

Conservation of Long-Distance Migratory Species and Coastal Zone Integrated Management Toolkit

APEC Oceans and Fisheries Working Group

October 2026



**Asia-Pacific
Economic Cooperation**



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Major Abbreviations and Acronyms

Abbreviation	Full Form
ABNJ	Areas Beyond National Jurisdiction
AHP	Analytic Hierarchy Process
AIS	Automatic Identification System
AI	Artificial Intelligence
ANN	Artificial Neural Network
APEC	Asia-Pacific Economic Cooperation
API	Application Programming Interface
AUC	Area Under the Curve
BBMM	Brownian Bridge Movement Model
BCE	Before Common Era
BIM	Building Information Modeling
BIOCLIM	Bioclimatic Prediction System
BRT	Boosted Regression Trees
CART	Classification and Regression Trees
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CI	Confidence Interval
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMAR	Eastern Tropical Pacific Marine Seascapes Ecological Corridor
CMS	Convention on the Conservation of Migratory Species of Wild Animals
CTA	Classification Tree Analysis
Conefor	Conefor Sensinode
CRS	Coordinate Reference System
CSR	Corporate Social Responsibility
CTI-CFF	Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security
CSV	Comma-Separated Values
DOM	Dynamic Ocean Management
dPC	Delta Probability of Connectivity
DSS	Decision Support System
EEA	Exclusive Economic Area
EcoCast	EcoCast (Platform Name)
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
ENMeval	ENMeval (R software package name)
ESG	Environmental, Social and Governance
FAO	Food and Agriculture Organization of the United Nations
FIO	First Institute of Oceanography
FIO-AOW	FIO Air-Sea-Wave Coupled Model
FIO-COM	First Institute of Oceanography – Coupled Ocean Model

Abbreviation	Full Form
FIO-CPS	FIO Climate Prediction System
GAM	Generalized Additive Model
GBM	Gradient Boosting Machine
Gdal / GDAL	Geospatial Data Abstraction Library
GEF	Global Environment Facility
GIS	Geographic Information System
GLM	Generalized Linear Model
GNSS	Global Navigation Satellite System
GUI	Graphical User Interface
HMM	Hidden Markov Model
IAC	Inter-American Convention for the Protection and Conservation of Sea Turtles
IATTC	Inter-American Tropical Tuna Commission
ICZM	Integrated Coastal Zone Management
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Programming
IMO	International Maritime Organization
IOSEA	Indian Ocean – South-East Asian Marine Turtle Memorandum of Understanding
ISC	International Scientific Committee for Tuna and Tuna-like Species in the North Pacific
ISO	International Organization for Standardization
IUCN	International Union for Conservation of Nature
IUU	Illegal, Unreported and Unregulated Fishing
IWC	International Whaling Commission
L1/L2	L1/L2 Norms
Lasso	Least Absolute Shrinkage and Selection Operator
LCP	Least Cost Path
LightGBM	Light Gradient Boosting Machine
LPT	Lagrangian Particle Tracking
MARS	Multivariate Adaptive Regression Splines
MaxEnt	Maximum Entropy Model
MPA	Marine Protected Area
MiCO	Migratory Connectivity in the Ocean
MSP	Marine Spatial Planning
MSC	Marine Stewardship Council
MSY	Maximum Sustainable Yield
NTT	East Nusa Tenggara Province
OCEANUS	Ocean and Climate Early Warning Universal System
OECM / OECMs	Other Effective Area-based Conservation Measure(s)
OFWG	Ocean and Fisheries Working Group
PAMS	Passive Acoustic Monitoring System
PC	Probability of Connectivity
PDF	Portable Document Format
PES	Payment for Ecosystem Services
PEW	The Pew Charitable Trusts
PGIS	Participatory Geographic Information System

Abbreviation	Full Form
PICES	North Pacific Marine Science Organization
PNAS	Proceedings of the National Academy of Sciences
QA/QC	Quality Assurance / Quality Control
RF	Random Forest
RFMOs	Regional Fisheries Management Organizations
ROC	Receiver Operating Characteristic
R&D	Research and Development
SIDS	Small Island Developing States
SAR	Search and Rescue
SDM	Species Distribution Model
SDMs	Species Distribution Models
SRE	Surface Range Envelope
SSS	Sum of Sensitivity and Specificity
SST	Sea Surface Temperature
STC	Sea Turtle Conservancy
TEK	Traditional Ecological Knowledge
TFI	Terrestrial Fish and Invertebrates
TNC	The Nature Conservancy
TRAFFIC	Wildlife Trade Monitoring Network
TSS	True Skill Statistic
TZCF	Transition Zone Chlorophyll Front
UAV	Unmanned Aerial Vehicle
UD	Utilization Distribution
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Programme
VIF	Variance Inflation Factor
VR	Virtual Reality
WCPFC	Western and Central Pacific Fisheries Commission
WGWAP	Western Gray Whale Advisory Panel
WWF	World Wide Fund for Nature
XGBoost	Extreme Gradient Boosting

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1. Introduction

Marine long-distance migratory species—including marine mammals, sea turtles, seabirds, and large pelagic fish - frequently traverse vast ocean expanses and rely on a mosaic of disparate ecosystems for survival. Consequently, their conservation requires robust cross-border cooperation. Multilateral platforms, such as the Asia-Pacific Economic Cooperation (APEC), play a pivotal role in this cooperative framework; hence, the sustainable management of these species remains a cornerstone of global biodiversity conservation.

In recent years, escalating anthropogenic pressures on marine environments have increasingly disrupted biological connectivity within marine ecosystems. This fragmentation has triggered population declines, accelerated biodiversity loss, and degraded critical ecosystem functions. To counter these trends, there is an urgent need for a scientifically rigorous, operationally viable conservation and management toolkit. By integrating modules such as species distribution modeling (SDM), ecological corridor identification, and connectivity evaluation, this toolkit provides both the theoretical foundation and practical guidance required to safeguard long-distance migratory species. Ultimately, this paper aims to construct a comprehensive management framework that bridges advanced ecological corridor mapping with cutting-edge marine spatial planning (MSP), thereby delivering vital decision support for marine protected area (MPA) management and the enhancement of regional ecological connectivity.

From the perspective of domestic macro-strategy and regional collaborative governance, the conservation of marine migratory species has transcended purely biological dimensions. It has evolved into a complex public policy challenge that intersects domestic marine ecological security, the sustainable development of the regional blue economy, and multilateral maritime geopolitics. Concurrently, climate-driven shifts in marine hydrological environments mean that traditional MPA models—relying on static geographical boundaries—are increasingly ill-equipped to accommodate the significant spatial and temporal shifts in migratory species' core habitats and migratory routes. This spatiotemporal mismatch between rigid administrative boundaries and dynamic ecological entities leads to inefficient allocations of public financial resources and enforcement efforts, while introducing

substantial decision-making risks into cross-sectoral marine spatial resource planning.

Consequently, transitioning from static, reactive preservation to data-driven, dynamic spatial management is imperative to modernizing marine governance systems and capacity. The proposed toolkit is designed to dismantle long-standing data barriers and institutional silos across sectors such as fisheries supervision, maritime transport, law enforcement, and environmental protection. By introducing a joint-likelihood data assimilation framework, the toolkit harmonizes disparate datasets—including opportunistic observation records, satellite telemetry trajectories, and environmental monitoring data—into a unified, transparent, and authoritative repository. This enables decision-makers to move beyond subjective experience or fragmented information when resolving conflicts over marine spatial use, allowing them instead to perform systematic marginal trade-offs grounded in a standardized ecological connectivity index.

To address these complex sociotechnical challenges, the toolkit transcends basic statistical algorithms, translating advanced ecological analytics into agile management instruments. For instance, to address the distinct threats migratory species face at different life-cycle stages, the toolkit integrates hidden Markov models (HMMs) for behavioral state decoding. From a policy implementation perspective, this capability allows management authorities to not only pinpoint species locations but also predict their specific behavioral states. This high-resolution spatiotemporal matching mechanism empowers governments to implement highly targeted, flexible, and temporary control measures - such as seasonal vessel speed restrictions, dynamic avoidance protocols, or short-term localized fishing closures - during critical residency, foraging, or high-speed transit periods. By confining rigid regulatory controls to precise windows of time and space, this behavior-driven management style mitigates biodiversity loss while minimizing economic disruption to vital blue economy sectors like maritime shipping and commercial fisheries, successfully balancing ecological preservation with economic development.

Within multilateral frameworks like APEC, which govern transboundary jurisdictions and Areas Beyond National Jurisdiction (ABNJ), the connectivity conservation of long-distance migratory species invariably intersects with intricate geopolitical interests. Historically, traditional conservation initiatives have struggled to secure legally binding commitments in transboundary negotiations due to a lack of

standardized, quantitative benefit-accounting methodologies. To resolve this, this toolkit innovatively incorporates omnidirectional connectivity analysis and ecological network resilience assessments to objectively quantify the weight and contribution of each participating economy's jurisdictional waters in sustaining the regional ecological network. These scientifically quantified metrics can serve as core parameters in multilateral negotiations, providing a solid scientific foundation for establishing transboundary ecological compensation mechanisms, optimizing regional public resource allocation, and delineating dynamic protection zones in the high seas.

Importantly, the life cycles of marine migratory species are profoundly intertwined with nearshore and coastal zones. These areas serve as essential spawning grounds, nurseries, and feeding hubs, yet they also bear the brunt of intensive human activities and environmental pressures. Integrating Integrated Coastal Zone Management (ICZM) into this toolkit is therefore of paramount value.

The Dual Value of Coastal Integration: Ecological Connectivity: Restoring and protecting coastal wetlands, mangroves, and seagrass beds directly safeguards the land-sea interface nodes of migratory corridors. Climate Resilience: These healthy coastal ecosystems function as natural infrastructure for disaster risk reduction—mitigating shoreline erosion, buffering storm surges, and enhancing the climate resilience of coastal communities. Through this comprehensive assessment framework, managers can holistically regulate land-based activities and marine spatial use, preserving habitat integrity for migratory species while bolstering coastal defense against natural disasters. In summary, this report delineates the underlying logic, technical architecture, and public policy translation pathways of an integrated toolkit for migratory species conservation and coastal zone management. Addressing a challenge that spans borders, sectors, and disciplines, this system leverages data assimilation, dynamic spatial control, and behavioral decoding as its core methodologies, while deeply embedding the principles of ICZM and disaster risk reduction. Subsequent chapters will detail the core modules — including species distribution modeling, ecological corridor identification, behavioral state decoding, and adaptive management framework—complemented by empirical case studies demonstrating how this toolset empowers governments and cross-economy organizations. In an era of escalating marine environmental uncertainty, this comprehensive spatial governance framework will guide decision-makers in crafting

marine ecological policies that are scientifically rigorous, operationally flexible, and economically inclusive.

2. Background

2.1 Ecological Connectivity and Spatial Planning in the Marine Environment

Marine Spatial Planning (MSP) serves as a vital governance framework that balances multi-sectoral interests with ecological objectives. Its primary purpose is to optimize the allocation of marine resources and foster the sustainable growth of the blue economy, while simultaneously safeguarding marine ecosystems. Within the MSP framework, ecological corridors are increasingly recognized as a critical mechanism for maintaining marine biological connectivity. These corridors establish an interconnected ecological network that links Marine Protected Areas (MPAs) with Other Effective Area-based Conservation Measures (OECMs), thereby ensuring the continuity of species migration, genetic exchange, and overarching ecological processes.

Traditionally, in the field of ecological protection, the ecological corridor identification methodology proposed by Popescu et al. provides a three-step systematic framework — namely habitat suitability modeling, resistance or connectivity modeling, and ecological network construction. Although this methodology was developed for terrestrial species (such as brown bears), its basic concepts, data standardization processing, weight parameterization, and analysis steps based on GIS technology are highly valuable for reference. At the same time, studies focusing on the marine environment have paid more attention to using the least-cost path method and circuit theory to quantify the migration and connectivity of marine organisms, which take into account multiple influencing factors such as seawater flow, seabed topography, primary productivity distribution, and temperature gradients.

However, with the continuous evolution of global climate change and the deepening of marine ecology theory, the static marine spatial planning model is facing unprecedented challenges.

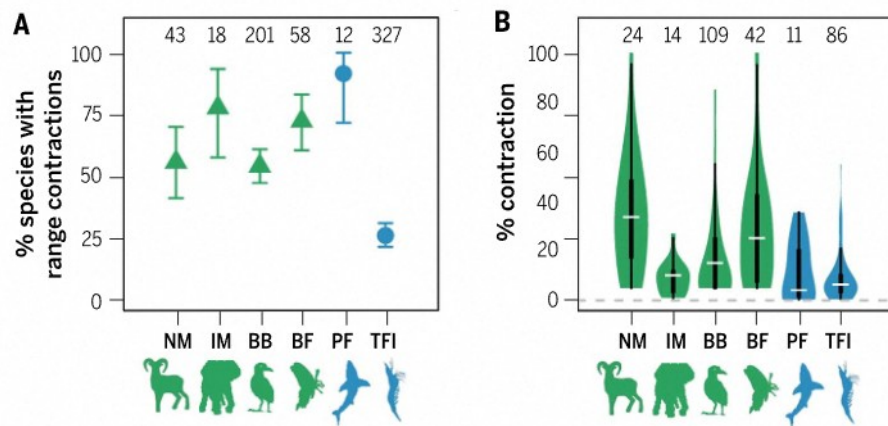


Figure 1: Distribution of geographical range contraction of animal species (McCauley et al., 2015)

As mentioned earlier, human activities are causing damage to marine biological connectivity, which is intuitively reflected in the sharp changes in species' geographic ranges. Figure 1 compares the geographic range contractions of some marine and terrestrial animals (McCauley et al., 2015). The data shows that similar to the historical contraction trends of terrestrial species (marked in green) such as North American mammals and British birds, marine species (marked in blue) have also faced severe spatial compression over the past few decades. In particular, global large pelagic fish (PF, representing long-distance migratory species) and North American marine fish and invertebrates (TFI) both show a high proportion of population range contraction. This significant contraction and change in habitats and activity ranges not only serve as a warning bell for biodiversity decline but also directly expose the fragility of the current protection system, highlighting that the core living spaces of long-distance migratory species are no longer fixed.

The habitats of long-distance migratory species exhibit strong dynamic drifting characteristics. They undergo spatiotemporal displacements with the formation and dissipation of mesoscale eddies, the movement of temperature fronts, and the occurrence of sea surface temperature anomalies. Once protected area boundaries are delineated based on fixed geographic coordinates, it becomes difficult to continuously encompass these core habitats that shift with hydrological conditions, ultimately leading to spatial mismatches between policy-protected areas and the actual distribution regions of species. To address this practical need, the concept of dynamic

ocean management has gradually moved to the forefront of connectivity research. This concept advocates using near-real-time marine environmental observation data and satellite remote sensing technology to conduct high-frequency tracking of potential activity hotspots of migratory species, thereby enabling ecological networks to be adaptively reshaped based on changes in environmental covariate inputs. This paradigm shift from static boundary delineation to dynamic tracking provides a theoretically feasible solution to address the deviation of protection routes under the background of climate change.

At the same time, compared with the planar attributes of terrestrial ecosystems, the marine environment presents strong three-dimensional structure and complex hydrodynamic characteristics, which requires the evaluation of ecological connectivity to break the limitations of traditional two-dimensional grids. For those long-distance migratory species with deep diving foraging habits, changes in the vertical structure of water bodies constitute physiological resistance that cannot be ignored. For example, fluctuations in the thermocline, variations in the thickness of the mixed layer, and spatial expansion of the deep-sea anoxic zone can all change the energy consumption of species on the vertical profile. Therefore, when evaluating the thrust and resistance caused by ocean currents, it is particularly critical to incorporate the physicochemical gradient between vertical water layers into the consideration framework. Based on this, the advanced connectivity theory introduces a three-dimensional evaluation perspective of anisotropy, which not only pays attention to the horizontal distance and environmental attributes on the sea level grid, but also integrates the ecological constraints of different water depths. By taking hydrological vertical stratification as the core parameter affecting migration energy consumption, the researchers constructed a three-dimensional resistance surface with dimensions, thus more realistically restoring the moving cost and physiological limitations of species in three-dimensional marine media.

In the vast pelagic environment, complex hydrodynamic processes govern the evolutionary trends of macro-connectivity patterns (Steele, 1991; Stommel, 1963). For long-distance migratory species with long lifecycles and complex life histories, their migration and aggregation often span multiple spatiotemporal scales to track dynamic oceanographic features (Block et al., 2011; Hazen et al., 2013). Therefore, connectivity assessment needs to go beyond the short-term perspective of single adult

migration and expand the temporal dimension to a systematic level encompassing multiple generations and the entire lifecycle. Coupling existing ecological connectivity frameworks with advanced analytical processing and habitat modeling technologies such as Lagrangian particle tracking models (Hobday et al., 2011; Hazen et al., 2012) can effectively simulate the passive diffusion processes of fertilized eggs and early larvae under the influence of complex ocean current systems. This nesting of passive drift networks with active adult-stage pathfinding networks enables the complete resolution of closed-loop ecological cycle pathways from breeding grounds to feeding grounds and then to overwintering grounds. In addition, real ocean current fields are often disturbed by large-scale climate variability. For example, the habitats of top predators in the Pacific Ocean have been predicted to shift under climate change (Hazen et al., 2012; Maxwell et al., 2013), such that originally stable migration corridors may face the risk of disruption in abnormal climate years. It is evident that abandoning traditional stationarity assumptions and incorporating the non-stationarity of spatial patterns driven by climate variability into model considerations has become a core aspect of the current upgrading of spatial planning theory, as ocean management needs to become as spatiotemporally fluid as the marine environment and marine resource users (Hyrenbach et al., 2000; Game et al.).

