0 + \mathbf{N}_{i,t} \mathbf{\beta}_N + \mathbf{M}_{i,t} \mathbf{\beta}_M + \mathbf{G}_{i,t} \mathbf{\beta}_G + \mathbf{E}_{i,t} \mathbf{\beta}_E + \pi_i + \sigma_i + \tau_t + u_{i,t}$$

where β_0 is the constant; $\mathbf{N}_{i,t}$, $\mathbf{M}_{i,t}$, $\mathbf{G}_{i,t}$ and $\mathbf{E}_{i,t}$ are the timevariant $1 \times k$ spatial-ecological and socioeconomic variable factors for city *i* in year *t*; $\boldsymbol{\beta}_N$, $\boldsymbol{\beta}_M$, $\boldsymbol{\beta}_G$ and $\boldsymbol{\beta}_E$ are the corresponding $k \times 1$ parameters; $u_{i,t}$ is the error term. The empirical model also utilizes robust standard errors that can produce more rigorous results than traditional panel Poisson regressions (Santos Silva and Tenreyro, 2006; 2011; 2022).

2.2.2 Threshold calculation

The threshold calculation is based on the threshold regression developed by Hansen (1999; 2000). However, since currently no statistical packages are designed for threshold calculation in PPMLHDFE models, the study adopts a modified grid search algorithm to determine the threshold θ where coefficients change course. Suppose the estimated coefficient of independent variable xis β , then the algorithm splits x into two parts: $x \leq \theta$ and $x > \theta$ to estimate the two parts separately with the same empirical model. To avoid missing critical values or depleting datasets, θ ranges from the 25th percentile ($Q_1(x)$) to the 75th percentile ($Q_3(x)$) of x, until the true threshold θ^* is found. In practice, a discrete approach was adopted, by adding a minuscule increment each time from $Q_1(x)$ to $Q_3(x)$.

As $\beta = f(\theta)$ is a function of the threshold range θ , the three concrete conditions for true threshold θ^* are: (1) Local extremity. According to the mathematical definition of an extremum, $f(\theta)$ has a local relative maximum (or minimum) point at θ^* , if for all θ within distance $\varepsilon > 0$ of $\theta^* \in [Q_1(x), Q_3(x)]$, there are no $f(\theta)$ values larger (or smaller) than $f(\theta^*)$; (2) Forward extremity. For all $Q_3(x) \ge \theta > \theta^*$, $f(\theta)$ should be smaller (or larger) than $f(\theta^*)$, meaning that no forward values can surpass the current coefficient in terms of extreme high or extreme low; (3) Transcendentality. Finally, for a sufficiently small diameter $\delta \rightarrow 0$, there exists one point within the neighborhood $[\theta^* - \delta, \theta^* + \delta]$ of θ^* where the 95% confidence intervals of $f(\theta)$: $(CI_{95\%}(f(\theta \pm \delta)) = [LB_{95\%}(f(\theta \pm \delta)), UB_{95\%}(f(\theta \pm \delta))])$ should be on different sides of the axis to represent the transition from one regime to the other. The three key conditions for θ^* can be compactly formulated as:

$$\begin{cases} \exists \varepsilon > 0 \left(\left(f(\theta^*) \ge f(\theta^* \pm \varepsilon) \right) \lor \left(f(\theta^*) \le f(\theta^* \pm \varepsilon) \right) \right) \\ \forall \ \theta \in (\theta^*, Q_3(x)] \left(\left(f(\theta) < f(\theta^*) \right) \lor \left(f(\theta) > f(\theta^*) \right) \right) \\ \exists \delta > 0 \left(LB_{95\%} \left(f(\theta \pm \delta) \right) UB_{95\%} \left(f(\theta \pm \delta) \right) \right) < 0 \end{cases}$$

where the left conditional branch indicates a downward threshold effect, while the right branch indicates an upward effect. The left branch does not interfere with the right branch because the conditions are mutually exclusive. In practice, δ was set as 5% of the grid search interval: $Q_3(x) - Q_1(x)$. After determining the supposed threshold θ^* , the coefficients should be significant for both $x \leq \theta^*$ and $x > \theta^*$ to formalize it as the true threshold.

2.3 Data sources and statistics

2.3.1 MPA area and number

The area and number of MPAs are from the compiled list by Bohorquez et al. (2021), currently the most comprehensive database on area-based marine conservation in China. After cleansing, a total of 288 MPAs (123,891 km²) were included, corresponding to 49 prefecture-level coastal cities. MPAs built in provincial directlygoverned county-level cities were excluded due to difficulty in attributing data. Following previous studies, the total or cumulative area (Fox et al., 2012; Wu et al., 2018; Yang and Wu, 2022) and number (Fox et al., 2012) of MPAs were used and interpolated linearly. Given the log link for $A_{i,t}$ and the identity link for $n_{i,t}$, the coefficients capture semi-elasticity for both proportional and absolute changes in the dependent variable resulting from a one-unit independent variable increment.

2.3.2 Natural conditions

Natural conditions (resource system) N, such as precipitation (Precip), wind speed (Wind) and urban green space (Green), can be reflective of the underlying resource system. According to the ecosystem pulse theory (Souto-Vieira et al., 2024), precipitation can increase species richness, abundance, taxonomic, phylogenetic and functional biodiversity of fish assemblages in neritic zones (da Silva et al., 2021) through the estuarization process (Macedo et al., 2021) as deep as 30 m (Passos et al., 2016). The effect works in several ways, first through the influx of freshwater that supports certain estuarine species, such as polychaeta, isopoda, crustaceans (Checon et al., 2023) by regulating salinity levels, enhancing habitat connectivity and facilitating species movements (da Silva et al., 2021). It also drives biomass exchange between estuarine and marine ecosystems (Macedo et al., 2023). Second, freshwater runoff from terrestrial sources brings in nutrients that can stimulate primary and secondary production in estuarine environments, increasing the trophic complexity, resilience and maturity (Macedo et al., 2023). Third, rainfall can trigger migration and breeding behaviors in fish, allowing for organic matter and energy transfer and creating a trophic meta-ecosystem convergence (Macedo et al., 2021). Since the majority of China's MPAs are in shallow and medium waters, hourly observed climatology data for precipitation (mm) from the National

Centers for Environmental Information (NCEI) (2023) divided by 10 is used as a predictor of natural condition and MPA establishment, by averaging the yearly indicators from each city's weather stations.

Wind also affects marine organisms by enhancing marine connectivity, inducing coastal upwelling, transporting fish larvae and accelerating migration and recruitment (Arteaga et al., 2024; Suca et al., 2025). First, wind-driven surface connectivity and circulation influence the distribution of nutrients and organisms in marine environments (Xu et al., 2023a). Strong winds can also cause nutrient-rich water to circulate and support the growth of phytoplankton and other marine species (Moore-Maley and Allen, 2022). Second, wind-induced vertical upwelling generates high biological productivity due to nutrient enrichment of the surface layers to stimulate primary and secondary productivity, which has been intensifying in the four China Seas during 1982-2020 (Wang et al., 2021; Liu et al., 2023; Luo et al., 2023; Xu et al., 2023b). This increased productivity facilitates the boom of phytoplankton, other primary producers and finally fish (Bai et al., 2020). Third, winddriven transport of larval fish has been reported in various literature (Schilling et al., 2022; Śmejkal et al., 2023; Arai and Kimura, 2024). Therefore, city-average wind speed data (m/s) from NCEI divided by 10 is included as a positive factor.

Urban green space can also reflect MPA development through several theoretically and empirically verified pathways. First, as a nature-based solution (NbS), urban green space directly absorbs rainwater and stormwater run-off (MacKinnon et al., 2019), which is a major contamination source for aquatic and coastal ecosystems (Werbowski et al., 2021; Lapointe et al., 2022). Features like green roofs, bioretention systems, and constructed wetlands also help in improving air quality to eventually favor adjacent marine ecosystems like mangroves, seagrass meadows and salt marshes (Pinto et al., 2023; Sun et al., 2024), especially providing cooling under climate change and extreme events (Li et al., 2024b). Second, urban green space development increases the planning ability and experience of the city through path dependence (Addas, 2023; Bille et al., 2023), which also furthers later development in MPAs. Third, urban green space extends ecological corridors in fragmented coastal habitats connecting MPAs and other effective area-based conservation measures (OECMs) (Podda and Porporato, 2023). The integration of green space and marine ecosystems is pronounced in water cycles (Yuan and Kim, 2024). Considering these effects, urban green area (100 km²) of the municipal district from China City Statistical Yearbook (CCSYs) is used as a positive factor.

2.3.3 Land-sea space

Land-sea space (resource unit) M is reflected in maritime passenger traffic (*Traffic*), population density (*Density*) and builtup area (*Built*). Larger maritime traffic flow is a reflector of the size of sea space, which provides more ample room for the existence of an MPA (Yap and Loh, 2019). While maritime traffic is often associated with negative impacts on marine ecosystems, such as habitat disturbances, higher vessel density might in turn invoke conservation measures due to raised awareness and economic growth based on the EKC, as witnessed by international empirical studies on marine transport sectors (Go et al., 2021; Kalaycı and Özden, 2021; Pata et al., 2023). These theoretical and empirical foundations support using maritime traffic (10 million) from CCSYs as a positive factor. On the other hand, coastline length may also be related to MPA development, but some cross-national evidence reported insignificant effect on the spatial extent of MPAs (Fox et al., 2012; Fouqueray and Papyrakis, 2019). Moreover, literature also suggests countries with limited coastlines may prioritize MPAs due to scarcity value (Horowitz, 2002). Therefore, coastline is not adopted as the sea space variable.

Higher population density in surrounding coastal areas can result in increased anthropogenic pressures on MPAs. It can lead to intensified fishing, pollution, coastal development, and habitat destruction, which can threaten the effectiveness and conservation goals of the MPA (Mascia et al., 2017). As human populations grow, especially in coastal areas, the competition for marine resources, such as fishing and tourism, intensifies, which may reduce the political will or capacity to implement MPAs and has been observed in various cross-national empirical studies (Sims, 2010; Opršal et al., 2018; Wu et al., 2018; Fouqueray and Papyrakis, 2019; Yang and Wu, 2022). Therefore, municipal-level population density (1000/ km²) from CCSYs is included as a negative factor.

The extent of coastal construction and urbanization can directly impact available habitat and ecological connectivity within and around MPAs (Bulleri and Chapman, 2010). It is noteworthy that this impact pertains to not only marine construction, but also inland built-up areas. Studies identified high pressure of built-up areas on protected coastal areas such as mangroves or salt marshes due to fragility, vicinity and vulnerability (Romañach et al., 2018; Fuente et al., 2020). The urban expansion, along with sea level rise, constitutes the coastal squeeze faced by many habitats along global coastlines (Kirwan and Megonigal, 2013; Smart et al., 2021; Lansu et al., 2024). Hence, built-up area (100 km²) of the municipal district from CCSYs is used as a negative factor.