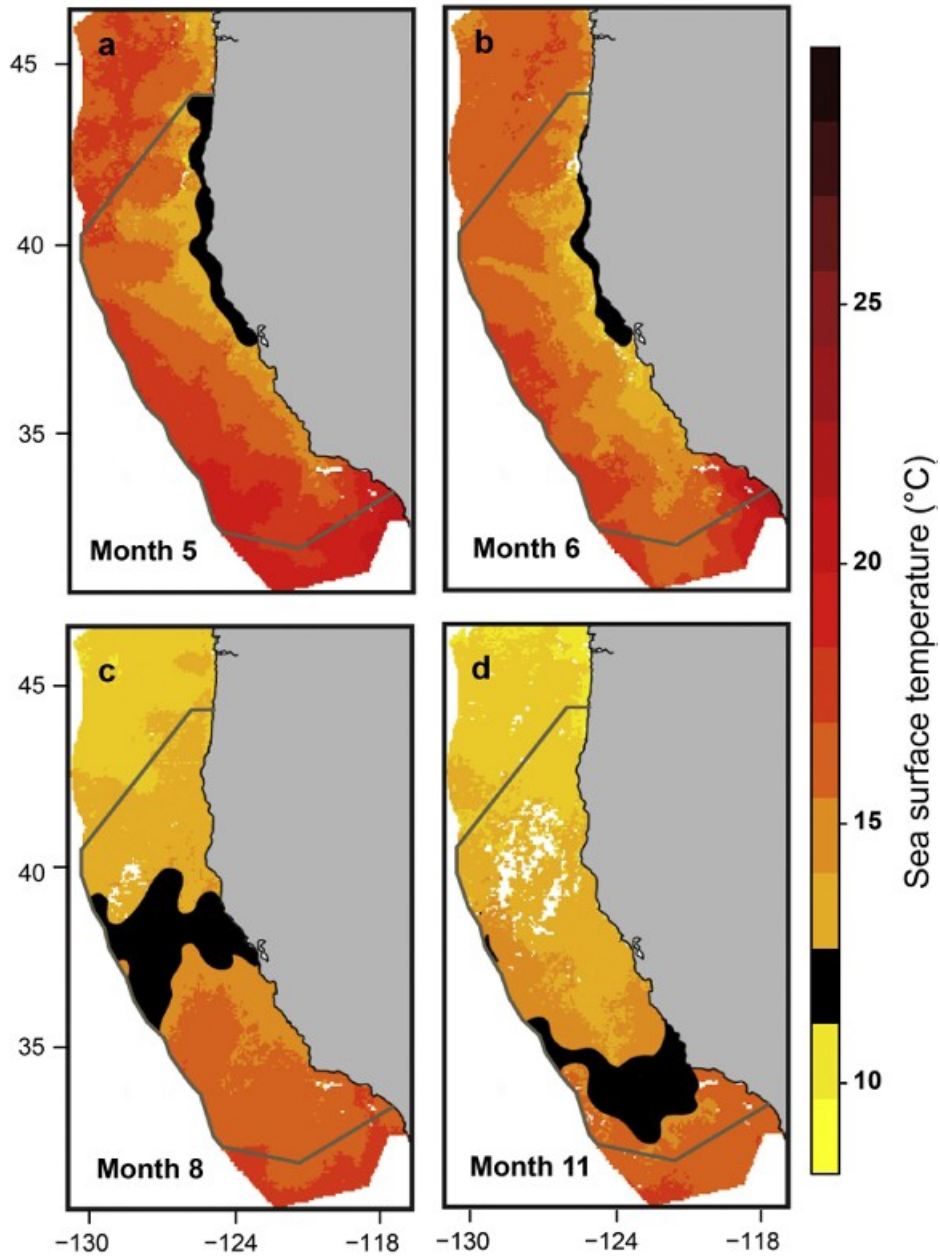


Figure 2: Dynamic Ocean Management Under Hypothetical Scenarios (Maxwell et al., 2015)

As shown in Figure 2, a large static management area (gray box) would need to encompass a vast region along the U.S. West Coast to cover all animal habitats dependent on specific temperatures (13 – 14°C; methods see Supplementary Materials) throughout a year (A – D). In contrast, dynamic management areas that follow potential animal habitats (black polygons) can manage smaller, movable areas on a monthly basis, thereby opening up more areas for human activities. Simulation results indicate that under this temperature-dependent habitat scenario, the dynamic

management approach requires 34.2% to 82.0% less area than static management (when calculated seasonally) or 62.1% to 86.1% less area (when calculated annually), thus better balancing ecological and economic objectives while providing protection equivalent to large-scale closures (Maxwell et al., 2015).

Furthermore, practical experience in designing transoceanic, macro-protection networks demonstrates that a single, isolated connective path possesses inherent vulnerability. Consequently, the overall resilience of ecological networks has emerged as a core criterion for evaluating the efficacy of planning schemes. As marine industrialization expands and ocean shipping density intensifies, localized disruptions to a single critical migratory corridor can severely impede or halt entire population movements. In view of this, advanced spatial planning theories emphasize the construction of redundancy in network topological structures. On the vast basin scale, multiple alternative connection paths need to be identified and maintained between source and sink areas. By introducing multiple paths and graph theory connectivity analysis, planners can identify main corridors with lower energy consumption while quantitatively evaluating and prioritizing the protection of secondary corridor networks that serve as alternatives when the main corridors are blocked. This structural optimization based on the thinking of network resilience and invulnerability can provide a broad survival buffer space for species when facing uncertain future environmental changes, and it is also a key defense line to ensure the long-term survival of long-distance migratory populations on a global scale.

2.2 Species Distribution Models and Ecological Corridor Identification Tools

In marine ecological protection, Species Distribution Models (SDMs) such as MaxEnt are widely used to predict the spatial distribution and environmental suitability of species habitats. These models integrate environmental variables (such as sea water temperature, salinity, sediment type, etc.) with species observation data to establish probability models, thereby predicting the potential distribution areas of species. This method provides input data support for subsequent ecological corridor identification and can clarify which areas are the core areas for population activities. At the same time, the identification of marine ecological corridors often relies on least-cost path analysis and models based on circuit theory. The least-cost path

method assigns specific resistance values to each cell in the marine environment and calculates the minimum cumulative resistance path between core areas to determine the most likely migration corridors; circuit theory, on the other hand, analogizes the marine environment to a circuit network and identifies multiple possible migration paths and their redundancy by analyzing current flow, thereby discovering bottleneck areas in the biological migration process.

Looking at the larger geographical scale, the vastness and depth of the marine environment invisibly brings a natural barrier to species observation. Compared with the increasingly mature infrared camera network or grid manual patrol in terrestrial ecosystem, ocean-going scientific expedition is not only expensive, but also faces severe constraints from harsh sea conditions at all times. Many long-distance migratory species spend most of their life cycles in deep seas far away from human sight, leaving researchers often with only fragmented records from accidental strandings, sporadic sightings, or commercial fishing. The scarcity of data, which is determined by the natural attributes of the ocean, constitutes an urgent background in the early species connectivity research.

Faced with the realistic dilemma of the widespread lack of high-precision satellite tracking trajectories, how to deduce dynamic transoceanic migration routes relying solely on discrete static occurrence points has become a core proposition that planners urgently need to solve. In this context, the combined strategy of Species Distribution Models (SDMs) and Least Cost Path (LCP) has demonstrated irreplaceable application potential. In specific operations, researchers first use the habitat suitability maps output by SDMs and invert them into environmental resistance surfaces through mathematical transformation—meaning that the lower the suitability of a sea area, the greater the physiological cost and environmental resistance for species to traverse. Subsequently, using known breeding grounds or feeding grounds from historical records as discrete sources and sinks, the LCP algorithm can automatically calculate a theoretical pathway with relatively low cumulative energy consumption within these fluctuating marine grids. This strategy cleverly bypasses the reliance on continuous trajectory data, and only needs to rely on basic observation points to outline the underlying logical framework of species migration at the basin scale, thus providing a valuable initial baseline for conservation planning in data-poor marine areas.

Although the basic SDM combined with LCP strategy has played a pivotal role in

the era of data scarcity, with the continuous deepening of spatial ecology, single statistical algorithms have gradually exposed the shortcoming of being unable to fully capture complex nonlinear relationships when dealing with highly dynamic marine environments. Spatial sampling bias is prevalent in traditional marine fisheries surveys and public databases, and data on long-distance migratory species often only include presence records without clear absence records, which makes basic models prone to generating spurious environmental correlations. Once relying on these biased data for static resistance surface demarcation, it is easy to cause the predicted corridors to deviate from the real ecological needs of species.

Faced with these historical limitations, the Ensemble Modeling framework gradually stands out and becomes the mainstream paradigm to improve the robustness of spatial prediction. This new paradigm abandons the idea of insisting on finding a single optimal model, and instead uses rigorous weighted average or coefficient of variation mechanism to scientifically aggregate the prediction results of multiple machine learning algorithms. In practice, researchers usually rely on cross-validation strategies (such as k-fold cross-validation) and specific evaluation indicators (such as TSS or ROC threshold) to screen out underperforming underlying models. This ensemble operation effectively weakens the fluctuation interference of single prediction value, and can also synchronously generate spatial uncertainty distribution map while outputting habitat suitability map. In order to strip out the false correlation more accurately, the advanced modeling strategy also introduces point process model and spatial autocorrelation penalty function, so as to restore the true physiological and ecological preferences of species on environmental gradients as much as possible. The purpose of this combined toolbox is to help users manage dozens of underlying algorithms to cope with complex ocean flow fields. The following table systematically explains the core specific models contained in the current integration toolbox and their specific ecological applicable scenarios:

Table 1: Species Distribution Model Type Matrix

MAJOR ALGORITHM SCHOOL CATEGORIES	CORE MODEL NAME (ENGLISH ABBREVIATI ON)	CORE MATHEMATICAL LOGIC OF THE ALGORITHM	CORE APPLICABLE ECOLOGICAL SCENARIOS FOR MARINE MIGRATORY SPECIES

PRESENCE POINT SPECIALIZATION ON GENRE (FOR MISSING DATA)	Maximum Entropy Model (MAXENT)	Based on the maximum Entropy principle, infer the most uniform probability distribution model in the target space under the constraint conditions of known environmental variables.	Suitable for the assessment of deep-sea species lacking "explicit Absence data". When only sporadic occurrence points of species are obtained (such as accidental sightings of whale sharks), this model shows extremely high algorithmic robustness.
	Surface Range Envelope (SRE / BIOCLIM)	Relying on the envelope algorithm of multi-dimensional environmental space, define the extreme value boundaries of environmental parameters corresponding to species occurrence records.	Suitable for delineating the absolute "physiological tolerance red line" of species. Used to quickly assess the physiological limit boundaries of endangered sea turtles and other species to extremely low temperatures or hypoxic water masses, and efficiently exclude unsuitable sea areas.
CLASSICAL REGRESSION AND REGULARIZATION SCHOOLS (GRADIENT EXTRACTION AND DIMENSIONAL ITY REDUCTION)	Generalized Linear Model (GLM)	Establish linear or polynomial regression equations between species occurrence probability and environmental variables through specific link functions.	Suitable for exploring the linear evolution law of macro basic environmental gradients. Verify the basic response trend of species habitat suitability with decreasing latitude or increasing sea surface temperature (SST) in large-scale space.
	Generalized Additive Model (GAM)	Use Smoothing Splines instead of strict linear assumptions to fit nonlinear responses between variables.	Suitable for depicting complex nonlinear "ecological niche transition zones". For example, describe the unimodal preference curve of cetaceans

			for chlorophyll a concentration, and explain the migration and aggregation mechanism in medium productivity sea areas.
	Multivariate Adaptive Regression Splines (MARS)	Adopt non-parametric regression method to identify variable interactions and response threshold by constructing piecewise linear basis functions.	Suitable for identifying "environmental mutation thresholds" in ecosystems. Good at analyzing the spatial intersection boundaries of ocean thermoclines or haloclines, and locking hidden hydrological fronts relied on by species such as tuna.
	Penalized Regression (Lasso / Ridge / Elastic Net)	Introduce regularization penalty terms (L1 / L2 norm) to shrink regression coefficients, realizing automatic feature selection and dimensionality reduction	Suitable for solving the "multicollinearity" problem of marine environmental data. When inputting dozens of highly coupled satellite remote sensing parameters, automatically strip redundant information and lock core ecological driving factors.
TREE MODELS AND ENSEMBLE LEARNING (COPING WITH NONLINEAR COMPLEX SYSTEMS)	Classification and Regression Trees (CART / CTA)	Use binary recursive partitioning technology to divide the environmental feature space into homogeneous subsets according to the principle of maximizing information gain.	Suitable for deriving spatial management rules based on clear environmental thresholds. The output decision tree branches can be directly converted into administrative boundaries (example: sea areas with sea temperature >18 °C and water depth < 200m are

			designated as speed-limited zones).
	Random Forest (RF)	Use the Bagging method to build multiple independent decision trees, and significantly reduce model variance through random subsets of features.	Suitable for processing rough observation datasets with significant noise. Ocean observations are often accompanied by position errors, and this algorithm has strong anti-overfitting ability, effectively avoiding the interference of abnormal noise points on global prediction.
	Gradient Boosting Machine (GBM / BRT)	Combines gradient descent optimization with decision trees, iteratively fitting residuals using a forward distribution algorithm to gradually improve prediction accuracy.	It is good at capturing "multivariable interaction effects" in complex ocean flow fields. Isolated hydrological features do not necessarily constitute obstacles, but specific combinations can form physical blocks, and this model can keenly capture this nonlinear interweaving.
	Extreme Gradient Boosting (XGBoost / LightGBM)	An efficient gradient boosting framework that optimizes the objective function based on Taylor second-order expansion and introduces structural regularization terms.	Suitable for "real-time assimilation of massive spatiotemporal big data" at the ocean basin scale. When processing hundreds of millions of grid pixels covering the entire Pacific Ocean with missing values, it provides strong underlying concurrent computing power support.

For the few long-distance migratory species for which continuous observation

data can be obtained, the core modeling challenge focuses on how to break through the algorithmic barrier between static occurrence point data and dynamic trajectory data. To this end, the development of integrated species distribution models has spawned a groundbreaking joint likelihood framework. This advanced method integrates traditional static observation data with valuable satellite beacon tracking trajectory data and acoustic telemetry data. By constructing a joint probability distribution of different data structures at the bottom of the model, researchers can closely couple the individual's true active migration trajectory with the environment-based distribution probability. As a result, the extrapolation ability of the model in unsampled sea areas has been significantly improved, and the predicted ecological corridors have evolved from the previous static suitability connections to dynamic utilization probability surfaces that can reflect the seasonal migration rhythms of species.

While introducing trajectory data, the feeding and migration of long-distance migratory species are often accompanied by complex behavioral state transitions. For example, in wintering or baiting fields, species typically exhibit resident search behavior with large steering angles and short steps; While in the transoceanic region, it changes to the directional movement with small steering angle and long step length. Based on this, the advanced modeling strategy introduces time series analysis tools such as hidden Markov model. First, the behavior state of trajectory data is decoded, and then independent distribution prediction models are constructed for different behavior states. Considering that the migration of top predators tends to lag behind the burst of primary productivity, the inclusion of environmental covariates with time lag effects into the model enables more reproduction of the lag-tracking dynamics of species following ocean fronts. These high-precision and multi-dimensional model outputs virtually provide an input basis that is highly consistent with time and space scales for the subsequent scientific identification of ecological corridors.

From the perspective of government macro-governance and policy formulation, species distribution models and ecological corridor identification tools are no longer confined to the scope of basic academic research but have profoundly transformed into the core digital foundation for domestic marine spatial planning and optimal allocation of public resources. In modern marine administrative management, decision-makers often face sharp conflicts between development and protection. At

such times, these increasingly sophisticated network technology tools have become key instruments for resolving conflicts and achieving scientific and quantitative decision-making.

By combining the combined model framework with the generation of spatial uncertainty distribution maps, management departments have obtained an intuitive evaluation benchmark for financial fund security and investment risk control in the field of marine protection. Traditional marine protected area demarcation often relies on experts' qualitative opinions, which can easily lead to over-protection in marginal sea areas where suitability is overestimated, thereby causing serious waste of public administrative resources. The new combined prediction model, by integrating multiple algorithms, provides management departments with a confirmation list of areas that need protection, along with a detailed decision-making risk hotspot map. For sea areas with high spatial uncertainty, the government can strategically postpone the establishment of rigid permanent protected areas and instead deploy monitoring buoys at a lower cost for data verification; for core areas with low uncertainty and confirmed suitability, the government can deploy law enforcement forces and actively guide economy-wide climate and biodiversity funds (such as GEF) to prioritize allocation to these areas. This quantitative risk management based on error boundaries has significantly improved the input-output ratio of public finance in the blue ecological field.

Postponing this management logic and the integration of multi-source heterogeneous data by the joint likelihood framework provide a technical breaking plan for breaking cross-departmental governance barriers from the height of administrative system reform. For a long time, many maritime-related departments, such as maritime rights protection, fishery law enforcement, shipping transportation and ecological environment, have mastered some data, forming a deep-rooted data island. The joint likelihood framework opens up multi-dimensional data such as static environment survey, commercial fishery fishing log and scientific research satellite telemetry at the bottom of the algorithm, thus promoting a unified digital government platform across departmental barriers at the policy level. When all maritime-related management agencies conduct administrative examination and approval based on the same set of debiased and corrected dynamic probability surfaces with credibility, the policy conflicts and management blind spots caused by the mutual non-recognition of

data between departments will be easily solved, and the synergy of comprehensive maritime space management will be truly realized.

Further expanded management methods and introduced hidden Markov model to decode behavioral states, which opened up a brand-new policy design space for the government to implement flexible and refined spatial control. The traditional marine management mode is accustomed to adopting a one-size-fits-all closure and control strategy. As long as a certain sea area belongs to the distribution area of migratory species, all human economic activities are completely banned. This extensive management is easy to lead to conflicts between coastal communities and maritime-related enterprises. Thanks to behavioral decoding technology, management can now know precisely whether species are residing in particular waters for food or are rapidly transiting. Based on these quantitative results, the government can tailor seasonal administrative measures: impose strict spatiotemporal fishing bans and route bans in the wintering and spawning residences identified by the model; In directional migration corridors that are judged to be fast-passing, only phased vessel speed restriction orders or acoustic detection equipment control orders are required, and there is no need to completely deprive the sea area of shipping or light fishing functions. This kind of management based on behavior policy makes the ecological protection and the elastic development of blue economic activities achieve Pareto optimum, which marks an important step towards scientific and humanized modern marine administration.

After obtaining high-precision suitability distribution and behavioral state prior information, deducing the connectivity corridors between core habitats becomes the next core link in spatial planning. Unlike the static grids of terrestrial landscapes, the marine environment is fluid, three-dimensional, and highly directional. Therefore, modern corridor identification and connectivity deduction are no longer limited to simple two-point connections but deeply integrate graph theory, physical circuit theory, fluid dynamics, and movement ecology statistical algorithms. The following table systematically disassembles the core ecological corridor identification algorithm system integrated within the current toolbox and its specific marine application scenarios:

Table 2: Ecological Corridor Identification Algorithm Matrix

ALGORITHM TECHNICAL SCHOOL	CORE ALGORITHM NAME (AND REPRESENTAT IVE TOOLS)	CORE MATHEMATICAL AND SPATIAL LOGIC OF THE ALGORITHM	CORE APPLICABLE ECOLOGICAL SCENARIOS FOR MARINE MIGRATORY SPECIES
STATIC GRAPH THEORY AND RESISTANCE PATH DEDUCTION	Minimum Cumulative Resistance Algorithm (Dijkstra / LCP) (Built into Linkage Mapper)	Based on graph theory for shortest path optimization assuming that species have global environmental perception, and deducing the deterministic single spatial trajectory with the lowest total travel cost on the cumulative cost surface.	It is suitable for defining the "theoretically optimal connected principal axis" in large-scale space. Used to connect discrete marine protected areas (MPAs) and delineate baseline channel boundaries based on minimum energy consumption in the early stages of data scarcity.
	Anisotropic Cost Model (Core Package: gdistance)	Breaking the resistance symmetry assumption, integrating fluid vectors (flow velocity and direction) into the cost distance matrix, and endowing spatial pixels with direction- dependent transfer penalty weights.	Suitable for simulating "asymmetric migration dynamics" driven by strong boundary currents. It truly restores the real physiological energy consumption of species such as sea turtles when accelerating with ocean currents or being blocked by warm currents, making the deduced trajectory conform to fluid dynamics laws.
PHYSICAL CIRCUIT THEORY AND OMNIDIRECT IONAL PROBABILIT Y ANALYSIS	Circuit Theory Based on Random Walk (Core Tool: Circuitscape)	Isomorphically transform the landscape resistance surface into a physical conductive network, and calculate the effective resistance	Suitable for Quantifying connectivity redundancy and identifying "Spatial Ecological Bottlenecks (Pinch points)". Target those vulnerable Throat waters that are constrained

		between nodes based on the random walk model using current density to characterize the probability of multi-path diffusion of species.	by high resistance in the surrounding area, leading to a high convergence of migration probability.
	Moving Window Circuitry (Core Tool: Omniscap)	Break through the limitation of preset source-sink nodes, use the moving window algorithm to perform global pixel-level iterative calculation on the continuous resistance surface, and evaluate the omnidirectional connectivity potential.	Suitable for conducting "global connectivity blind test" in high seas areas lacking prior data. Provide an objective connectivity spatial framework independent of prior assumptions for the site selection of high seas protected area networks.
TELEMETRY TIME SERIES AND BEHAVIOR DECODING	Hidden Markov Model (HMM / Move HMM) (Time Series Analysis)	Use bivariate time series (such as movement step length and turning angle) to fit hidden discrete state sequences, and statistically decode the instantaneous behavior patterns of species from continuous trajectories.	Suitable for "separating resident foraging and directional transit states" from telemetry data. Provide high-frequency behavioral evidence for the implementation of differentiated spatial management (such as fishing ban only in resident areas and speed limit in transit areas).
	Brownian Bridge Movement Model (BBMM) (Probability Space Estimation)	Based on the principle of conditional random walk, use the time and space coordinates of known trajectory endpoints to estimate the three-dimensional	Suitable for repairing "telemetry signal loss and trajectory fault" caused by deep diving. Intelligently fill the blind areas of marine species activities and generate a

		space utilization probability distribution (UD) of species during the observation interval.	time-continuous dynamic migration corridor probability surface.
	Step Selection Function (SSF / iSSF) (Behavior-Environment Interaction Analysis)	Combine conditional logistic regression to infer the fine-scale habitat preferences of individuals by comparing the differences in environmental covariates. Between actual observed step lengths and randomly controlled step lengths generated according to specific distributions.	Suitable for quantitative analysis of "active avoidance or trend behavior" of species to dynamic environmental gradients. Efficiently strip and quantify the stealth displacement effects of human ship noise or fishery operations on migratory trajectories.
FLUID DYNAMICS AND COMPLEX NETWORK TOPOLOGY	Lagrangian Particle Tracking (LPT / Ocean Parcels) (Physical Ocean Coupling Model)	Couple with high-resolution three-dimensional ocean circulation model, drive the Lagrangian motion equation of virtual biological particles with Eulerian flow field, and simulate the passive advection and diffusion process of plankton communities.	Suitable for simulating "planktonic larval diffusion distribution and intergenerational network connectivity". Reveal transboundary passive drift networks, and establish a hydrodynamic spatial link between upstream breeding grounds and downstream feeding areas.
	Network Betweenness Centrality (Built into Conefor / Graphab)	Using graph theory algorithms, calculate the frequency of specific nodes or edges in the set of shortest paths between all node	Suitable for identifying "absolute backbone stepping stones" in transoceanic networks. Recognize core seamounts or island reef groups that

		pairs in the network and quantify their intermediary control in global topological flow.	play a decisive supporting role in maintaining multiple important migration routes.
	Network Percolation and Invulnerability Simulation (Percolation Theory) (System Collapse Simulation)	Based on complex network phase transition theory, simulate the phase-level cascading disintegration process of the macroscopic cluster structure of the connected system by directionally or randomly removing network edges or nodes.	Suitable for conducting "network connectivity stress tests" in the face of extreme weather or cumulative disturbances. The critical damage threshold of the cliff-like structural collapse of the ocean ecological network is quantitatively calculated.

When ecological corridors interweave from a single path into a complex network, the topological assessment of their overall resilience becomes a core component of connectivity research. Traditional deterministic path methods struggle to fully reflect the trial-and-error processes and diffusion probabilities of species in complex environments. To address this, graph theory analysis from physical circuit theory and systems science is introduced to reconstruct the mathematical logic of marine connectivity assessment. For example, Circuitscape simulates marine space as a conductive network to quantify network redundancy and ecological bottlenecks (Pinch points) of multiple alternative paths; the omnidirectional connectivity tool Omniscape enables global algorithmic deduction without clear source and sink inputs; Conefor focuses on quantifying the node contribution of specific sea areas as ocean stepping stones; and Graphab, which incorporates percolation theory, provides algorithmic support for evaluating the cascading disintegration effects of ecological networks after local disturbances.

To systematically present the underlying framework of connectivity network evaluation, the following table categorizes and analyzes the core algorithm matrix for network topology analysis and invulnerability assessment, along with their applicable

marine scenarios:

Table 3: Global Mainstream Ecological Network Topology Analysis Tools

ALGORITHM TECHNICAL SCHOOL	CORE ALGORITHM NAME (AND REPRESENTAT IVE TOOLS)	CORE MATHEMATICAL AND SPATIAL LOGIC OF THE ALGORITHM	CORE APPLICABLE ECOLOGICAL SCENARIOS FOR MARINE MIGRATORY SPECIES
Physical Circuitry and Omnidirectional Probability Analysis	Circuit Theory Based on Random Walk (Core Tool: Circuitscape)	Isomorphically maps the landscape resistance surface to a conductive network, and calculates the effective resistance between nodes based on the random walk model, using current density to characterize the multi-path diffusion probability of species.	Suitable for quantifying connectivity redundancy and identifying spatial ecological bottlenecks (Pinch points). Identify throat waters with high resistance constraints in the surrounding area, leading to a high convergence of migration probability.
	Moving Window Circuitry (Core Tool: Omniscape)	Uses a moving window algorithm to perform global pixel-level iterative calculations on continuous resistance surfaces to evaluate omnidirectional connectivity potential without clear source and sink inputs.	Suitable for measuring global connectivity in areas with scarce prior data such as the high seas. Provides an objective connectivity spatial framework for the site selection of protected area networks.
Spatial Graph Theory and Node Importance Quantification	Probability Connectivity Index (PC) and Delta Probability of Connectivity (dPC)	Combining graph theory with habitat patch attributes, it calculates the attenuation impact on the overall network	Suitable for quantitatively identifying backbone stepping stones in marine networks. Evaluates seamount or archipelago systems that are small in

	(Core tool: Conefor)	connectivity after a single patch is removed, and decomposes it into internal, flux, and connectivity elements.	area but play a supporting role in maintaining multiple migration routes.
	Network Betweenness Centrality (Graph theory-based algorithm)	Calculates the frequency of specific nodes or edges appearing in the set of shortest paths between all node pairs in the network, quantifying their intermediary control in global topological flow.	Suitable for delineating core connectivity hubs in transoceanic networks. Identifies strategic sea areas where multiple independent migration corridors converge, providing an objective weight ranking for spatial use control.
Complex Network Theory and Invulnerability Simulation	Network Modularity Analysis (Core tools: Graphab, etc.)	Using graph aggregation algorithms to identify patch clusters (modules) with dense internal connections and sparse external connections within the network, revealing the hierarchical structure of ecological networks.	Suitable for evaluating the internal connectivity quality of marine protected area networks. Identifies local functional subnetworks with frequent population exchanges, guiding the division of regional collaborative conservation policies.
	Network Percolation and Invulnerability Simulation (Percolation Theory) (System Evolution Analysis)	Based on complex network phase transition theory, by setting conditions to remove network edges or nodes, simulate the cascading disintegration process of the macroscopic cluster structure of the connected system.	Suitable for conducting network resilience tests in the face of extreme climates or cumulative human disturbances. Measures the critical damage threshold that triggers structural collapse of oceanic ecological networks.

From the perspective of addressing future challenges, the combination of circuit theory and environmental covariates with time lag effects endows the government with strategic resilience for forward-looking governance and response to extreme climate shocks. In the migration networks of long-distance marine migratory species, there are numerous connectivity bottleneck zones formed by the intersection of underwater topography and complex ocean currents. Circuit theory can accurately identify these ecological bottlenecks that, once damaged, would trigger the collapse of the entire population's connectivity. In the administrative approval and environmental impact assessment processes of domestic marine-related projects, the identification results of these bottleneck zones will become insurmountable ecological red lines. At the same time, incorporating the lag effects of dynamic environments such as ocean fronts into the model means that the government's ecological early warning system can issue signals weeks or even months in advance of the actual arrival of species. This paradigm shift from post-remedial law enforcement to pre-judgment scheduling enables management departments at all levels to calmly deploy emergency intervention plans such as maritime escorts and temporary route adjustments before marine heatwaves or abnormal circulations occur, building a resilient digital defense line for safeguarding domestic marine biological security in the future where extreme climates are normalized.

2.3 The Importance of Multilateral Cooperation and Regional Organizations

The life cycles of long-distance migratory marine species typically span the exclusive economic zones (EEZs) of multiple economies as well as the high seas, making it often difficult for a single economy's closed management to cover their complete ecological needs. To trace the objective roots of this multilateral coordination requirement, it is inevitable to deeply examine the historical evolution and inherent limitations of the modern economy-wide marine legal framework. In accordance with the jurisdictional principles established by the 1982 United Nations Convention on the Law of the Sea (UNCLOS), the vast ocean is divided into different legal segments such as territorial seas, exclusive economic zones, and high seas. This static management model with a strong land-rights mindset reveals deep structural contradictions when dealing with long-distance migratory species that constantly

move following temperature fronts and ocean current systems: the integrity of ecological entities is fragmented under the administrative barriers of sovereign jurisdiction.

From the realistic dimension of the game between geo-economy and resources, the economic cost of protecting long-distance migratory species and the ecological benefits gained often show obvious spatial mismatch and asymmetry among different economies. In the absence of multilateral coordination mechanisms, unilateral conservation actions are prone to the governance quagmire of the commons tragedy—the conservation gains sustained by upstream economies may be harvested directly by high-intensity commercial fishing on the high seas or downstream economies. After sorting out this objective conflict of interest, the core demand of promoting multilateral cooperation naturally extends to the establishment of transparent and fair rules of ecological compensation and resource allocation. Pluralistic platforms such as Regional Fisheries Management Organizations (RFMOs) and the Asia-Pacific Economic Cooperation (APEC) are trying to build bridges for multilateral dialogue.

In this process, the involvement of scientific quantification tools is particularly crucial, as they can transform subjective political demands into data-based allocation quotas. To bridge geo-economic divides, the widely used systematic conservation planning software Marxan (and its advanced version Marxan with Zones) has become a quantitative intermediary for multilateral mediation. It utilizes simulated annealing algorithms for spatial multi-objective optimization, providing Pareto-optimal spatial solutions with relatively minimized economic opportunity costs (such as transboundary fishery losses and shipping detours) for cross-border negotiations, on the premise that the ecological connectivity of migratory networks meets the basic threshold, thereby injecting data-supported regional coordination plans into unilateral conservation actions.

Focusing on specific space protection technology tools, multilateral cooperation mechanism is a prerequisite for the effective operation of macro-ecological connectivity algorithm. High-quality marine data is expensive and involves domestic sensitive information. Data barriers prevailing among economies constitute the technical bottleneck of transboundary ecological network identification. If there is no regional mechanism to break these data silos, even the advanced statistical algorithms will output incomplete maps due to data faults. Relying on multilateral mechanisms to

establish standardized mutual recognition agreements for data has become the key to activating the digital engine. In the practice of transboundary data fusion, MiCO (Migratory Connectivity in the Ocean) platform has demonstrated remarkable mechanism efficiency. By building multilateral data alliance, it transforms the scattered satellite tracking scientific research data in the world into transboundary connected node knowledge with spatial explicit characteristics. At the same time, Global Fishing Watch (*), a transboundary human activity monitoring platform, normalized the external pressure layer of human ocean Fishing and shipping density by analyzing the AIS data of massive ships, and injected quantitative human disturbance parameters into cross-border joint early warning.

When these underlying spatiotemporal data and ecological deduction results are placed on the transboundary negotiation table, reaching a consensus becomes the challenge of the final link. The web-based collaborative marine spatial planning digital sandbox SeaSketch fills this application gap. It allows government officials, environmental organizations, and fisheries representatives from multiple economies to conduct scenario simulations on the same digital base map. The system instantly calculates and feeds back the comprehensive impact of planning boundaries on connectivity networks and the fisheries economy of all parties, effectively reducing communication costs caused by information asymmetry. In addition, in the face of transient ecological bottlenecks that shift with environmental fluctuations, the dynamic ocean management (DOM) platform EcoCast demonstrates the practical value of transboundary agile governance. By assimilating physical oceanographic data and predicting the spatiotemporal distribution overlap rate between migratory species and commercial fishery target species, EcoCast assists management authorities in flexibly adjusting control boundaries on a daily or weekly time step to seek a quantitative balance between ecological conservation and marine economy.