2.3.4 Policy factors

Policy factors (governance system) G are reflected in the number of scientific and technological personnel (Tech), infrastructure investment (Infra) and cultural promotion presented by the number of public library books (Book). Scientific and technological personnel, including protected area professional staff, are critical for MPA development (Appleton et al., 2022). According to the Marine Eco-Environmental Protection in China White Paper of The State Council Information Office (2024), China is committed to innovation in marine eco-environmental protection technologies, monitoring and evaluation, and institutions and mechanisms. It has made rational decisions and implemented targeted measures to transform and advance protection through digital and smart technology. Therefore, the number of scientific and technological personnel (10,000) from CCSYs will be directly indicative of each city's policy alignment with the central government and technological power to enhance marine conservation.

Although there might be some competition for funding between urban infrastructure and MPAs (Jaffé et al., 2025), the overall

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impact of infrastructure investment is beneficial to MPAs. Infrastructure provides basic physical conditions for MPAs to operate (Cao et al., 2021). Furthermore, infrastructure can buffer extreme natural events from intruding marine ecosystems, such as rainstorms, effectively acting as a separation wall (Giang and Khanal, 2024). Infrastructure investment is representative of the government's building capacity and efficiency (Geng and Lo, 2024). Finally, well-regulated infrastructure can spill over to MPA development through network externality and synergy (Roberts et al., 2023; Gong et al., 2024). Consequently, the yearly investment amount completed in urban environmental infrastructure construction (\$10 billion) from CCSYs is used as a positive factor. Since nominal infrastructure investment is directly related to the cost of building MPAs, it was not deflated.

Library books have long been an effective tool for building environmental management capacity opportunities in literature (Devine and Appleton, 2023; Phaka et al., 2023; Aregbesola et al., 2024). Public library books can promote and implement citizen science initiatives (Cigarini et al., 2021; Walker et al., 2023; Mumelaš and Martek, 2024), which helps to disseminate conservation awareness, increase social cohesion, and improve residents' acceptance towards MPAs. Moreover, at the macro level the number of books in public libraries is indicative of a city's cultural orientation, which is related to the degree of official focus on conservation (Jenkins, 2022; Andersson et al., 2024). Therefore, despite the digital age, the number of books in public libraries has been extensively used and verified in recent empirical studies to represent the sociocultural factor, especially in China (Xia and Zhai, 2022; Dong et al., 2023a, b; Zhang et al., 2025). Although other studies used national educational expenditure as an MPA predictor (Fouqueray and Papyrakis, 2019), this study uses each city's public library books per capita from CCSYs instead.

2.3.5 Economy size

Economy size (governance unit) *E* is reflected in the output (*GDP*), demand (Pop) and supply (Export). Although the MPA establishment in China is often state-driven, tied to centralized fiscal policies (e.g., Five-Year Plans) (Hu et al., 2020) or local government performance metrics (e.g., ecological civilization targets), funding from the central government only accounts for a limited portion of the overall budget, and a large amount of funding for protected areas is supported by local financing, especially for nonnational-level local protected areas (He and Cliquet, 2020). Since the 1994 Regulations give local governments the authority to apply for MPAs based on their situations (Food and Agriculture Organization, 2024), the total economic output (GDP) is included as a predictor of MPA establishment, as seen in previous studies of China's protected areas (Yang and Wu, 2022). Some international studies used GDP per capita (Fouqueray and Papyrakis, 2019; Mance et al., 2021) or HDI (Fox et al., 2012; Opršal et al., 2018; Mance et al., 2021) as determinants, but based on China's collectivist nature in cultural dimensions (Hofstede, 2011), it may be better suited by GDP (¥ trillion) from CCSYs as a whole (Yang and Wu, 2022). Since nominal GDP is directly related to the cost of building MPAs, it was not deflated in regressions, following other studies (Hao et al., 2022; Wang et al., 2024a; Zhou, 2024; Ulate et al., 2025), where inflation effects are also absorbed by time-varying high-dimensional fixed effects (Jaravel and Sager, 2019; Kunofiwa, 2022). The threshold analysis, however, used 1998-based deflators of each city's province from the Stata module "cngdf" (Song, 2021) to calculate real *GDPr*, the most accurate GDP deflator available for Chinese cities.

Besides population density (Sims, 2010; Fouqueray and Papyrakis, 2019; Yang and Wu, 2022), the total population in the vicinity of MPAs can also influence the demand for marine resources and coastal activities (Fox et al., 2012), with some studies using density and total population simultaneously (Opršal et al., 2018). As the empirical results of Opršal et al. (2018) demonstrate, total population significantly predicts more protected areas. Since in China, population-growing areas tend to have younger population structures through immigration (Gu and Xu, 2022; Gu et al., 2022b), the younger generations create higher demands for both nature-friendly economic development and ecological conservation, and they are more open to the concepts of MPAs (Turnbull et al., 2021). According to the urban scaling theory, the relationship between total population and density in Chinese cities is not perfectly collinear (Tan et al., 2025), thus the yearly average population (million) of each city from CCSYs is used as a positive factor.