The above decision support platforms and quantitative output results ultimately need to be transformed into specific public policy implementation plans relying on administrative and legal frameworks. In the practice of global ocean governance, governments and regional economy-wide organizations have explored various collaborative policy tools aimed at crossing jurisdictional boundaries. To systematically sort out the effectiveness of these policy tools, the following table objectively classifies and deconstructs the current mainstream transboundary joint

protection policy paradigms, core implementation mechanisms, and their ecological application scenarios in migratory species protection:

Table 4: Matrix of Global Mainstream Marine Cross-Border Policies and Joint Protection Practice Scenarios

POLICY GOVERNANCE SCHOOLS	TYPICAL ECONOMY-WIDE / REGIONAL PRACTICE CASES	CORE LOGIC AND POLICY IMPLEMENTATION MECHANISMS	ECOLOGICAL APPLICATION SCENARIOS FOR LONG-DISTANCE MIGRATORY SPECIES
Dynamic Spatiotemporal Restriction	Dynamic Fishing Restricted Areas in California, USA / Dynamic Navigation Avoidance Areas in the Bay of Fundy, Canada	According to the high-frequency hydrological characteristics and species observation and early warning, the speed limit or fishing ban instruction with a specific time window is triggered.	Reduce merchant ship collision rates and non-target species bycatch rates. Applicable to sea areas with significant migratory characteristics of thermodynamic fronts, which can reduce the economic opportunity cost caused by normalized rigid control.
Transboundary MPA Networks	Eastern Tropical Pacific Marine Seascapes Ecological Corridor (CMAR, covering Costa Rica and other four economies)	Through multilateral treaties, the isolated protected areas in their respective exclusive economic zones are spatially connected and jointly planned through core migratory corridors.	Ensure seamless migration of long-distance migratory species. Applicable to geopolitical plates that are geographically adjacent, located in the same major ocean current system, and have a good foundation for multilateral diplomacy.
Ecosystem-Based Fisheries Constraints	Western and Central Pacific Fisheries Commission (WCPFC) Cross-Species Quotas and Fishing Gear Regulations	Break through the limit of single species Maximum Sustainable Yield (MSY), implement bycatch mitigation devices (such as circle hooks)	Coordinate economic catches and food web resilience. Applicable to pelagic fishing areas that are highly dependent on commercial fishing and have a high spatial overlap

		and introduce food web cascade quota assessment.	rate between target catches and endangered species.
Market-Based Tools & Payment for Ecosystem Services (PES)	Belize Blue Bonds and Debt-for-Nature Swaps	Economy-wide financial institutions release fiscal space through debt restructuring, and provide targeted funding to coastal economies to implement marine spatial planning and ecological corridor maintenance.	Resolve the cross-border imbalance between conservation costs and economic benefits in developing economies. Applicable to regional node economies with good ecological bases but facing high public financial pressures.
Multilateral Soft Law Agreements	Economy-wide Maritime Organization (IMO) Particularly Sensitive Sea Areas (PSSA) and APEC Joint Concern Areas	Relying on economy-wide organizations to issue non-mandatory avoidance guidelines or deceleration initiatives, and promote de facto compliance through compliance review and industry reputation mechanisms.	Fill the legal vacuum in the high seas and Areas Beyond National Jurisdiction (ABNJ). Applicable to the protection of fragile habitats where the cost of reaching legally binding treaties is too high and rapid response is urgently needed.

By deeply integrating the above objective computational ecology tools, graph theory network analysis libraries, and social-ecological game platforms, supplemented by practical policy tools for transboundary joint protection, the protection management toolkit constructed in this paper will have the potential to be effectively implemented under multilateral frameworks such as APEC. This not only provides a quantitative benchmark for large-scale marine ecological governance, but also establishes a practical coordinate that unifies science and jurisprudence for the paradigm evolution of transboundary marine spatial planning in the future.

2.4 Improvement of Integrated Coastal Zone

Management Informationization for Protection and Management

Following the scientific paradigm of the aforementioned transboundary spatial planning, with the deep integration of information technology and marine science, Integrated Coastal Zone Management (ICZM) is undergoing a profound transformation from the traditional extensive model to a digital and intelligent model. Informationization is not only an innovation in technical means but also an elevation of the concept of coastal zone protection and management. The core value of the informationization toolkit lies in the dimensionality reduction and encapsulation of profound ecological calculations and complex marine environment forecasts, providing an "out-of-the-box" digital engine for the protection and regular management of coastal zone species. Specifically, the improvement of informationization on protection and management is reflected in the following four dimensions:

- 1. Strengthening the comprehensive disaster prevention and mitigation system, and enhancing the precise early warning capability for ecological and habitat protection.** Traditional coastal zone monitoring is often limited by human resources and natural conditions, making it difficult to achieve all-weather and large-scale continuous coverage, resulting in lag in disaster prevention and mitigation work. Nowadays, relying on informationization means such as satellite remote sensing, unmanned aerial vehicle (UAV) patrols, seabed online observation networks, and Internet of Things (IoT) sensors, managers can conduct high-frequency real-time dynamic monitoring of hydrodynamics, extreme climate trends, and typical ecosystems (such as mangroves and coral reefs that play the role of breakwaters).

More importantly, combined with big data analysis and artificial intelligence algorithms, the system can not only automatically identify ecological degradation trends but also achieve second-level early warning and disaster evolution simulation when facing sudden disasters such as marine heatwaves, storm surges, red tides, or oil spills. This improvement in disaster prevention and mitigation capabilities shifts the management focus

from "post-disaster remediation" to "pre-disaster prevention and rescue intervention", which not only ensures the safety of coastal social economy but also greatly avoids the devastating impact of extreme disasters on fragile species habitats.

2 Optimize the spatial planning of coastal zone and support the construction of dynamic marine protected areas (MPAs). The coastal zone is a complex area with land-sea interaction, with intensive human activities and fierce competition for resources, and the physical space for species protection is easily squeezed. With the help of geographic information system (GIS), building information modeling (BIM) and Digital Twin technology, three-dimensional visual modeling and high-precision superposition analysis can be carried out on the natural attributes, migratory paths of species and information of sea rights confirmation of coastal zone.

The improvement of spatial informationization not only enables managers to deduce the long-term ecological impact of different development schemes (such as port expansion and offshore wind power) on the virtual platform but also serves as a core tool to support the construction and optimization of Marine Protected Areas (MPAs). It provides an intuitive and quantitative basis for the scientific site selection, boundary delimitation, and ecological connectivity network construction of protected areas, and even the "dynamic adjustment" of protected area boundaries in response to species migration caused by climate change, thereby maximizing resource utilization efficiency and minimizing interest conflicts.

3 Break down data barriers to promote cross-departmental collaboration and scientific decision-making. The fragmented management of coastal zones has long been a universally recognized challenge, as it often involves multiple departments such as natural resources, ecological environment, maritime transportation, and fisheries. The construction of an integrated management information platform has effectively broken down data silos through unified data standards and cloud-based sharing mechanisms, forming a comprehensive coastal zone data foundation. Based on the shared Decision Support System (DSS),

various functional departments can conduct business collaboration, joint law enforcement, and planning consultations on the same digital base map, significantly reducing communication costs and improving administrative efficiency. At the same time, management decisions have truly shifted from relying on subjective experience in the past to scientific decision-making based on cross-validation of multi-source data.

- 4 Enhance public marine literacy and building a social co-governance ecosystem for species protection.** Species protection cannot be achieved without the participation of the whole society. Advanced integrated management toolkits often include built-in "marine literacy" and capacity-building modules, which bridge the gap between advanced science and ordinary people through visualized data products and interactive portals. Through this information transparency and the concept of Citizen Science, coastal residents and environmental organizations can more easily participate in species stranding rescue, illegal fishing reporting, or daily ecological observation, forming a bottom-up social supervision network and promoting the evolution of protection management towards a good situation of diversified co-governance.

In summary, the informatization of integrated coastal zone management is not only an upgrade of management tools but also a comprehensive reshaping of management systems and protection effectiveness. It is the only way to achieve the unity of high-quality economic and social development and high-level protection of the ecological environment in coastal zone areas.

3. Toolkit Framework Structure

The toolkit for long-distance migratory species protection and integrated coastal zone management proposed in this paper forms a complete decision support system of "front-end core business + underlying comprehensive support". Specifically, the toolkit mainly includes five closely related modules: the first four parts (3.1-3.4) constitute the core business chain of species protection, which unfolds in sequence along the scientific main line of "habitat prediction — corridor identification — connectivity evaluation — adaptive management"; the fifth part (3.5) is the

underlying environmental forecasting and integrated management base serving the above business chain, providing environmental data driving and macro-governance framework empowerment for the early species spatial distribution prediction, corridor identification calculation, and later joint policy implementation. Each module combines virtual and real elements, interlocking with each other, jointly forging a highly operable ecological conservation decision hub.

3.1 Species Distribution Model and Habitat Suitability Prediction

The main goal of this module is to establish a habitat suitability prediction model for long-distance migratory species, thereby identifying the core activity areas and key hubs of the population. The ecological characteristics of long-distance migratory species determine that they need to move across regions within a vast geographical space during different life history stages. This movement is often accompanied by important life activities such as foraging, reproduction, and overwintering. Understanding and mastering the habitat selection preferences and spatial distribution patterns of these species have significant reference value for formulating targeted ecological protection policies, delimiting marine protected areas, and optimizing marine spatial planning. Based on the niche theory, the habitat suitability prediction model can provide management authorities with an intuitive and quantifiable spatial distribution probability map by quantifying the relationship between species distribution and external environmental conditions.

The following will provide a detailed academic and application explanation of the core steps of this module.

- Data collection: Collect species observation data, marine environmental variables (such as sea temperature, salinity, substrate, ocean currents, etc.), and human activity data.

Data collection forms the basic support for the habitat suitability prediction model. In studies on long-distance migratory species, due to their wide range of activities and large environmental span, the multi-source nature, representativeness, and spatiotemporal continuity of data have a direct impact on the reliability of model output results. This stage mainly focuses

on the following three core dimensions:

First, species observation data is the direct basis for inverting species niche preferences. Such data usually includes species occurrence points, activity trajectories, and in some cases, abundance information. The data acquisition channels mainly include satellite beacon tracking, acoustic telemetry networks, ship visual surveys, scientific fishing records, and data collected by citizen science projects. Due to the particularity of the marine environment, observations of long-distance migratory species often show the characteristic of only presence records without exact absence records (i.e., presence-only data). During the data collection process, the specific time and latitude-longitude coordinates of the observation need to be recorded to facilitate subsequent matching with environmental data at the same spatiotemporal scale. Data from different acquisition channels often have different observation biases; for example, route survey data is often concentrated in specific waterways. Therefore, during the collection stage, the data source needs to be fully annotated to provide basic information for subsequent bias correction.

Secondly, marine environmental variables are important driving factors for explaining species distribution patterns. Long-distance migratory species exhibit varying degrees of sensitivity to physical oceanographic parameters and biological oceanographic characteristics. The marine environmental variables covered in this module mainly include but are not limited to the following categories: Sea temperature data is a key thermodynamic parameter affecting the physiological metabolism and distribution boundaries of marine organisms, and its surface and subsurface spatiotemporal distribution characteristics can be obtained through satellite remote sensing data; Salinity and ocean current data profoundly influence water mass properties and the passive transport processes of organisms, and play an important explanatory role especially during the larval dispersal stage; Sediment type and water depth distribution provide habitat structure descriptions for benthic organisms or life stages with specific water depth preferences; Primary productivity indicators (such as chlorophyll a concentration) can reflect the potential food abundance in sea areas and are

important factors driving species' foraging migrations. To ensure model accuracy, the collection of the above data must cover the entire study area and, as much as possible, ensure the continuity of the time series.

Finally, as an external disturbance factor that cannot be ignored, human activity data should be integrated into the data collection framework simultaneously. Ocean space is carrying increasingly intensive development and utilization activities, covering shipping transportation, fishing, seabed engineering construction and land-based pollution emissions. Such activities not only directly occupy or change the physical habitat of species, but also may produce indirect stress effects such as underwater noise, light pollution and water quality degradation. Collecting high-resolution spatial distribution data of human activities (e.g. shipping density, fisheries statistical grid data parsed by Automatic Ship Identification System data) can help quantify the negative moderating effect of human activities on habitat suitability in the model. The introduction of such anthropogenic variables into the model framework can assist management departments to assess the cumulative risks faced by ecosystems, and provide scientific evidence for the spatiotemporal allocation of marine functional zoning and resource exploitation intensity.

- Data preprocessing and standardization: Drawing on the rasterization and standardization processes in terrestrial methodologies, integrate and process data with different resolutions to ensure consistency among various data layers.

After completing the initial collection of multi-source data, the core challenges are the spatial resolution differences, time scale mismatches and potential data redundancy that exist in the data itself. Data preprocessing and standardization is the transition link between original data and mathematical model. It aims to eliminate data underground noise and extract effective information through a series of rigorous spatial analysis and statistical processing, thus reducing the uncertainty in the process of model operation.

The first step is rasterization processing and spatial alignment. Marine environmental variables and human activity data often come from different observation platforms and numerical simulation products, with original data

structures including vector polygons, discrete point arrays, and raster data with different pixel sizes. Drawing on spatial processing specifications in geographic information systems, this module needs to uniformly resample all spatial covariates to the same target resolution. The setting of target resolution requires comprehensive consideration of the species' activity range characteristics and the capacity of computing resources. During the resampling process, appropriate interpolation algorithms should be selected for different types of data: for continuous variables (such as sea temperature, salinity), bilinear interpolation or cubic convolution interpolation are usually used to preserve the smooth gradient characteristics of the data; for categorical variables (such as substrate type), the nearest neighbor assignment method must be adopted to maintain the clarity of category boundaries. All processed raster layers must be aligned to a unified geographic coordinate system and projection framework to ensure that at any given geographic coordinate point, each data layer has a strict spatial correspondence.

The second step is time scale matching and dynamic correlation. The distribution of long-distance migratory species exhibits significant seasonal and even interannual dynamic changes. Static environmental backgrounds often fail to accurately depict the species' immediate niche responses in complex marine systems. Therefore, the preprocessing workflow needs to achieve temporal matching between species observation points and environmental variables. This process requires extracting environmental characteristic values corresponding to the species observation time from time-series environmental raster datasets, thereby constructing a dynamic occurrence point-environment covariate matrix and enhancing the model's ability to capture spatiotemporal heterogeneity.

The third step is variable dimensionality reduction and multicollinearity testing. Environmental variables in nature often have complex interrelationships; for example, water depth and bottom water temperature, sea surface current velocity and wind stress usually have high correlations. Directly inputting highly correlated variables into the model can lead to multicollinearity issues, which in turn cause distortion in model parameter

estimation and reduce model interpretability. Therefore, the environmental variable set needs to be filtered before modeling. Routine operations include calculating the Pearson correlation coefficient matrix between variables or using Variance Inflation Factor (VIF) for quantitative evaluation. A reasonable threshold is set to eliminate variables with high correlation and relatively weak ecological significance, retaining a core factor set with strong independence and clear explanatory value for the target species.

The fourth step is identification and correction of sampling bias. Limited by marine operating conditions and survey costs, species observation data often exhibit obvious spatial clustering characteristics. If such sampling bias is directly introduced into the model without treatment, it will cause the model to overfit to densely sampled areas rather than reflecting real habitat preferences. To mitigate this phenomenon, the preprocessing workflow can adopt spatial filtering techniques to limit the density of observation points within specific spatial neighborhoods; alternatively, construct a Target-group background dataset by introducing background samples with similar observation biases, enabling the model to effectively distinguish between habitat preference signals and mere differences in sampling effort distribution.

- **Model Construction:** Use the MaxEnt model or other adaptable machine learning models to build statistical models based on existing observation data and environmental variables, outputting species presence probability distribution maps.

For example, for sea turtles or cetaceans, the current migration patterns of their juveniles and the distribution of adult breeding areas can be predicted by this model. Model construction is the core analysis link to transform the pre-processed ecological data into spatial prediction results. This module mainly relies on statistical principles and machine learning algorithms to mine the nonlinear mapping relationship between environmental variables and species occurrence probability, and then infer the potential spatial distribution pattern of habitat suitability of target species in the whole study sea area.

In terms of algorithm selection, the Maximum Entropy model (MaxEnt)

is a relatively mature baseline tool in this field due to its robustness when dealing with presence-only data. The MaxEnt model can automatically fit various complex feature functions and delicately depict the nonlinear response of species to environmental gradients. However, any single statistical model is based on its specific mathematical assumptions and data fitting preferences. When facing highly complex nonlinear ocean ecological data, a single algorithm may have structural prediction blind spots, such as being prone to overfitting at environmental extreme values.

Any single statistical model or machine learning algorithm is based on its specific mathematical assumptions and data fitting preferences. When facing highly complex nonlinear ocean ecological data, a single algorithm (such as the basic MaxEnt) may have structural prediction blind spots. To this end, the advanced module has achieved a comprehensive iteration towards the Ensemble Modeling framework.

This framework breaks through the limitations of a single algorithm and fully integrates high-level algorithms including Random Forest (RF), Generalized Additive Model (GAM), and Boosted Regression Trees (BRT): RF shows strong resistance to outliers; GAM can clearly depict the nonlinear response curve of species to a single environmental gradient; BRT has unique advantages in capturing complex variable interactions. The module has established a rigorous internal evaluation and weighting mechanism with the help of cutting-edge modeling architecture. During the ensemble calculation process, the system will eliminate underperforming base models according to the set validation index thresholds, and then use ensemble strategies such as weighted averaging or coefficient of variation calculation to aggregate the outputs of multiple independent algorithms.

Particularly important, this combined architecture not only outputs a single probability average surface, but also synchronously generates spatial prediction Uncertainty Maps. The spatial expression of error boundary enables decision makers to visually examine the confidence of prediction results. For the core areas with low uncertainty, the government can put law enforcement forces; For areas with extremely high uncertainty, the management department is prompted to give priority to monitoring resources

to fill the gap. This assessment framework based on risk and uncertainty has greatly improved the scientific allocation efficiency of public finance in the field of blue ecology.

- **Model Validation:** Using indicators such as cross-validation and AUC values to evaluate the accuracy of prediction models, and comparing them with field survey data to ensure that model outputs are scientifically credible. The value of scientific prediction is based on the accuracy and reproducibility of its results. To ensure that the generated habitat suitability maps can serve as effective evidence for policy-making and resource management, it is necessary to conduct quantitative testing of model performance through a rigorous evaluation framework. Model validation is a multi-dimensional evaluation system aimed at testing the generalization performance and prediction robustness of the model when faced with unknown data.

The primary step is internal statistical evaluation, mainly achieved through cross-validation technology. To prevent the model from overfitting on the training data (i.e., the model can perfectly memorize the training data but cannot handle new data), it is necessary to reorganize the collected species occurrence records according to a possible proportion (such as setting a split ratio parameter to separate the training set and test set). Common strategies include random resampling and K-fold cross-validation. By fitting the model on the training set and validating it on the test set that did not participate in modeling, and iterating this process repeatedly, the statistical distribution of model performance can be obtained, which objectively reflects the stability of the algorithm.

In the construction of the evaluation index system, the Area Under the Receiver Operating Characteristic Curve (AUC) is a widely adopted standard. The AUC value reflects the probability that the model ranks a randomly selected species presence point above a randomly selected background point, and its value range is usually between 0.5 (equivalent to random guessing) and 1 (perfect prediction). A higher AUC value indicates that the model has good discriminative ability. However, considering that the AUC index may have potential limitations when dealing with low species incidence or

excessively large background ranges, the module validation framework often supplements and introduces related derivative indicators such as the True Skill Statistic (TSS) or the Receiver Operating Characteristic (ROC). These indicators can comprehensively consider the sensitivity (the proportion of correctly predicting presence) and specificity (the proportion of correctly predicting absence) of the model, thereby providing a more comprehensive quantitative evaluation of the performance of a single model.

In addition to internal mathematical validation based on existing data, external independent data comparison forms the final closed loop of the validation system, that is, comparing with field survey data to ensure that model outputs are scientifically credible. High statistical scores do not directly equate to ecological truth. Areas with high suitability values output by the model need to be field-verified through subsequent independent special voyage surveys, unmanned aerial vehicle patrols, or acoustic detection arrays. If large-scale aggregations or key life activities of the target species are indeed observed at high frequencies in the core areas predicted by the model, the model can be considered to have high practical explanatory power. Conversely, if there is a significant deviation between the prediction results and field surveys, it is necessary to review whether there are blind spots in data collection, whether key driving factors are missing in the selection of environmental variables, or whether the disturbance weight of human activities is underestimated.

Through the above multi-dimensional verification mechanism, the uncertainty of model results has been effectively quantified and controlled. The scientifically credible prediction outputs can directly support government management departments in delineating marine ecological red lines and optimizing and adjusting fisheries spatial management measures (such as setting seasonal fishing ban areas). It not only provides a static picture of spatial distribution but also establishes a dynamic assessment tool that can continuously iterate and optimize as new data is injected, providing solid technical support for the implementation of ecosystem-based integrated marine management.

On the basis of the above core steps, to meet the needs of high-precision spatial

planning and management decision-making, this module has achieved academic upgrading in the screening and extraction of environmental variables. The distribution of long-distance migratory species is often strongly driven by complex hydrodynamic processes, and traditional static environmental layers can no longer fully explain the spatiotemporal heterogeneity of their habitat preferences. Therefore, the advanced module compulsorily introduces dynamic oceanographic covariates. In traditional habitat assessment practices, management departments often rely on static topographic and climatic background layers such as annual or seasonal average sea surface temperature, water depth, and substrate. However, the life history strategy of long-distance migratory species requires them to search for fleeting foraging windows with high primary productivity in the vast pelagic environment. This ecological demand has led to the coupling of their distribution patterns with hydrodynamic processes in the ocean.

To accurately characterize this spatiotemporal heterogeneity, the advanced module has achieved technical upgrades in the data extraction process, compulsorily introducing a series of dynamic oceanographic covariates that characterize the vertical structure and horizontal transport of water bodies. First, mesoscale eddy kinetic energy is a key indicator for measuring the energy and physical activity of marine water bodies. Cyclonic and anticyclonic eddies, during their movement, can cause vertical upwelling of deep nutrient-rich seawater or convergence of surface seawater. This hydrodynamic process directly drives the explosive reproduction of phytoplankton, which then transfers upward along the food chain, forming temporary high-density aggregation areas of pelagic fish and top predators. Incorporating eddy kinetic energy into the model can help decision-makers identify ecological hotspots that dynamically shift in time and space.

Secondly, the sea surface temperature front probability reflects the severity of the intersection of different water masses. The front area is usually accompanied by strong physical and biogeochemical gradients, which is a natural barrier for nutrient enrichment, interception and aggregation of bait organisms. Long-distance migratory species often use these fronts as navigational landmarks and energy replenishment stations for migration. By calculating the frequency and duration of the front, the model can more acutely capture the habitat preference boundary of species in a given season. In addition, the introduction of three-dimensional hydrological features such

as mixed layer breaks the limitation of focusing only on kelp width in the past. The depth of the mixed layer directly regulates the effective radiation range of photosynthesis and the distribution of the maximum chlorophyll value in the subsurface layer, and then determines the vertical foraging space of deep-diving migratory species. On the whole, the fusion of these dynamic three-dimensional covariates makes the prediction model transcend the static zonal distribution law and more realistically restore the dynamic ecological response of species in complex three-dimensional ocean flow field. This provides a strong scientific data base for government management to develop conservation measures based on dynamic ocean management.

At the same time, in order to ensure the stability of the model structure, the module quantifies the degree of collinearity between variables by calculating the variance expansion factor, and performs orthogonal transformation and dimensionality reduction on highly coupled environmental dimensions with principal component analysis. This series of operations further purifies the independent ecological explanatory power of each environmental variable, and effectively avoids the risk of model overfitting caused by redundant variables.

At the core algorithm level of model construction, the module comprehensively integrates a variety of high-order machine learning algorithms including random forest, generalized additive model and elevated regression tree, etc., to build a robust combinatorial prediction framework. The framework integrates a series of high-performing algorithms: random forests exhibit robust resistance to outliers by building a large number of decision trees and voting on them; The generalized additive model can clearly depict the nonlinear response curve of species to a single environmental gradient by fitting the data with a smoothing function; The lifting regression tree has unique advantages in capturing the interaction of complex variables through iterative optimization. With the help of these algorithms, the module establishes a strict internal evaluation and weighting mechanism, and adopts strategies such as weighted average or calculating coefficient of variation, which significantly neutralizes the prediction fluctuation and overfitting tendency that a single model is prone to appear when facing the edge or extreme value of environmental gradient.

Especially important, the combined architecture not only outputs a single probability average surface, but also generates a spatial prediction uncertainty map

synchronously. In the context of policymaking, knowing exactly what we don't know is often as critical as knowing what we know. The spatial expression of error boundary enables decision makers to intuitively examine the confidence of prediction results. For example, when planning a large transoceanic marine protected area, policymakers can prioritize resources for delimitation and protection legislation in a high-suitability area if the uncertainty index is low, indicating a high degree of consistency in the assessment of habitat values in multiple models; On the contrary, if an area shows high suitability but is accompanied by extremely high uncertainty, this suggests that the management department needs to list this area as a key investigation object in the future, and invest more on-site monitoring resources to fill the data gap, rather than immediately implement tough control measures. This assessment framework based on risk and uncertainty provides a scientific and prudent reference for marine resource allocation.

Finally, in the model validation system, to compensate for the mathematical shortcomings of traditional subject operating characteristic curves when evaluating only existing data, the module introduces a continuous Boyce index with more acuity to changes in the marine environmental background. Designed specifically to evaluate the predictive performance of existence-only data, this index measures the ability of the model to distinguish between suitable and unsuitable habitats by analyzing the correlation between the suitability gradient window predicted by the model and the frequency of actual observation points without relying on spurious absent points.

In the design of the validation strategy, the module combines the spatial block cross-validation technique. Because the data of long-distance migratory species often exhibit strong autocorrelation in space, the traditional random cross-validation easily leads to information leakage in space, thus virtually increasing the prediction accuracy of the model. Spatial block validation rigorously tests the geospatial transfer and generalization ability of the model by forcing the model to be independently tested across different ocean basin scales. Only if the model can accurately infer the habitat preferences of species across different ocean basin scales can it be confirmed that the model captures the universal ecological laws that drive species distribution. Through this rigorous verification system, it is ensured that the toolkit will ultimately deliver not only a static map with statistically high scores, but a set of spatial succession models with predictive toughness. It can not only reveal the current spatial pattern of

species, but also reliably deduce the potential response and habitat migration trajectory of long-distance migratory species in the face of climate disturbances such as extreme flow field variability and frequent ocean heat waves when the model is applied to a wider range of unknown sea areas or input into predicted environmental data under future climate change scenarios. This has built a solid scientific moat for government departments to carry out future-oriented and climate-resilient marine space strategic planning.

3.2 Identification method of marine ecological corridor

After grasping the spatial distribution pattern of habitat suitability for long-distance migratory species, the focus of modern marine ecosystem management needs to shift from single, static patch protection to dynamic network connectivity protection. The life cycle of long-distance migratory species depends on multiple spatially separated core habitats (such as breeding grounds, feeding grounds, and overwintering grounds). The spatial connectivity between these core areas is a key support for maintaining population genetic exchange and ensuring species complete their full life history. This module introduces the connectivity analysis framework from landscape ecology to transform habitat suitability into dynamic migration network maps, providing quantitative scientific basis for government departments to plan Marine Protected Area Networks (MPA Networks), formulate cross-regional joint protection policies, and carry out marine spatial use control. This module aims to use the output data of species distribution models to model and identify the movement paths of long-distance migratory species, thereby deriving ecological corridor networks. The specific process includes:

- Resistance surface construction: Assign resistance values to marine space using marine environmental variables and human activity data to construct a resistance surface reflecting the level of ecological connectivity. Drawing on the idea of weighting roads, buildings, and population density in terrestrial ecological corridor methodology, parameters such as current intensity, ship density, and seabed obstacles can be considered in the ocean. The construction of the Resistance Surface is the cornerstone of all spatial connectivity analysis. In the

context of landscape ecology, resistance represents the physiological energy consumption that organisms need to overcome when moving in space, the survival risks they face, and the physical obstacles they encounter. The resistance surface is essentially a continuous grid matrix, where each pixel is assigned a specific cost value; the larger the value, the higher the difficulty or cost for species to cross the area.

To construct a resistance surface in the marine environment, it is first necessary to invert the Habitat Suitability Index. The habitat suitability probability map output by Ensemble Modeling in the early stage is usually regarded as a characterization of habitat quality. In the construction of the resistance surface, mathematical methods such as negative exponential transformation or linear inversion are often used to convert high-suitability areas into low-resistance areas (i.e., species tend to move in these areas) and low-suitability areas into high-resistance areas. This transformation logic ensures that the operation basis of the migration model is firmly rooted in the biological preferences of the species.

However, relying solely on static habitat suitability is insufficient to truly characterize the complex movement costs in the ocean. Therefore, this module draws on and develops the method system for terrestrial ecological corridor assessment. In terrestrial ecosystems, transportation networks and urban built-up areas are core sources of resistance; when mapped to the marine environment, the module introduces more complex multi-dimensional resistance parameters:

First is the dynamic resistance in the dimension of physical oceanography. Ocean currents are the core physical force driving the spatial movement of long-distance migratory species. Unlike scalar resistance on land, ocean currents have significant vector characteristics (i.e., including flow speed and direction). For turtle hatchlings or passively floating organisms, the movement resistance in the downstream direction is close to zero or even negative (with an accelerating effect), while the resistance in the upstream direction increases exponentially. Therefore, the module introduces an anisotropy algorithm in the construction of the resistance surface, which integrates three-dimensional ocean current model data to assign direction-

dependent dynamic resistance values to pixels, thereby more realistically simulating energy consumption paths in a hydrodynamic environment.

The second is the risk resistance of the human interference dimension. Human maritime activities constitute a significant survival stress faced by migratory species. The module converts the channel distribution and ship density analyzed by the Automatic Ship Identification System (AIS) into the resistance layer of underwater noise and ship impact risk; Translate operational grid data from commercial fishing into miscatch risk resistance; At the same time, fixed facilities such as submarine cables and offshore wind farms are regarded as physical submarine obstacles, and specific space avoidance costs are given.

Through the Analytic Hierarchy Process (AHP) or a weighting mechanism based on expert knowledge, the module performs spatial superposition and matrix operations on the above multi-dimensional resistance layers, and finally generates a global resistance surface that comprehensively reflects the connectivity limitations of marine space. This resistance surface is the input data for subsequent algorithms and also provides management authorities with an intuitive map of marine ecological passage costs, facilitating the examination of the fragmentation effect of human development activities on natural connectivity at the macro level.

- **Least Cost Path Analysis:** Based on resistance surface data, the least cost path method is applied to calculate the optimal migration path between different core areas. This method can intuitively show the movement trend of species under the condition of minimum energy consumption and reveal possible migration corridors. After constructing the resistance surface and identifying core habitats (i.e., network nodes, such as known important feeding grounds and breeding grounds), Least Cost Path (LCP) analysis constitutes the first set of core tools for identifying the spatial direction of ecological corridors.

The underlying mathematical logic of the least cost path method originates from the shortest path algorithm in Graph Theory (such as Dijkstra's algorithm). This algorithm assumes that species have perfect spatial perception ability in complex landscapes, and their migration strategies are based on the principle of minimizing energy consumption and

survival risk. In the calculation process, the algorithm takes a core habitat as the starting point (source node), iteratively expands outward in the surrounding continuous resistance grid, accumulatively calculates the total passage cost to reach the target core habitat, and finally traces back a continuous spatial linear trajectory with the minimum cumulative resistance value.

From an ecological perspective, this ideal migration path outlines the low-energy, low-risk corridors that species tend to select when undertaking large-scale movements between two separate habitat patches. For example, in the case of adult sea turtles or baleen whales that need to migrate across oceans for breeding, LCP analysis can clearly reveal how they skillfully utilize favorable ocean current corridors, avoid high-intensity human fishing areas, and navigate around unfavorable water mass characteristics (such as cold eddies) to establish a migration main axis with clear geographical coordinates.

In the practical application of public policy and spatial management, the output results of LCP are highly directive. These linearly distributed path trajectories can be directly transformed into linear ecological protection red lines or priority management waterways in marine spatial planning. For instance, when planning a new transoceanic shipping route or laying large-scale submarine cables, management authorities can overlay LCP analysis results to assess whether the proposed project spatially conflicts with the core migration corridors of long-distance migratory species. If a conflict exists, based on this quantitative data, the project party can be required to adopt detour measures or implement seasonal construction avoidance, thereby ensuring economic development while maintaining the unimpeded flow of core ecological pathways.

- **Application of Circuit Theory:** Utilizing circuit theory methods to quantify marine connectivity, by simulating the distribution of electric current in a resistance surface, evaluating the redundancy and key nodes of all possible migration paths, thereby identifying which areas act as bottlenecks in ecological connectivity.

Although least cost path analysis can provide a clear and direct connectivity corridor, its fully deterministic premise may have potential limitations when faced with complex marine natural systems. The actual movement of wild animals often does not follow a single shortest path but is accompanied by a large amount of random exploration and environmental trial-and-error. To address the theoretical blind spot of a single linear path, this module introduces the more macroscopic and probabilistic Circuit Theory.

Circuit Theory creatively applies Ohm's Law from physics and the mathematical model of Random Walk to the field of landscape ecology. Within this analytical framework, marine space is abstracted as a large conductive network: core habitats are set as nodes that inject current (power sources) or absorb current (ground terminals); each grid cell in the resistance surface is regarded as a resistor in the connected network. When the model runs, virtual current flows between the source and target, and the intensity of the current represents the sum of probabilities that species pass through that specific area.

This simulation mechanism brings about a fundamental shift in the perspective of connectivity assessment. Circuit theory not only focuses on a single path with the least resistance, but also evaluates the Redundancy of multiple possible paths in the whole spatial network more comprehensively. When there is a vast low-resistance sea area between two habitats, the current will appear in a dispersed state, indicating that the species have multiple migration route options, and the ecological connectivity of this area is resilient to resist local environmental disturbances.

More importantly, by calculating the current density in local sea areas, circuit theory can identify key nodes in the network, namely connectivity bottlenecks (Pinch points). Bottleneck areas are usually narrow spaces surrounded by high-resistance environments (such as areas with intense human activities or unfavorable hydrological fronts), forcing most currents to converge and pass through. In marine connectivity networks, these high current areas mean that species' migration routes are highly compressed here.

At the management decision-making level, the identification of bottleneck areas has irreplaceable strategic defense value. Once these narrow connectivity hubs are irreversibly damaged or cut off, the entire population's migration network will face the risk of paralysis. Therefore, when formulating marine protected area plans, government departments need to prioritize these bottleneck sea areas, implement strict use control and environmental impact assessment mechanisms, and ensure the preservation of these fragile nodes that maintain overall ecological connectivity.

- Bridge area identification: Combining the results of the above two methods to further identify stepping stones or buffer zones connecting multiple core areas, which are strategically significant for long-term migration. A single analytical model often struggles to encompass all the complexities of the natural world. At the end of the process design, this module emphasizes the comprehensive evaluation and spatial overlay of multi-source model results. By spatially intersecting and comprehensively analyzing the linear main channels presented by the Least Cost Path (LCP) with the current dispersion surfaces and bottleneck points revealed by circuit theory, the module can deconstruct the marine connectivity network with a more hierarchical perspective, thereby identifying key stepping stones and buffer zones that connect multiple core areas.

Long-distance migration is not an instantaneous spatial transfer but a process that often spans months or even years and thousands of kilometers. During this process, species cannot rely on energy reserves from the starting point to support the entire journey and need to stop, replenish energy, or take shelter from extreme weather midway. Combining the two connectivity models, the patchy sea areas that are not only near the main axis of the least cost path but also show potential current convergence characteristics in circuit theory constitute the bridge areas or stepping stones in the migration network.