Regions heavily dependent on exports may prioritize economic growth over environmental conservation, leading to a lack of investment in MPAs (Acheampong and Opoku, 2023). Wang et al. (2024b) examined the impact of export expansion on local environment in China during 2000–2020 and found regions with larger export expansion experienced more pronounced initial environmental deterioration. The inclusion of exports (¥ trillion) from CCSYs in the model corresponds to the south-north diversity of export-orientation in China's coastal cities (Li et al., 2022; Chen and Xu, 2024d) due to the Maritime Silk Road (Li et al., 2024a), which is less obviously conveyed by GDP. Since exports are an inflated reflector of real goods, they were adjusted using provincial GDP deflators with 1998 as the base year.

2.3.6 Descriptive statistics

The descriptive statistics covering a total of 23 years, 49 cities and $49 \times 23 = 1127$ samples are shown in Table 1. The start point of 1998 is due to multiple historical and statistical facts. Internationally, the United Nations proposed "International Year of the Ocean" in 1998. Domestically, the Outline of the Planning of Nature Reserve Development of China (1996-2010) required local governments to complete nature reserves planning by July 1998. The same year, the State Oceanic Administration merged into the newly established Ministry of Land and Resources to supervise ocean management, which saw an instant boost of MPA number and area (Figure 1). Several important ocean laws and regulations (e.g., GB/T17504-1998) were also promulgated that year. The end year of 2020 is attributed to China's early completion of the Aichi Biodiversity Targets to conserve 12.98% of the seas (Bohorquez et al., 2021), which led to a slowdown. Besides, the COVID-19 pandemic post 2020 also decelerated MPA construction. Missing data were extended to 1998-2020 using the fittest ARIMA models.

Variable	Unit	N	Mean	SD	Min	Q1 (25%)	Median	Q3 (75%)	Max
Area	km ²	1127	1690.591	4083.238	0	93.588	327.961	894.52	24000
Number		1127	4.079	4.144	0	1.769	3	5	24
Precip	10 mm	1127	2.310	1.430	-0.192	1.215	2.180	3.214	6.989
Wind	10 m/s	1127	2.757	0.784	0.000	2.418	2.579	3.195	5.706
Green	100 km ²	1127	0.206	0.332	0.002	0.047	0.092	0.206	2.198
Traffic	10 million	1127	0.531	2.167	0.001	0.018	0.101	0.264	15.315
Density	1,000/km ²	1127	0.642	0.569	0.123	0.362	0.530	0.695	11.564
Built	100 km ²	1127	1.561	1.953	0.080	0.530	0.910	1.690	12.380
Tech	10,000	1127	0.833	2.081	0.010	0.177	0.319	0.527	30.590
Infra	¥10 billion	1127	0.202	0.322	0.000	0.054	0.105	0.213	2.332
Book		1127	0.753	1.276	0.020	0.189	0.337	0.701	9.372
GDP	¥ trillion	1127	0.247	0.396	0.002	0.048	0.115	0.273	3.870
GDPr	¥ trillion	1127	0.182	0.277	0.002	0.043	0.090	0.200	2.647
Рор	million	1127	4.367	2.817	0.481	2.401	3.510	6.534	14.660
Export	¥ trillion	1127	0.090	0.185	0.000	0.008	0.019	0.089	1.096

TABLE 1 Descriptive statistics of variables.

Using the Stata module "coldiag2" (Hendrickx, 2004), the condition number of variables is 17.64<30, indicating no high multicollinearity issues. The study also explicitly tested the overdispersion of the dependent variables $A_{i,t}$ and $e^{n_{i,t}}$ using the Stata module "overdisp" without previously estimating Poisson or binomial negative models (Fávero et al., 2020). The coefficients of $\hat{u} = E(y_i|x_i)$ in $Var(y_i|x_i) = \hat{u} + \alpha \hat{u}^2$ were 2.62 (p<0.001) and 0.47 (p < 0.001) and rejected the equidispersion hypothesis, demonstrating the necessity of using the PPMLHDFE model to robustly estimate overdispersal data. According to Santos Silva and Tenreyro (2011), the PPML estimator with 1000 samples is robust with only <3.5% bias even when $Var(y_i|x_i) = 3E(y_i|x_i) + 30E(y_i|x_i)^2$, which is close to the sample size (1127) in this study. Other studies also support using PPML instead of negative binomial regression under strong overdispersion (Head and Mayer, 2014; Curzi and Huysmans, 2022; Saussay and Sato, 2024).

3 Results

3.1 Spatiotemporal distribution

Figure 3 shows the development of Chinese MPAs in the last two decades (2000-2019) can be divided into four stages. During the first stage (2000-2004), most cities had 1 to 5 MPA each, and only the city of Zhanjiang had more than 10 MPAs. Most MPA areas were under 5,000 km², with one exception, and most of them were settled in the south. In the second stage (2005-2009), two cities emerged, Zhanjiang and Yangjiang, with more than 10 MPAs, and there were four MPAs with areas larger than 10,000 km² from north to south, making the spatial distribution more balanced. The third stage (2010-2014) set a milestone in the quantitative and qualitative development of MPAs, where Zhanjiang and Yantai achieved more than 20 and four other cities exceeded 10. Large-scale MPAs became more common along the coastline and the largest MPA thus far (23,219 km²) had appeared. Compared to the rapid progress in stage three, the fourth stage (2015-2019) is more conservative, with only 18 newly built cities, mostly in cities already with more than 10 MPAs.