These stepping stones may be isolated seamounts with upwelling characteristics in the high seas or cold eddy zones with abundant seasonal primary productivity. Like service areas on intercontinental highways, they

provide indispensable energy relays and survival shelters for long-distance migrating species.

At the same time, based on the core migration channels and key stepping stones, the model can also delineate buffer zones with gradient resistance characteristics. In management practice, directly implementing absolute closed management on core migration channels often faces huge socio-economic resistance. By delineating buffer zones, management departments can adopt more flexible hierarchical management strategies. For example, low-intensity traditional fishing activities may be allowed in buffer zones, but large-scale bottom trawling or high-intensity industrial development is restricted; during core migration seasons, temporary speed limit orders or dynamic acoustic control can be issued to provide a temporal and spatial window of safety for migrating species.

In summary, through the identification of corridor areas and the systematic establishment of a buffer system, this module provides a set of operable and quantifiable spatial management solutions for economies and the economy-wide community. It not only helps to enhance ecological connectivity within marine areas under domestic jurisdiction but also provides solid and persuasive scientific data to support the development of a globally connected protected area network. This marks the official transition of marine ecological protection from isolated island-style emergency management to a strategic depth characterized by systematization, networking, and spatial coordination.

Based on the above classical process, the Advanced Analysis Module further responds to the practical needs of modern maritime spatial planning for managing flexibility and multilateral diplomatic negotiations. However, in the traditional connectivity assessment, planners often only obtain a slender optimal route or a few fixed hub patches. This stereotypical spatial output is inadequate to deal with the climate variability and complex economy-wide interest game.

To provide more buffer room for policy formulation, the module introduces stochastic shortest path network analysis. This method transforms a single deterministic route into a probabilistic corridor network containing multiple potential

alternative routes. In transboundary spatial planning, this transformation from linear corridors to probabilistic planar corridors holds profound policy-guiding significance. When the predicted main route inevitably overlaps with an economy's key waterways, the probabilistic network allows decision-makers to see alternative secondary wandering paths on the map. Regional economy-wide organizations can thereby coordinate coastal states to carry out spatial replacement of ecological assets, allowing economies to maintain moderate openness to sea areas of high economic value while implementing protection compensation on alternative corridors under the premise of ensuring overall network connectivity, thus enhancing the political acceptability of multilateral protection treaties.

In areas with severe data scarcity, such as the high seas, traditional analytical methods often fail to function due to a lack of known core areas. The introduction of omnidirectional connectivity analysis framework has completely changed the passive situation of lack of scientific support for the site selection of high seas protected areas. Without the input of any prior source and sink nodes, the framework directly develops the hidden fluid network skeleton from the contiguous ocean deep water by global solution. On the multilateral negotiation platform, this kind of global spatial data, which is not interfered by the subjective will of a single economy, provides a neutral and objective judgment benchmark for states parties to reasonably share the responsibility for protection and draw the economy-wide common ecological red line.

In addressing the temporal heterogeneity of the marine environment, temporal network topology analysis has formally incorporated the time dimension into management perspectives. Ocean current fields reverse with seasonal alternations, and many key hub nodes are merely transient stepping stations that exist only briefly. Requiring an economy to implement round-the-clock permanent containment of specific nodes within its jurisdictional sea areas lacks economic rationality. Temporal network models, by capturing time-window corridors, have facilitated the implementation of the Dynamic Ocean Management (DOM) concept. Adjacent economies can, through a shared platform, jointly declare that a protection order for a certain boundary sea area takes effect only within the few weeks when connectivity is activated during specific hydrological seasons. This dynamic transboundary coordination mechanism, shifting from spatial purchase to temporal leasing, releases marine development space that was locked by excessive protection and provides a

pragmatic management paradigm for achieving a balance between sustainable resource utilization and ecological protection.

3.3 Connectivity Evaluation and Key Node Identification

After completing the spatial identification and network construction of ecological corridors, the core of management decisions will shift from spatial delineation to network health checks and risk management and control. To this end, the toolkit will also provide a set of connectivity evaluation index systems and key node identification methods, aiming to provide quantifiable and comparable evaluation standards for the planning and resource allocation of marine protected area networks from the perspectives of systems science and graph theory.

The main contents include:

- Connectivity index calculation: Using graph theory methods to calculate connectivity indices of the entire ecological network, such as average shortest path length, node degree centrality, network connectivity index, etc. These quantitative indices help judge the integrity and robustness of the ecological network.

Marine ecological network is a complex system with a specific topological structure. Relying solely on visual map review makes it difficult to objectively evaluate the system's ability to maintain when facing environmental fluctuations. Therefore, this module embeds Graph Theory algorithms, abstracting habitat patches as Nodes and ecological corridors as Edges, thereby deriving a series of standardized network connectivity evaluation indices. The specific evaluation indices are as follows.

- Average Shortest Path Length is a core macroscopic index for measuring the efficiency of species' spatial movement throughout the network. This index calculates the average cost or distance required for movement between any two habitat nodes in the network along existing ecological corridors. A shorter average path length indicates excellent hydrodynamic accessibility within the ecological network, allowing species to freely migrate between different functional areas (such as feeding grounds and

overwintering grounds) with lower physiological energy consumption, which plays a key supporting role in maintaining population genetic exchange and long-term evolutionary potential.

Node Degree Centrality is an evaluation parameter focusing on the micro perspective. It quantifies the number of direct connections of a single habitat patch in the local network. Nodes with high degree centrality mean they maintain close ecological connections with many surrounding patches. In marine spatial planning, these highly connected patches often act as crossroads for ecological flows; once such nodes lose function, the connectivity of large surrounding areas will be paralyzed accordingly.

- The Network Connectivity Index integrates the area weight of patches and the resistance cost of corridors, providing a comprehensive score reflecting the cohesion of the entire ecological network. Through continuous monitoring of the above multi-dimensional quantitative indicators, management departments can intuitively judge the integrity and robustness of the regional marine ecological network and evaluate whether the current protection network can effectively resist the habitat fragmentation trend caused by climate disturbances.
- Key Node Identification: Identify regions (hub nodes) that play a key role in the network through sensitivity analysis and vulnerability testing, which provides important guidance for future protection planning and resource allocation.

Under the constraints of limited administrative and financial resources, marine ecological protection cannot achieve equal coverage across the entire region. How to target the core areas that have a decisive impact on maintaining global ecological security, which can affect the whole situation with a single move, is the core demand faced by management departments. This module realizes the scientific screening of Key Nodes through dual inspections of sensitivity and vulnerability at the system level.

On the one hand, the module uses Sensitivity Analysis to evaluate the intrinsic ecological value of nodes. Its underlying logic is Node Deletion Simulation. The system removes specific habitat patches or corridor sections

from the virtual network one by one, and simultaneously recalculates the global connectivity index decay rate. Those patches that, once removed, will lead to a cliff-like decline in the global connectivity index and even lead to network disintegration and fragmentation are defined as Hub nodes or Cut nodes in the ecological sense.

However, merely identifying such "absolutely irreplaceable" cut nodes is not sufficient to fully characterize the structural vulnerability of the ecological network. In the network, there are also a wide range of patches that play the role of "stepping stones". Although their removal will not immediately lead to network disintegration (i.e., alternative paths exist), they play a pivotal role in maintaining the efficient flow of the network. To more intuitively understand how patches act as "stepping stones" to support the connectivity of the entire network and how to quantitatively identify the indispensable key nodes among them, we can use a simplified landscape network model for analysis (Figure 3).

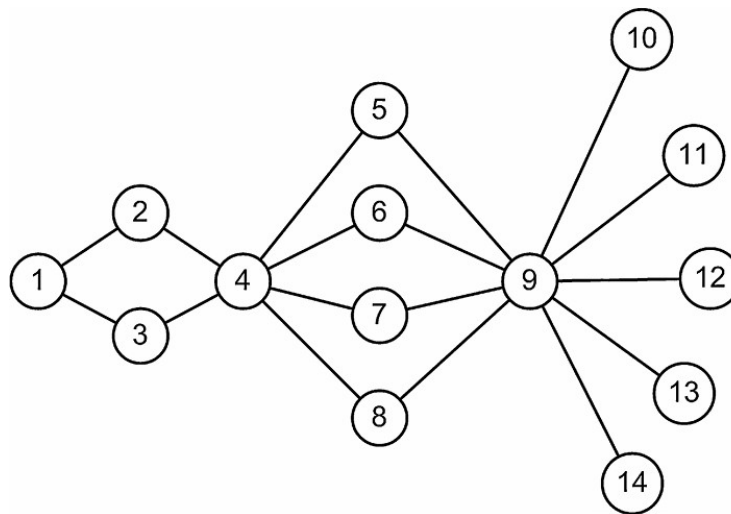


Figure 3: A simplified landscape network model showing the scores of patches on different connectivity indicators (Bodin and Norberg, 2007)

Two key graph theory indicators are involved here: dPCconnectork (connectivity contribution) measures the direct loss to the overall network connectivity when a patch is removed as a "stepping stone" (Saura and Pascual-Hortal, 2007; Saura and Rubio, 2010). A higher value indicates that the patch is more irreplaceable, belonging to an "absolute stepping stone"

whose loss would lead to network fragmentation; while BCPCk (generalized betweenness centrality) measures how many optimal ecological flow paths in the complete network need to pass through the patch (Bodin and Saura, 2010). A higher value indicates that the patch plays a stronger role as a "hub" or "backbone" in the network (Bodin and Norberg, 2007).

As can be seen from Figure 3, there are significant differences in the scores of different patches on these two indicators. For example, patches 4 and 9 have the highest dPCconnectork scores, making them typical "cut vertices"; while patches 2-3 and 5-8, although having lower dPCconnectork scores (the network can still barely connect after removal), have higher BCPCk scores, indicating that they are crucial "backbone stepping stones" in the network. Once such patches are lost, although the network may not break immediately, it will greatly increase the connectivity cost and risk between other patches, and even make the remaining network extremely vulnerable to subsequent disturbances (Bodin and Saura, 2010; Urban et al., 2009). Therefore, through sensitivity analysis combining these two indicators, we can better identify the nodes that have a decisive impact on maintaining global ecological security and avoid "blind spots" in protection planning.

On the other hand, module synchronization introduces Vulnerability Testing. Vulnerability depends not only on the ecological importance of the node itself but also on the degree of risk it is exposed to external stressors. The system will conduct spatial overlay analysis between the spatial distribution of hub nodes and existing industrial development zones, high-intensity waterways, and high-incidence areas of water pollution. When a hub node is simultaneously within the radiation range of high-intensity human activities, its vulnerability rating will significantly increase.

Based on this, policymakers can generate a priority protection list, prioritizing core regulatory efforts, financial subsidy funds, and ecological restoration projects toward these high-vulnerability hub nodes, thereby achieving a substantial leap in protection effectiveness.

- Scenario simulation and evaluation: Construct connectivity change models under different human activity impact scenarios (such as

increased maritime shipping, increased fishing pressure), predict the potential destruction risks to ecological corridors, and evaluate the effectiveness of protection measures.

Future-oriented environmental management requires policies to be forward-looking and preventive. Traditional environmental impact assessments are often limited to static reviews of individual projects, making it difficult to capture the dynamic impact of cumulative human activities on macro ecological networks. To address this, this module integrates a dynamic scenario assessment engine that supports assumption-based What-if simulations.

Under this framework, the system allows managers to set multiple benchmarks and extreme scenarios. For example, when simulating the scenario of increasing maritime shipping, the module can transform the ship flow data of the proposed new deepwater port and planned route into future underwater noise disturbance layer and collision resistance surface; When simulating the scenario of increasing fishery pressure, the risk of local survival rate decline caused by mistake fishing can be quantified by superimposing the spatial distribution of fishing quotas of different nets. With the injection of these simulated variables, the system will dynamically recalculate the ecological network and visually demonstrate the possible risk of damage to ecological corridors, such as whether some original corridors will be forced to disrupt or whether species will be forced to divert into unsuitable sea areas with higher energy consumption.

What is more valuable for management is that this toolkit can be used in reverse to evaluate the effectiveness of conservation measures. When formulating new marine spatial use control policies (such as setting seasonal fishing moratoriums in a certain bay, or requiring large merchant ships to sail at reduced speeds and noise in specific waters), policymakers can input these control parameters into the model in advance to observe the recovery rate of the protection network connectivity index. This policy rehearsal mechanism enables government departments to quantitatively compare the ecological input-output ratios of different management plans before the official implementation of the plan, thereby selecting the ideal spatial allocation plan

that balances economic development and natural conservation, and promoting marine governance towards refinement and scientization.

On top of the above basic evaluation index system, in response to the high directionality of marine flow fields and the asymmetry of ecological processes, the advanced module of the toolkit has carried out topological transformations on traditional undirected graph theory analysis. The movement of long-distance migratory species driven by ocean currents often shows strong source-sink dynamics, that is, the gene flow or individual migration in the downstream direction is much greater than that in the upstream direction. Therefore, the advanced module uses an asymmetric connection matrix to reconstruct the ecological network and introduces advanced graph theory indicators such as current flow closeness centrality based on random walk and directed betweenness centrality. These advanced indicators can effectively distinguish passive nodes that simply serve as transit channels in the network from core source nodes that truly have the ability to radiate and maintain population connectivity, thereby providing a weight ranking that is more in line with fluid dynamics for marine spatial planning.

Oceans in nature are not static culture dishes; the movement of water directly endows ecological processes with strong directional properties. Traditional graph theory models usually assume that the passage resistance between nodes is symmetric (i.e., the cost from A to B is equivalent to that from B to A). While this may be applicable in terrestrial ecosystems, it leads to significant cognitive biases when applied to pelagic migratory species. Take the dispersal of planktonic larvae or the migration of adult individuals driven by monsoon currents as examples: downstream dispersal is a low-energy passive process, whereas upstream migration constitutes a high-energy physiological barrier. This energy asymmetry gives rise to spatial Source-Sink Dynamics.

The core academic innovation of the advanced module lies in completely abandoning the symmetric matrix in the basic module and instead constructing an Asymmetric Adjacency Matrix. Within this framework, the topological characteristics of the network have undergone fundamental changes. The Directed Betweenness Centrality introduced by the module can identify hubs that are frequently traversed in the downstream direction; while the Random-walk Current Closeness Centrality, based on random walk, quantifies the potential of a node to radiate energy and

individuals to the entire network by considering the diffusion effect in fluid media.

This kind of physics upgrading at the level of graph theory brings a brand-new strategic perspective to marine spatial planning. Through the above asymmetric indicators, policymakers can clearly distinguish between two types of regions with different ecological functions: one is a transit channel with high connectivity but only plays a physical transit role, and the other is a real source node with the potential to continuously export biomass outward. When resource allocation faces bottlenecks, giving priority to high-grade marine protected areas (MPA) quotas to the latter can significantly improve the resilience and biomass spillover effect of the whole regional ecosystem.

With the aggravation of global change, the external stress faced by marine ecosystem is increasingly sudden and concurrent. Although the single-node sensitivity analysis in the basic module can lock the local vulnerable points, it is difficult to simulate the nonlinear collapse characteristics of the system when multiple pressure sources act simultaneously. In terms of critical node vulnerability assessment, the module breaks through static sensitivity testing for single node removal and innovatively introduces seepage theory in complex network science. Ecological networks of marine long-distance migratory species face a combination of threats from climate warming, habitat degradation and high-intensity fishing. Based on seepage theory, the toolkit is able to simulate the cascading disruption effects of targeted attacks of different intensities (e.g., prioritized disruption of highly centralized hub nodes) with random perturbations (e.g., environmental abrupt changes in random sea areas) on overall network connectivity. Through this dynamic destructibility simulation, researchers can accurately measure the critical threshold at which the entire migratory network undergoes structural paralysis and fragmentation, and subsequently identify those keystone node clusters whose damage would trigger irreversible ecological collapse.

In the context of ecological networks, percolation theory focuses on the phase transition process in which the entire network evolves from a connected state to a completely fragmented state when nodes or edges in the network are gradually removed. Long-distance migration networks exhibit typical characteristics of Scale-free Networks, meaning they have strong resilience against randomly distributed disasters (such as occasional local oil spills or non-specific marine heatwaves).

However, they show high systemic vulnerability when facing targeted attacks on core hubs (such as systematic overfishing or large-scale reclamation in core breeding grounds).

By constructing a dynamic iterative algorithm, the module simulates the Cascading Failures of disturbance factors spreading along the ecological corridor. When a key node loses its function, its original ecological flow pressure will be forced to transfer to adjacent nodes, which may lead to overload and successive paralysis of secondary nodes. By increasing the intensity of the simulated perturbation, the system can accurately capture the phase transition Critical Threshold that triggers the cliff-like collapse of global connectivity. This process not only reveals the mathematical law of network collapse, but also draws a clear security bottom line for protection practice-that is, in order to prevent the irreversible disintegration of the network, policy making needs to ensure that specific cornerstone node clusters are protected from any form of substantial damage.

For the scenario simulation of human activities and climate change, the advanced module abandons the traditional single-level environmental factor superposition method, and instead constructs a multi-layer complex network model with spatiotemporal coupling. Long-distance migratory species not only span multiple exclusive economic zones in horizontal space, but also face spatial competition from different sources in vertical water columns. This multilayer network model allows the radiation areas of underwater noise pollution brought by high-density waterways at sea, fishing effort hotspots of commercial fisheries, and the abnormal warming areas of future surface seawater predicted based on global climate models to be mathematically topologically aggregated with ecological connectivity networks as independent blocking levels. By calculating the network connectivity attenuation curve under this multi-dimensional interference, the toolkit can realize the deduction of multiple pressure superposition scenarios in the next fifty years, and provide rigorous mathematical derivation support for formulating forward-looking adaptive protection strategies and dynamically adjusting the boundary of no-fishing areas.

In the face of complex global ocean governance challenges, relying only on the superposition of risks on a two-dimensional plane can no longer meet the long-term spatial planning needs. The ocean development activities and climate change have high temporal and spatial heterogeneity on the temporal and spatial scales. Advanced

scenario simulation module realizes a substantial leap from two-dimensional to multi-dimensional risk assessment dimension by introducing Multiplex Complex Networks.

In this model architecture, the ecological network is no longer a flat plane but consists of a series of mutually coupled virtual topological layers. The model fully considers the ocean's characteristics as a three-dimensional medium and incorporates spatial competition in the vertical water column into its operational logic. For instance, the bottom physical destruction network caused by bottom trawling operations and the surface and subsurface acoustic pollution network caused by large merchant ships are transformed into parallel resistance layers. These layers undergo topological aggregation with the natural migration network of species in mathematical space based on different attenuation functions and action mechanisms.

More prominently, this module integrates data output interfaces for Global Climate Models (GCMs). By inputting long-term climate variables such as future abnormal increases in sea surface temperature, intensified ocean acidification, or expansion of the minimum dissolved oxygen zone as dynamic blocking layers into the model, the system possesses the ability to conduct long-term simulations of future environmental evolution.

By calculating the network connectivity attenuation curve under multi-dimensional cumulative interference, the toolkit can project the evolution trajectory of species habitat connectivity for decision-makers over the next fifty years. This projection based on multi-layer spatio-temporal coupling breaks the rigid traditional model where protected area delineation is fixed once established. It provides a scientific basis for management departments to implement adaptive management, enabling government departments to establish trigger mechanisms based on the long-term prediction curves provided by the model, and realize dynamic adjustments in time and space for no-fishing zone boundaries and channel speed limit zones, thereby providing lasting and resilient spatial shelter for long-distance migratory species in an uncertain climate future.

3.4 Transboundary Joint Protection and Adaptive Management Module

After completing static habitat identification and connectivity assessment, the

implementation focus of transboundary ecological protection needs to shift to solving the practical governance dilemmas caused by jurisdictional fragmentation. The life cycle of marine long-distance migratory species inevitably spans the jurisdictional waters of multiple sovereign economies and vast high seas. This natural attribute of crossing geographical and political boundaries determines that local protection actions by a single economy are often ineffective. To ensure the integrity of migration corridors, the primary task of multi-economy joint protection is to establish regional marine ecological data sharing and mutual recognition and trust mechanisms. Under a multilateral cooperation framework, contracting parties need to integrate their respective coastal survey data, oceanographic expedition records, and ship navigation information to cover the entire life path of long-distance migratory species. Through unified spatial identification standards, economies can clarify the spatial distribution and seasonal characteristics of migration corridors in different economies' exclusive economic zones. Establishing an information sharing mechanism based on scientific consensus can maximize the elimination of protection blind spots caused by information asymmetry, providing a persuasive factual basis for subsequent multilateral diplomatic consultations and the delineation of transboundary ecological protection red lines.

After clarifying the spatial orientation of transboundary ecological corridors, the key to implementing collaborative protection lies in the alignment of cross-border policies and joint spatial management and control. Long-distance migration corridors usually overlap significantly with economy-wide core shipping lanes and traditional commercial fishing grounds, which requires economies to conduct cross-border overall coordination when formulating domestic marine industry policies. Under the mediation of regional economy-wide organizations, neighboring economies or economies located on the same migration route can sign multilateral protection memorandums targeting critical corridor bottleneck areas and implement coordinated protection actions. For example, during specific seasons when migratory species pass through in large numbers, multiple economies along the corridor can simultaneously issue speed limit and noise reduction orders, or jointly designate seasonal fishing ban areas with clear time windows. This cross-border synchronized response mechanism can effectively avoid the "tragedy of the commons" where species immediately fall into high-intensity fishing areas of another economy after leaving a protected area of

one economy, ensuring the dual smoothness of ecological corridors in both space and time through policy continuity. At the same time, joint protection can also be extended to cross-border maritime joint law enforcement and cruise interoperability, forming a regional deterrent against illegal fishing or acts that damage corridor habitats across domestic borders.

To maintain a long-term transboundary corridor joint protection mechanism, the unavoidable core challenge is to resolve the imbalance between ecological protection costs and economic benefits among different economies. Certain key nodes on migration corridors are often concentrated in some coastal economies. These economies often have to make economic concessions by restricting local fisheries or sacrificing coastal development to implement corresponding protection measures, while the overall ecological and resource dividends brought by migratory species are shared by the entire ocean region. To bridge this geo-economic divide, multi-economy joint protection needs to be accompanied by the establishment of a fair and reasonable transboundary ecological cost-sharing and compensation mechanism. Through multilateral financial platforms such as economy-wide biodiversity funds, beneficiary economies downstream in the ecological network and major high-seas fishing economies can provide necessary financial assistance, fishing quota preferences, or marine technology transfers to source economies that bear the main protection costs. This institutional design that binds ecological responsibility with economic compensation can effectively alleviate the worries of coastal economies, transforming unilateral protection willingness into a strong regional community consensus, thereby ensuring the long-term stable operation of joint protection actions for transboundary ecological corridors.

Its underlying logic lies in the deployment of a dynamic Bayesian update framework, which takes the suitability probability surface output in the early stage as the initial prior distribution. As multi-source heterogeneous monitoring streams (such as changes in human resistance revealed by high-frequency AIS, real biological trajectories returned by satellite telemetry, and physical field jumps captured by buoy networks) continue to be accessed, the Bayesian engine can calculate a new posterior probability distribution, driving real-time calibration of the probability boundaries of species migration corridors. This process not only updates scientific understanding but also provides a standardized policy evaluation feedback interface for cross-border

collaboration. Under the framework of multilateral protection agreements, marine management agencies of various contracting parties can use this interface to directly convert scientific offset vectors into operational parameters for Dynamic Ocean Management (DOM) (Lewison et al., 2015; Hazen et al., 2018). Based on this, management departments can issue control instructions with temporal attributes, such as flexibly adjusting seasonal fishing ban windows in exclusive economic zones or issuing speed limit warnings to merchant ships in specific sea areas according to newly identified temporary high-value migration areas. This monitoring-evaluation-adjustment cycle enables transboundary protection actions to cover the core ecological context while minimizing unnecessary restrictions on regular maritime economic activities. For example, the EcoCast tool developed by Hazen et al. (2018) in the California drift gillnet fishery dynamically adjusts closed areas through daily satellite data, achieving more flexible and efficient bycatch avoidance than static protected areas (Figure. 4).

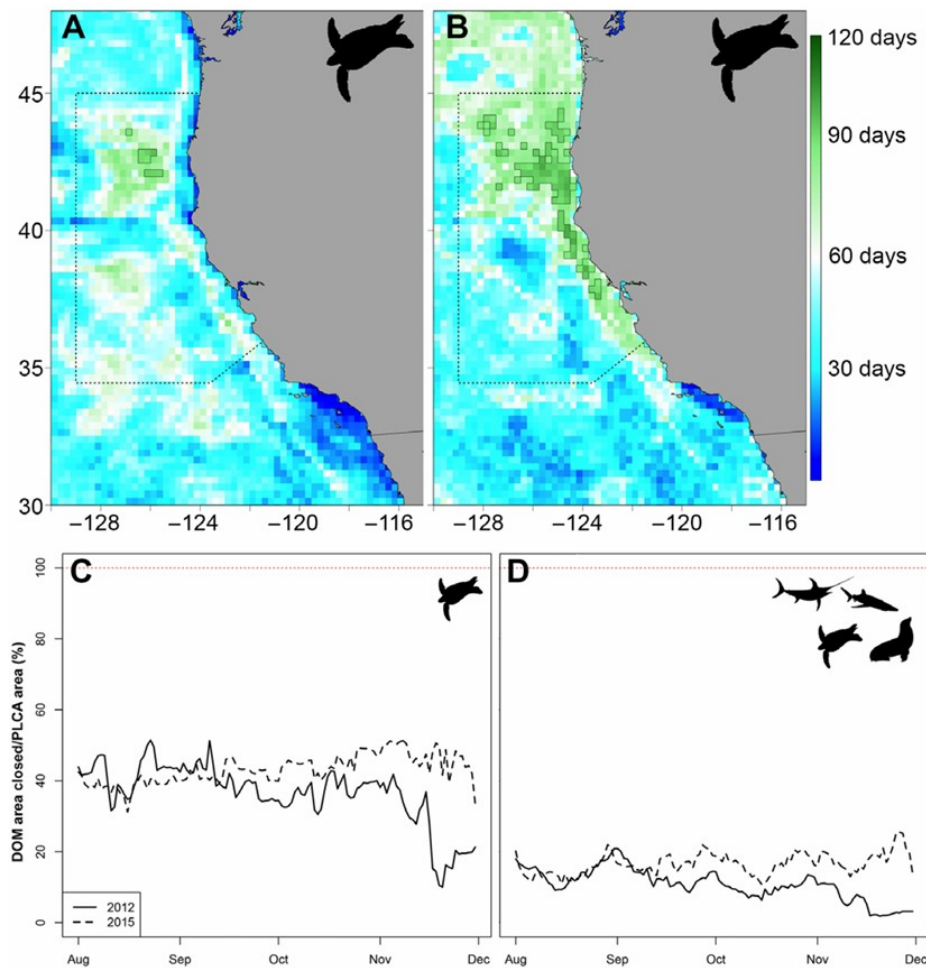


Figure 4: Comparison of Dynamic Ocean Management (DOM) approach with existing seasonal PLCA (Hazen et al., 2018).

This case tested two management objectives: dynamic closure based on a conservative threshold of 25% habitat suitability for leatherback turtles, and dynamic closure based on the EcoCast 50% threshold.

- (A) vs. (B) Spatiotemporal persistence: shows the differences in the distribution of high turtle bycatch risk areas across climatic years. In the 2012 fishing season (normal year), only 9 pixels (dark green, black outline) had a high risk of bycatch for 90 days or more; And in 2015 (an unusually warm water year), that number surged to 79 pixels. This intuitively reflects the drastic remodeling of the habitat distribution of species by climate variation. Furthermore, 86% of the pixels with a high risk of by-capture were located within the static PLCA in 2012, whereas this decreased to 63% in 2015, indicating that static protected areas have a significant decrease in coverage effectiveness in climatic anomalous years, exposing inherent flaws in static management.
- (C) and (D) Area Ratio Time Series: For leatherback sea turtle single-species conservation and integrated multi-species EcoCast risk prediction, the time series of DOM and PLCA area ratios highlights the effectiveness and flexibility of dynamic approaches compared to static conservation. Under integrated EcoCast risk prediction, the area required for dynamic closures accounts for only 3% to 28% of the vast static PLCA area (and only 11% at the end of November 2012). This strongly demonstrates that dynamically adjusting management boundaries through real-time data not only covers the core ecological context but also releases a large amount of fishing operation space originally overly restricted by static protected areas, truly achieving a win-win situation for ecological conservation and the blue economy.

Although basic Bayesian inference provides an iterative mechanism, it still faces a bottleneck in response rate when dealing with marine dynamic processes characterized by high nonlinearity and transience. Traditional ecological modeling relies on the aggregation and refitting of phased data, and this lag-based analysis model often fails to be effective in the face of sudden ecological events. To overcome this limitation, the advanced module has interdisciplinary transplanted the core technology of numerical weather forecasting — Data Assimilation. This technology

regards observation data as the key driving force to correct the model's deviation from the real state. The Ensemble Kalman Filter (EnKF) algorithm integrated into this module can immediately evaluate the deviation between the background physical ocean prediction field and real-time acoustic array or telemetry data by running multiple state ensembles representing system uncertainty in parallel. Subsequently, the algorithm uses the dynamically evolving covariance matrix to perform transient correction on the species probability distribution surface at the entire basin scale. This algorithm upgrade has substantially enabled the system function to leap from post-statistical fitting to near-real-time ecological forecasting. When mesoscale eddies affected by abnormal cyclones cause migrating fish schools to suddenly deviate from the established safe navigation channel and approach high-intensity operation grids, the assimilation forecasting engine can issue trajectory deviation warnings several days in advance. This forward-looking time window provides irreplaceable strategic depth for the temporary deployment of transboundary coast guard forces and the initiation of joint law enforcement operations.

At the decision support level of transboundary policy coordination, the advanced module breaks through the traditional perspective of maximizing single-species protection and innovatively embeds a spatially explicit multi-objective optimization algorithm. Since the ecological corridors of long-distance migratory species will inevitably overlap spatially with commercial fishing grounds, economy-wide core waterways, and deep-sea mining reserved areas, purely ecological protection schemes often lack political feasibility in multilateral negotiations. Therefore, this module uses integer linear programming technology to systematically solve the spatial layout scheme that minimizes the loss of human marine economic activities under the premise of ensuring that the core population connectivity threshold is not breached. By generating a series of Pareto optimal boundary scenarios, the toolkit can accurately calculate the implicit economic shadow price of implementing protection measures in different exclusive economic zones and high seas waters, providing a solid quantitative tool for various contracting parties to find the optimal balance between blue economy and ecological protection in multilateral interest games.

Conservation networks designed purely on the basis of ecological criteria often face challenges when they are brought to the negotiating table of regional fisheries management organizations, as they affect a broad range of economic interests. How to

fill the gap between the ecological ideal model and the complex geo-economic reality is the core task of the decision support layer. To this end, the advanced module constructs a multi-objective optimization framework based on spatial explicitness. The framework adopts integer linear programming (ILP) techniques in operations research to deconstruct the vast planning sea area into discrete decision grid cells. In the mathematical model, the core population connectivity threshold obtained by graph theory evaluation in the previous period is set as the basic constraint condition; The objective function is explicitly set to minimize the expected opportunity cost of human marine economic activity (such as the expected loss of production caused by a specific grid being designated as a closed fishing zone, or the fuel cost premium caused by requiring route detours). Through high-intensity iterative optimization in hundreds of millions of grid combinations, the system can plan compromise corridors that not only meet the basic access needs of species, but also cleverly avoid high economic value producing areas. The output of the operation is not a single rigid drawing, but a series of Pareto optimal boundary scenarios. In these scenarios, management is able to clearly read out the implicit economic shadow price of ecological control for a particular latitude and longitude sea area. This technical means of uniformly quantifying abstract ecological values and concrete economic costs effectively strips away the emotional debate in multilateral negotiations and allows states parties to reach a broad consensus between conservation inputs and blue economic growth based on cost-benefit accounting.

The high seas region has long been faced with the tragedy of commons caused by the lack of sovereignty. For large flagship species that migrate across the oceans, their breeding grounds, migration corridors, and feeding grounds often extend across multiple jurisdictions. This transboundary character leads to an asymmetry between conservation inputs and resource outputs: the source economies providing critical breeding grounds may suffer higher conservation costs and fishery losses, while ocean-going fleets located in bait yards reap resource dividends. The lack of a balanced responsibility-sharing mechanism would easily lead to the disintegration of the willingness of some states parties to protect. To solve this governance dilemma, the top-level architecture of this module integrates the cooperative game theory framework. The built-in transboundary ecological compensation simulator comprehensively considers the temporal and spatial occupation weight of species in

each jurisdiction, the contribution of habitat resistance and the importance of life history stages, and uses classical allocation algorithms such as Shapley value to calculate the relative benchmark contribution rates of source economies, transit economies and sink economies in maintaining global connectivity network. This quantitative list can provide mathematical support for the targeted assistance of the Global Environment Facility and the transboundary transfer of bilateral fisheries quotas, thus consolidating the foundation of cooperation for transboundary conservation alliances at the level of economic interests.

In the process design for responding to emergency ecological crises, the module sets early warning thresholds based on network topological resilience. Combining the system collapse critical point calculated by percolation theory, the system continuously monitors real-time assimilated environmental pressure variables in the background. When various indicators approach the safety bottom line, indicating that key migration corridors are about to face paralysis, the system will replace the time-consuming consultation process in the traditional administrative system through an automated response mechanism, and automatically trigger cross-border emergency intervention plans (such as immediately distributing speed limit and navigation suspension instructions for high-risk sea areas through the International Maritime Organization, or activating regional emergency fishing moratorium notices). This marks a leap in the collaborative protection effectiveness of regional economy-wide organizations and truly completes the closed-loop construction of dynamic management of large-scale marine spaces.

3.5 Underlying Environmental Forecasting and Data Integrated Management Base of the Toolkit

To effectively support the above core business chain for the protection of long-distance migratory species, the toolkit constructed in this paper relies on advanced marine dynamics forecasting and multi-source data products, and further integrates a multi-dimensional, visualized underlying comprehensive support system. By deeply aggregating marine big data, high-order numerical models and artificial intelligence technologies, this underlying architecture not only provides a physically consistent environmental driving field for species distribution models and corridor identification, but also forms a macro governance platform capable of one-stop response to complex

marine sustainable development pain points.