The local Moran's *I* for MPA size indicates that there is significantly (p<0.05) positive but slight (0.084) spatial correlation, with the Bohai Sea and Yangtze River Delta being the two aggregation centers, and the high-high parts are mainly in the Yangtze River Delta. Local Moran's *I* for MPA number also indicates a significantly (p<0.05) positive and larger (0.118) spatial correlation, with the Bohai Sea and Pearl River Delta being the two aggregation centers, and the high-high parts are mainly situated along the Bohai Sea.

3.2 Full regression

Table 2 shows averagely MPA size grows $e^{0.066} - 1 = 6.82\%$ each year with the time trend. Wind speed consistently shows a positive and statistically significant effect across all four models, with particularly strong coefficients in the models explaining the number of MPAs (Models 3 and 4), reaching as high as 2.950 (*p*<0.001). This indicates that higher wind speeds may be associated with both larger areas and greater numbers of MPAs, verifying the enhancement of wind on marine ecosystems. Green space (*Green*) also demonstrates a robust and positive influence, significant at the 1% level in Models 1, 2 and 3, suggesting that urban green coverage



is a meaningful proxy for environmental considerations and improvement in MPA establishment. However, precipitation (*Precip*) shows weak and mostly insignificant effects, with significance only emerging in Model 4 (0.619, p<0.001). Averagely, 10 km² more urban green space makes MPA size $e^{2.046 \times 0.1} - 1 = 22.70\%$ to $e^{4.089 \times 0.1} - 1 = 32.34\%$ larger, or adds 0.47 more MPAs.

Maritime traffic (*Traffic*) is positively associated with MPAs, being significant in all area models and especially in Model 4 (1.767, p<0.001), which suggests that increased maritime movement encourages more and larger MPAs, possibly due to higher monitoring needs or conservation pressures. Density, by contrast, exhibits a negative effect in Models 3 (-13.352, p<0.001), highlighting that higher population density may constrain the establishment of MPAs, particularly in terms of their number. Built-up area (*Built*) shows a negative and robust association with area-based models (-0.374 and -0.376 in Models 1 and 2, both p<0.001), as well as in Model 3 (-0.201, p<0.05).

Infrastructure investment (*Infra*) stands out with large positive effects on area-based models (4.089 and 4.037 in Models 1 and 2, both p<0.001), and an exceptionally large coefficient in Model 4 for the number of MPAs (60.363, p<0.05), underlining the importance

of government investment in supporting conservation infrastructure. Technological personnel (*Tech*) shows a positive and significant effect in Model 3 (2.343, p<0.01), suggesting that a higher number of scientific and technological personnel facilitates the creation of more MPAs. Cultural promotion (*Book*), proxied by the number of books, is significant and positive in the numberbased models, particularly in Models 3 and 4 (5.124 and 24.805, both p<0.001). Averagely, investing ¥1 billion in infrastructure increases MPA size by $e^{4.037 \times 0.1} - 1 = 49.74$ % or $e^{4.089 \times 0.1} - 1 =$ 50.52%, while increasing 10 thousand technological personnel boosts MPA number by 2.343 to 3.497.

GDP positively affects the number of MPAs, with significant coefficients in Models 3 (17.403) and 4 (9.164), both p<0.01 and suggesting that wealthier regions are more likely to establish MPAs. Population (*Pop*) shows a positive and significant effect in Model 3 (1.192, p<0.01) but becomes insignificant in other models, indicating that population demand may drive MPA numbers only under certain conditions. Interestingly, exports (*Export*) demonstrate a negative and significant effect on the number of MPAs in Models 3 (-6.218, p<0.01) and 4 (-6.718, p<0.001), implying a possible trade-off between economic openness and conservation priorities. In contrast, these economic variables are

TABLE 2 Full regression results.

Variables	(1)	(2)	(3)	(4)
	Area	Area	Number	Number
Time	0.066***		-0.175	
	(0.007)		(0.158)	
Precip	0.024	-0.043	0.001	0.619***
	(0.026)	(0.030)	(0.068)	(0.155)
Wind	0.268**	0.223**	1.041**	2.950***
	(0.090)	(0.076)	(0.352)	(0.410)
Green	2.046**	2.802***	4.697**	3.134
	(0.739)	(0.721)	(1.625)	(5.248)
Traffic	0.585**	0.548**	1.256	1.767***
	(0.215)	(0.196)	(0.895)	(0.454)
Density	-0.843	-1.030	-13.352***	-12.623
	(0.777)	(0.852)	(3.483)	(12.272)
Built	-0.374***	-0.376***	-0.201*	0.003
	(0.084)	(0.081)	(0.084)	(0.067)
Tech	0.015	0.015	2.343**	3.497***
	(0.029)	(0.034)	(0.770)	(0.566)
Infra	4.089***	4.037***	-5.314	60.363*
	(0.909)	(0.971)	(26.171)	(23.442)
Book	0.091	0.091	5.124***	24.805***
	(0.113)	(0.099)	(1.478)	(5.547)
GDP	-0.064	-0.276	17.403**	9.164**
	(0.271)	(0.282)	(5.672)	(3.385)
Рор	-0.009	-0.058	1.192**	0.830
	(0.061)	(0.069)	(0.422)	(1.490)
Export	0.274	1.535	-6.218**	-6.718***
	(0.415)	(1.026)	(1.893)	(0.926)
Constant	6.613***	7.998***	8.189	-25.459***
	(0.462)	(0.502)	(6.241)	(5.781)
Observations	1,127	1,127	1,127	1,127
Province FE	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE		YES		YES
Pseudo R ²	0.899	0.910	0.994	0.999

Robust standard errors in parentheses. * p < 0.05, ** p < 0.01, *** p < 0.001 for all tables. The Pseudo R² of PPMLHDFE models is calculated using McFadden's method, defined as one minus the ratio of the log-likelihoods for the model being fitted and the null model.

generally insignificant in explaining the area of MPAs (Models 1 and 2). The variable coefficients of *GDP*, *Built* and *Traffic* merit further threshold analysis to determine the key point of taking effects on area.

3.3 Threshold analysis

3.3.1 GDP

The N-shaped curve in Figure 4 features a critical real GDP value of \$55 billion (1998-based, equal to \$106.5 billion in 2020), which indicates a significant shift in the relationship between GDP and MPA size. Below this threshold, the effect on MPA size appears to be negative, with the coefficient values being low or even negative. However, above the threshold, the effect on MPA size becomes positive and increases gradually, as shown by the rising coefficient values. The shaded area represents the 95% confidence intervals (CI), which show considerable uncertainty below the threshold, but as the GDP rises, the confidence intervals become narrower, suggesting more certainty in the positive relationship between GDP and MPA size.

Table 3 displays threshold regression results with control variables hidden, where Models (1) with real GDP≤¥55 billion, has a significant negative (-5.611, *p*<0.001) coefficient. In contrast, Models (3) and (4), with real GDP>¥55 billion, show a positive and significant relationship (0.512, *p*<0.001). This shift suggests a marked change in the effect of GDP on MPA size at the ¥55 billion threshold. The Pseudo R² values suggest a strong fit, confirming the robustness of the regression results. Increasing nominal GDP by ¥1 trillion results in e^{0.512} – 1 = 66.86 % increase in MPA size.

3.3.2 Built-up area

Figure 5 demonstrates an N-shaped curve, with a slightly positive relationship before the threshold of 63 km², suggesting that as builtup areas increase, the size of marine protected areas tends to grow. However, once the built-up area exceeds this threshold, the relationship becomes negative, indicating that further urbanization leads to a decrease in the size of marine protected areas. This suggests that in more urbanized regions, competing land use pressures may restrict the establishment of larger MPAs.

Table 4 highlights a shift in the relationship between built-up area and MPA area. For built-up areas $\leq 63 \text{ km}^2$, both the time and built-up area variables are positively correlated with the dependent variable, with the built-up area coefficient being statistically significant (1.208 in Model 1, p < 0.01), suggesting that increases in built-up area are associated with increases in the dependent variable. However, for built-up areas $>63 \text{ km}^2$, the relationship changes, with the built-up area coefficient turning negative (-0.295 in Model 3 and -0.280 in Model 4, both p < 0.001), indicating that as urbanization increases beyond this threshold, the dependent variable decreases. Building up 100 km² results in $1 - e^{-0.280} = 24.42 \%$ or $1 - e^{-0.295} = 25.55 \%$ decrease in MPA size.

3.3.3 Maritime traffic

Figure 6 illustrates the inverted N-shaped curve. Before this threshold at 0.33 million, the coefficient is insignificantly negative. After the threshold, the coefficient rises sharply, becoming significantly positive and stabilizing as maritime traffic increases beyond 0.33 million persons. Once maritime traffic exceeds the threshold, the positive relationship becomes more stable, suggesting a diminishing negative impact or a shift to a positive association



with the dependent variable. This proves that maritime traffic is not necessarily antagonistic to MPA development.

Table 5 presents a threshold at 330,000 in the traffic variable. In Model 2 (*Traffic* ≤330,000), the coefficient for traffic is negative and statistically significant (-26.362, *p*<0.001), indicating a strong negative relationship. After surpassing the threshold in Models 3 and 4 (*Traffic* >330,000), the coefficient becomes significantly positive (0.502 and 0.472, *p*<0.01), showing a shift to a positive relationship. Averagely, 1 million more traffic is related to $e^{0.472\times0.1}$ -1 = 4.83 % or $e^{0.502\times0.1}$ - 1 = 5.15 % increase in MPA size.

4 Discussions

4.1 Theoretical contributions

4.1.1 Determinants of MPA establishment

Applying the SES theory, the study highlights the importance of spatial-ecological and socioeconomic factors in decision-making processes, thus contributing to the theoretical foundation of environmental governance and management. Although previous MPA studies did consider spatial scale as a factor (Fox et al., 2012;

Variables	(1)	(2)	(3)	(4)	
	<i>GDPr</i> ≤¥55 billion	GDPr \leq ¥55 billion	GDPr >¥55 billion	GDPr >¥55 billion	
Time	0.073***		0.065***		
	(0.006)		(0.012)		
GDP	-5.611***	-2.873	0.512**	0.242	
	(1.435)	(1.814)	(0.191)	(0.205)	
Constant	8.203***	7.409***	7.698***	9.351***	
	(0.292)	(0.348)	(0.545)	(0.499)	
Observations	325	325	764	764	
Province FE	YES	YES	YES	YES	
City FE	YES	YES	YES	YES	
Year FE		YES		YES	
Control	YES	YES	YES	YES	
Pseudo R ²	0.992	0.993	0.939	0.951	

TABLE 3 Threshold regression results of the effect of GDP.

Observations can be dropped that are either singletons (Correia, 2015) or separated (Correia et al., 2021) by a fixed effect.



Fouqueray and Papyrakis, 2019; Yang and Wu, 2022), ecological capacity was unavailable due to data difficulty. This study demonstrates that conditions such as precipitation, wind speed, and green space also play a crucial role in shaping the richness and abundance of marine species and thus MPAs. Additionally, maritime traffic is not necessarily negative for MPA establishment. Further studies can use conclusions in this article to construct land-sea datasets despite ocean data scarcity.

4.1.2 Rethinking the EKC in MPAs

Results confirmed environmental Kuznets curves for GDP (Nshape), built-up area (N-shape) and maritime traffic (inverted Nshape) but offers some new insights. Although previous studies used quadratic terms (parabola) to fit the U-shaped EKC in MPA establishment (Fouqueray and Papyrakis, 2019; Mance et al., 2021; Bimonte and Stabile, 2024), including in China (Wang et al., 2025a), this article highlights the N-shaped (cubic) pattern. At the GDP

Variables	(1)	(2)	(3)	(4)
	<i>Built</i> ≤63 km²	<i>Built</i> ≤63 km²	<i>Built</i> >63 km²	<i>Built</i> >63 km²
Time	0.027*		0.084***	
	(0.013)		(0.012)	
Built	1.208**	0.676	-0.295***	-0.280***
	(0.426)	(0.507)	(0.070)	(0.064)
Constant	11.562***	9.750***	6.741***	8.796***
	(1.658)	(1.520)	(0.568)	(0.511)
Observations	352	352	750	750
Province FE	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE		YES		YES
Control	YES	YES	YES	YES
Pseudo R ²	0.940	0.955	0.933	0.945

TABLE 4 Threshold regression results of the effect of built-up area.



threshold of ¥55 billion (1998-based), the coefficient initially drops slightly before gradually increasing and stabilizing, unlike the Ushaped expectation of a smooth, continuous shift toward environmental improvement (Tatoğlu and Polat, 2021). This behavior introduces a more refined understanding of the EKC, indicating that the shift toward environmental improvement may involve temporary setbacks before stabilization, pointing to the need for nuanced policy interventions during periods of economic transformation.

The N-shaped curve of marine conservation corresponds to the inverted N-shaped curve of environmental degradation, which

often involves complex systems with multilateral interactions, feedback loops and regime shifts (Wu et al., 2022; Zhao et al., 2022; Warchold and Pradhan, 2025). This implies that linearizing and simplifying MPA establishment are insufficient. The economy, society and ecosystem should be considered complex adaptive systems intertwined in SES theories, including the original linked SES (Folke and Berkes, 1998), the Panarchy framework with connected adaptive cycles at different scales (Gunderson and Holling, 2002), the Telecoupling framework with coupled human and natural systems (Liu et al., 2016), common-pool resource institutional analysis (Ostrom, 2007; 2009), the robustness

Variables	(1)	(2)	(3)	(4)
	<i>Traffic</i> ≤330,000	<i>Traffic</i> ≤330,000	<i>Traffic</i> >330,000	<i>Traffic</i> >330,000
Time	0.029**		0.072***	
	(0.010)		(0.009)	
Traffic	-14.340	-26.362***	0.502**	0.472**
	(7.605)	(7.191)	(0.164)	(0.151)
Constant	4.508**	7.440***	6.161***	7.708***
	(1.428)	(1.280)	(0.358)	(0.372)
Observations	365	365	760	760
Province FE	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE		YES		YES
Control	YES	YES	YES	YES
Pseudo R ²	0.918	0.944	0.927	0.936

TABLE 5 Threshold regression results of the effect of maritime traffic.



framework (Anderies et al., 2004), social-ecological action situation (SE-AS) (Schlüter et al., 2019) and socio-oceanography (Popova et al., 2023; Chen et al., 2024; Chen and Xu, 2024b).

4.1.3 Mathematically based threshold

This study also developed a PPMLHDFE threshold algorithm, which effectively enabled the discovery of the N-shaped GDP curve. Despite the excellence of PPMLHDFE to address overdispersion and heteroskedasticity, a threshold regression program was not universally applicable (Usman and Alola, 2023). Previously, PPMLHDFE was only able for robustness check, and the threshold calculation relies on other commands (Hansen, 1999; 2000). This article demonstrates that by controlling the three key mathematical conditions (local extremity, forward extremity and transcendentality), the algorithm could correctly find thresholds that ensure the significance of coefficients on both sides of the point.

4.2 Practical implications

4.2.1 Balance between conservation and development

According to CCSYs, in 1998, more than half (36) coastal cities were below the ¥55 billion (1998-based) threshold. In 2020, only 5 coastal cities are below the ¥106.5 billion (2020-based) threshold. This means most coastal cities have passed the first turning point of the N-shaped EKC. However, there are still 17 coastal cities below the second critical point of around ¥209.1 billion (2020-based). They are (in descending 2020 GDP): Rizhao, Haikou, Qinhuangdao, Zhoushan, Qinzhou, Yangjiang, Yingkou, Panjin, Beihai, Shanwei, Chaozhou, Jinzhou, Dandong, Huludao, Fangchenggang, Sanya and Danzhou. The cities relatively even out to south (10) and north (7). For these cities, the strife between development and conservation persists. This ongoing conflict emphasizes the need for targeted policies to foster both economic prosperity and environmental protection. In fact, many of these cities were approved for the Central Marine Ecological Protection and Restoration Fund since 2021 (Ma et al., 2022). This study delivers a data-driven argument in favor of sustained policy interventions for these cities.

4.2.2 Spatial-ecological and socioeconomic alignment

Multivariate results demonstrate that MPAs must be strategically planned and managed through the dual lens of spatial-ecological dynamics and socioeconomic realities. The study's log-link model ($A = e^{x\beta}$) reveals that MPA expansion exhibits percentage-based growth, where each contributing factor (e.g., GDP, infrastructure, green space) exerts proportional influence. This aligns with Liebig's Law of the Minimum: MPA growth is constrained by the scarcest resource, not cumulative inputs. Cities experiencing diminishing marginal returns in GDP or infrastructure development could reallocate efforts toward ecological restoration or technological development to unlock MPA scalability. For instance, upgrading wastewater systems or restoring coastal habitats may yield greater marginal gains in MPA effectiveness than further industrial or urban expansion. As China turns to high-quality instead of GDP-oriented development (Pan et al., 2021), this study offers an empirically grounded framework to operationalize this paradigm shift in marine conservation. Altogether, these call for social-ecological fit (Chen and Xu, 2024a; Chen and Xu, 2024c) and top-down adaptive governance in China's context, given its centralized governance structure.

4.2.3 Top-down adaptive governance

Judging from the city-level determinants of MPA establishment, marine adaptive governance works not only on the national level, but also operates locally. The implementation of adaptive governance in China's MPAs necessitates a dynamic interplay between institutional rigidity and implementation flexibility within a centralized framework and three essential phases (Figure 7). In Phase 1 (active conservation), drawing upon the tenets of the SES theory, the central government (governance system) (Gao et al., 2024) is empowered to legislate, thereby delineating the governance framework. Meanwhile, the establishment of a hierarchical decision-making apparatus grants local governments (resource units) the latitude to effectuate necessary adjustments. Provincial governments are authorized to designate "adaptive management areas" outside national protected areas based on ecological threshold indicators such as coral reef coverage and fishery stock levels, dynamically adjusting the intensity of development. This "top-down design, local innovation" model ensures the authority of the national ecological strategy while responding to regional differences through datadriven, dynamic management and control.

In Phase 2 (moderate conservation), the central government must incorporate ecological indicators, such as the MPA connectivity index and species recovery rate, into local performance assessments and establish direct links with fiscal transfer payments. Concurrently, innovative market instruments such as "blue carbon trading" should be developed to enable regions that have met ecological standards to convert the amount of carbon sequestered by mangroves into cross-regional trading quotas. This will encourage local governments to transition from passive compliance to active innovation and internalize the external costs of protected areas through economic leverage. The judicious integration of rigid constraints and flexible instruments is pivotal in operationalizing the principle of adaptive governance, persuading government departments to proactively arbitrate between the imperatives of conservation and development.

In Phase 3 (smart conservation), at the knowledge integration level, the establishment of a cross-scale information collaboration mechanism is imperative. By integrating multi-source data, such as satellite remote sensing, artificial intelligence monitoring, and community observations, and by opening hierarchical permissions to local governments, the deep integration of scientific models and traditional ecological knowledge can be promoted. The restructuring of the incentive system emerges as a pivotal institutional lever. These contribute to the enhancement of China's "adaptive governance" approach, a contribution that is set to be disseminated globally for the enhancement of MPA management.

4.3 Limitations and future research

The study can be improved in data quality, spatiotemporal heterogeneity, and methodological rigor. First, the granularity of the spatial-ecological data should be refined, ideally upgrading to satellite images, long-term hydrological monitoring or oceanographic databases. Second, comparative studies across different regions would be suitable for China's diverse coastlines. Finally, as the results indicate strong nonlinearity and complexity, future research should dive into complex system methods, such as hypergraph system dynamics to study the higher-order interactions of MPA establishment.

5 Conclusions

Adapting the SES approach, this article provides a comprehensive framework and analysis of the spatiotemporal distribution and determinants of China's MPAs. The influencing factors are categorized into spatial-ecological capacity (natural conditions and land-sea space) and socioeconomic capacity (policy factors and economy size), corresponding to the resourcegovernance systems and units in the SES framework. Using overdispersion-robust PPML regressions with high-dimensional fixed effects and a mathematically based threshold algorithm, results reveal the thresholds are ¥55 billion (1998-based, equal to ¥106.5 billion in 2020) for GDP to be conducive to MPA establishment. Built-up areas over 63 km² are antagonistic to MPA development. It also suggests that urban green space can be helpful to MPA establishment, and that maritime traffic is not necessarily impeditive. Illustrated by an N-shaped curve, the article supplements previous studies of the U-shaped environmental Kuznets curve in MPA establishment, providing new theoretical insights from a complex system perspective. Drawing on the results, practical implications were given for balance between conservation and development, spatial-ecological and socioeconomic alignment and top-down adaptive governance. Future studies and international research can apply nonlinear conclusions in this study to deepen MPA establishment mechanisms with higherorder interactions and complex dynamics.

Data availability statement

The number and area of China's MPAs are shared by Bohorquez et al. (2021) and can be found at https://datadryad. org/dataset/doi:10.5061/dryad.9zw3r22g2#. Precipitation and wind speed data from the Global Historical Climatology Network-hourly (GHCNh) at https://www.ncei.noaa.gov/metadata/geoportal/rest/ metadata/item/gov.noaa.ncdc:C01688/html#. China City Statistical Yearbooks can be found from CNKI (China National Knowledge Infrastructure) at https://data.cnki.net. The compiled dataset, replicable Stata codes and descriptive statistics are stored at https://github.com/3220001030/MPA.

Author contributions

MC: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ZX: Data curation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. YW: Data curation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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