In the top-level design of the system ecology, the data flow and technical framework of this support base can be extended outward, covering six core governance dimensions (a total of 24 specific marine governance sub-scenarios), thus comprehensively escorting large-scale species protection and marine space management work:

- Marine Environmental Early Warning System: Relying on the large scientific forecasting platform, it provides typhoon evolution, sea level rise, extreme climate event (such as marine heatwaves, droughts/floods) predictions, and dynamic search and rescue predictions for specific target areas.
- Marine Navigation Safety: Focusing on navigation risks in global core commercial routes and polar waterways, providing optimal navigation path planning and customized disaster prevention guarantees.
- Coastal and Oceanic Ecological Health: Providing ocean ecological connectivity assessment, coral reef bleaching early warning, pollution source tracing and drift prediction, and dynamic marine protected area zoning.
- Integrated Marine Space Management: Including coastal zone and spatial planning standard upgrading, environmental capacity monitoring, estuary pollution and island reef governance.
- Blue Economy Support: Providing marine renewable energy potential calculation, blue carbon storage estimation, cumulative environmental impact assessment and ecotourism index.
- Scientific Literacy and Capacity Building: Focusing on transboundary joint technical training, multilateral data alliance construction, and seamless transformation of public marine knowledge.

The following figure is the framework diagram of the toolkit's data management base:

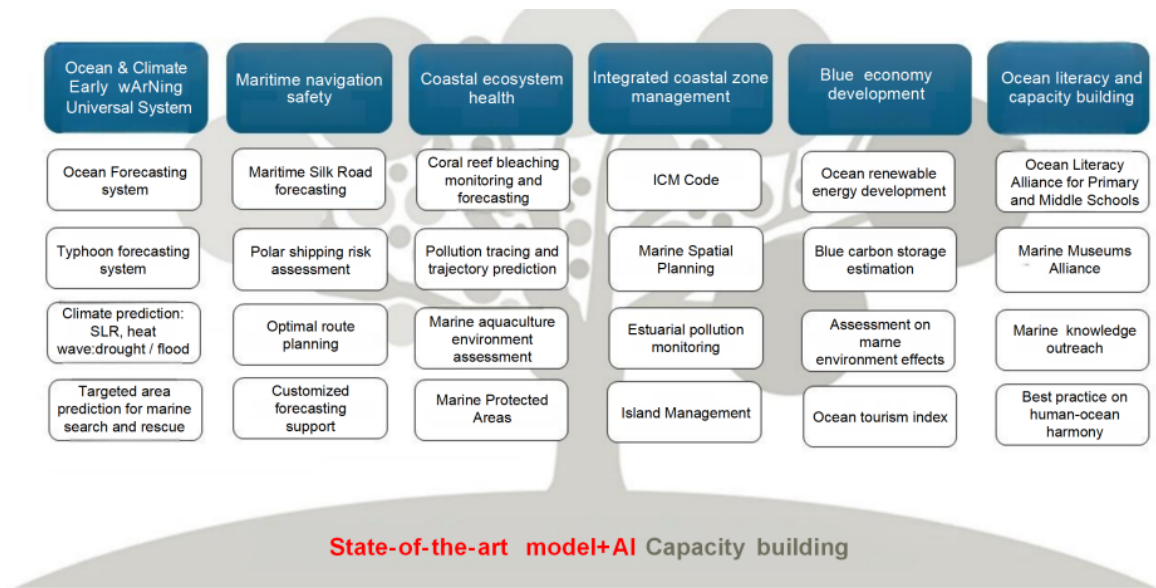


Figure 5 Framework Diagram of Data Management Base

Behind this macro-application matrix, the foundational predictive power driving the entire toolkit — including the species distribution models — is anchored by the Early Warning Universal System (OCEANUS). This centralized hub deeply integrates cutting-edge oceanographic and atmospheric sub-models, featuring:

- **FIO-COM:** Global ocean numerical forecasting (First Institute of Oceanography - Coupled Ocean Model)
- **FIO-AOW:** Typhoon dynamic forecasting (FIO Air-Sea-Wave Coupled Model)
- **FIO-CPS:** Climate evolution prediction (FIO Climate Prediction System)

The core innovation of this system lies in breaking through the technical bottleneck of ocean forecasting from the bottom up: by originally incorporating the wave-induced mixing theory and the air-sea flux coupling scheme that includes ocean waves, it fundamentally overcomes the systematic simulation bias of traditional ocean models that has persisted for decades. On the observation input side, the toolkit integrates a new generation of intelligent multi-parameter buoys. This type of buoy has overcome a series of key technologies in hardware design and data processing, characterized by miniaturization, low cost, and multi-parameter measurement.

Together with shipborne sections and satellite remote sensing, it has built a multi-source three-dimensional observation base. This "theoretical breakthrough +

intelligent perception" dual-drive model, through marine multi-source heterogeneous data fusion technology, seamlessly connects cutting-edge prediction models with high-precision observations, providing a stable and reliable environmental driving field for species habitat simulation and spatial connectivity analysis.

To ensure the inclusiveness of scientific research results and the efficiency of policy transformation, the support system adopts an open Internet cloud architecture. Global end-users and decision-making departments can easily log in to the cloud platform to obtain visualized ocean forecasting, disaster tracking, and ecological assessment products. This "co-design, co-development, co-benefit" digital collaboration model has completely opened up the knowledge transfer channel from cutting-edge science to public policies and public users, providing an indispensable underlying digital infrastructure for solving transboundary marine problems, especially the dynamic joint governance of long-distance migratory species, with extremely high cost-effectiveness.

3.6 Architecture and Implementation Tutorial for an Automated Species Distribution Model (SDM) Software Platform

Against the backdrop of global biodiversity conservation, numerous coastal economies possess rich resources of endangered species and urgently require scientific data support to guide protected area planning and ecological management. However, frontline researchers and conservation practitioners often face a severe "technical divide." Existing Species Distribution Models (SDMs) are mostly based on complex R or Python programming environments, requiring users to possess high-level capabilities in code writing and debugging. This high barrier to entry makes it difficult for grassroots units to efficiently utilize cutting-edge algorithms when facing heavy species assessment tasks, thereby constraining the scientific rigor and timeliness of conservation decisions.

To break this deadlock and achieve the democratization of technology, the key lies in "de-coding" (making code-free) and "automating" tools. We are committed to transforming obscure, pure-code toolkits into fully encapsulated "one-click" automated software programs. This means the system will automatically take over the

complex logic of underlying data cleaning, model computation, and parameter tuning, encapsulating it in the background. Users only need to complete the entire process from data input to result output through a concise and intuitive frontend interaction interface. This transformation is not only an upgrade at the software engineering level but also the only path for truly sinking high-end ecological analysis technology into grassroots applications and empowering frontline conservation work.

The following is a standardized construction tutorial and technical implementation roadmap for this automation platform. It aims to provide practical technical guidance for member economies to build easy-to-use, efficient, localized, or cloud-deployed species distribution analysis systems.

Phase 1: Technology Selection and System Architecture Design

To achieve automation, a robust software architecture must first be established. We recommend adopting the mainstream "R/Python Computational Kernel + Web GUI Frontend" architecture from the economy-wide open-source community to facilitate low-cost deployment within local economies.

Core Computing Engine (Backend Engine):

- Retain the powerful computing capabilities of the original toolkits. The background computing modules are written in R (integrating core spatial ecology packages such as maxnet, terra, ENMeval) or Python (integrating libraries such as scikit-learn, GDAL).
- These scripts will be encapsulated as standard API interfaces or independent processes and will not be directly exposed to the user.

Frontend Interaction Framework (Frontend Framework):

- It is strongly recommended to use the R Shiny framework or Python's Streamlit / Dash frameworks. Designed specifically for data scientists, these frameworks can directly convert complex backend analysis code into feature-rich web-based Graphical User Interfaces (GUIs) without incurring the high costs of developing standalone desktop software.
- Adopt a web-based responsive design. Users only need to access the system via a local browser, avoiding complex local environment configurations.

Localization and Cloud Deployment (Deployment Options):

- **Lightweight Local Deployment:** For grassroots protected areas with poor network conditions, the system can be packaged as a Docker Image. Users only need to run the Docker container with one click on a local computer or small server to launch a complete SDM automation platform on the intranet.
- **Cloud Service Mode:** Economies with the capacity can deploy the system on domestic public cloud servers as a unified internal office system for login by maritime and fishery law enforcement departments at all levels.

Phase 2: Developing a "Zero-Code" Graphical User Interface

The core goal of the frontend interface is "foolproof operation." All ecological parameter adjustments should be converted into intuitive UI components.

Drag-and-Drop Data Access Module (Data Upload Module):

- Develop a drag-and-drop upload window supporting multiple formats (CSV, Excel, TXT).
- The system must have a built-in geographic coordinate verification mechanism. After the user uploads species occurrence point data, the interface automatically pops up an interactive verification map built with open-source components like Leaflet. This visually displays whether the data points accurately fall within the jurisdictional waters.

Visual Environmental Factor Configuration (Environmental Variables Panel):

- Abandon code input for paths. Design the environmental variable configuration as collapsible menus or check boxes.
- For global marine environmental data built into the system (such as raster files for sea surface temperature, salinity, etc.), users only need to check the required layers on the frontend. The system background will automatically align the resolution, Coordinate Reference System (CRS), and spatial extent of all layers, completely eliminating the tedious manual GIS processing.

Model Parameters and Scenario Sandbox (Modeling & Scenario Wizard):

- Hide complex MaxEnt model parameters (such as feature classes, regularization multipliers) in an "Advanced Settings" menu. For ordinary users, provide a "One-click Auto-tuning" button.
- Add a "Future Climate Scenario" drop-down menu. Users can directly select preset scenarios like "2050 Warming 1.5 ° C," and the background will automatically call the corresponding predicted environmental layers for calculation.

Phase 3: Building an Automated Backend Data Pipeline

This is the true "moat" of the automation system — how to use code to replace human expert judgment to achieve process automation.

Automated Data Cleaning and Dimensionality Reduction (Automated QA/QC):

- When the user clicks "Run," the backend pipeline first initiates a Spatial Thinning script to automatically remove duplicate observation points within the same grid, eliminating sampling bias.
- Immediately following, the backend algorithm automatically calculates the Variance Inflation Factor (VIF) for the selected environmental factors. If the VIF value of a variable exceeds a threshold (e.g., >5), the system will automatically remove it to prevent model failure due to multicollinearity.

Automated Grid Search and Model Evaluation (Auto-Tuning & Evaluation):

- The backend automatically initiates a Grid Search, traversing dozens of different parameter combinations for cross-validation.
- The system automatically compares evaluation metrics such as AUC (Area Under the Curve) and TSS (True Skill Statistic), allowing the machine to select the parameter set with the best performance for the final prediction.

Phase 4: One-Click Generation of Visualized Decision Reports

The final output of the software must directly serve policy-making rather than merely providing raw data.

Dynamic Suitability Heatmap Rendering:

- After calculation, the system renders the predicted raster map generated in the background in real-time and overlays it on the frontend base map. This generates a dynamic heatmap that displays specific suitability probabilities as the mouse moves.

GIS Spatial Vector File Export:

- Based on an automatically calculated optimal threshold (such as Max SSS - Maximizing the Sum of Sensitivity and Specificity), the system instantly slices the continuous probability map into clear "Core Protected Area" and "Non-protected Area" boundaries.
- Provide a "One-click Download" button, allowing users to directly export the boundaries as standard Shapefile (.shp) or GeoJSON files for easy import into domestic government GIS systems.

Standardized Technical Report Generation (PDF Report Generation):

- Using layout generation engines like R Markdown, the system automatically captures model accuracy scores, percentage charts of environmental variable contributions, and species response curves.
- It supports one-click export to a formatted PDF or Word version of the "Species Suitability Assessment Technical Report," ready for use as an attachment material for administrative approval or Environmental Impact Assessment (EIA).

Through the architectural design and development roadmap outlined above, advanced ecological modeling techniques originally confined to laboratories will be encapsulated into a standardized digital workbench accessible via a web browser. This software engineering implementation plan of "highly complex backend, extremely simple frontend" will truly break the grassroots technical bottleneck, making scientific, data-driven protected area management a working paradigm normalized across all economies.

4. Toolkit Design of Methodology

In view of the transboundary and highly dynamic survival characteristics of

marine long-distance migratory species, traditional local and static protection models can no longer meet the current complex global marine governance needs. Therefore, this paper draws deeply on the classic Landscape Connectivity theory and combines the cutting-edge achievements in the field of modern Marine Spatial Planning (MSP) to propose a methodology for the protection of long-distance migratory species and integrated coastal zone management. This methodology system breaks the isolation of traditional ecological spatial models and innovatively constructs a complete toolkit architecture driven by the "front-end ecological spatial analysis chain" and the "underlying marine physical environment base" in a dual-wheel manner, which are organically coupled.

In terms of front-end business logic, in response to the special demands of species protection management, we propose a progressive three-stage design framework: the first stage focuses on species distribution models and habitat suitability prediction to lock in the core patches for species survival; the second stage is committed to the spatial identification of marine ecological corridors to dynamically depict the continuous paths of species' cross-domain migration; the third stage carries out global network connectivity evaluation and key node identification, so as to output quantitative spatial strategies for subsequent transboundary joint protection and adaptive management.

However, all the above large-scale and high-precision ecological spatial calculations need to be based on a solid data foundation. Therefore, while proposing these three-stage core business solutions, this methodology deeply integrates a high-fidelity marine dynamics forecasting system and a multi-source intelligent observation base at the bottom, providing a physically consistent driving matrix for the transient habitat characteristics relied on by long-distance migratory species.

4.1 Stage 1 — Habitat Suitability Modeling

At this stage, researchers need to collect and integrate species distribution data and multiple marine environmental variables, and establish species habitat suitability maps using machine learning methods such as the MaxEnt model. The model output can not only reflect the spatial probability of population distribution but also reveal the seasonal changes in population activities and key areas of the life cycle. For example, for sea turtles, the distribution of their breeding, foraging, and resting areas

can all be reflected in this model.

In the habitat suitability modeling process, although Ensemble Models are often mentioned in academic circles, this toolkit advocates using a finely tuned single model (such as the classic MaxEnt model) as the core computing engine in the standard operating procedure, with the ensemble model used as an auxiliary. This design is based on actual management needs: a single model has higher interpretability and can output clearer response curves of environmental variables, allowing decision-makers to intuitively understand whether it is water temperature or salinity that limits species distribution. In addition, facing the current situation of generally scarce observation data of marine species, the finely tuned single model shows better algorithm robustness and lower computing cost when processing only presence-only data, making it more conducive to promotion and implementation in management departments compared to ensemble models.

The standard operating process is advanced in the following three steps:

First, collect species distribution and marine environmental data. After obtaining the species occurrence coordinates, the operation guide requires using R language (such as the spThin package) to set a specific spatial distance threshold (e.g., 10km) for filtering, and compulsorily delete redundant coordinates of repeated sampling within this radius to restore the real distribution density. Subsequently, for the initially selected environmental variable layers such as water temperature and chlorophyll, the toolkit requires calculating the Variance Inflation Factor (VIF) and Pearson correlation coefficient matrix. In practice, it is necessary to eliminate highly collinear layers with $VIF > 5$ or correlation coefficient $|r| > 0.7$ to complete the physical dimensionality reduction of the data.

Second, use the MaxEnt model to construct a suitability distribution map. In the operation execution stage, the toolkit abandons the default parameters of the software and requires calling the ENMeval package for systematic grid search. The specific method is: set the regularization multiplier (RM) to test incrementally from 0.5 to 4.0, and combine and test different feature classes such as linear (L), quadratic (Q), and hinge (H). The corrected Akaike Information Criterion (AICc) score is calculated, and the parameter combination with the lowest AICc is selected for formal modeling, thereby producing a continuous suitability probability raster layer in cloglog format

that provides high statistical confidence.

Finally, it is necessary to validate and calibrate the model output. To convert the continuous probability ranging from 0 to 1 into clear boundaries that can be directly used for policy-making, the operational procedure stipulates the use of maximizing the sum of training sensitivity and specificity (Max SSS) as the segmentation threshold. Researchers need to input this specific threshold into the raster calculator of the GIS platform, reclassify pixels above this value as 1 (core suitable areas) and pixels below this value as 0 (non-suitable areas), thereby generating a binarized hard boundary base map, which directly serves as the "source" and "sink" for the next stage of connectivity analysis.

4.2 Stage 2 — Ecological Connectivity and Resistance Surface Construction

Using the output data from the first phase model, combined with factors such as marine environmental resistance (e.g., ocean currents, seabed topography) and human activity pressure (e.g., shipping lanes, fishing activities), a resistance surface for the sea area is constructed. With the help of the least cost path method and circuit theory model, connectivity is quantitatively evaluated, and the optimal corridors and potential barriers between various habitats are calculated. The results of this phase include both single corridor models and can also form a complete ecological network map.

First, construct the marine environmental resistance surface. In the GIS raster calculator, operators need to first use a negative exponential decay function (such as $Resistance = 100 \times \exp(-c \times Suitability)$) to invert the probability surface into a basic resistance surface. Subsequently, extract the ocean current vector components and calculate the angle between the species' expected movement azimuth and the ocean current vector. Using map algebra tools, apply directional penalty weights to the basic resistance surface ($\cos > 0$) proportionally reduce resistance values in downstream pixels ($\cos < 0$) and exponentially increase resistance values in upstream pixels, thereby synthesizing a dynamic, anisotropic comprehensive fluid resistance raster. For the fishing pressure layer, it is necessary to introduce human activity layers for risk weighting: convert high-density waterways parsed from AIS ship trajectories

and commercial fishing operation grids into penalty layers, increasing the passage resistance in these areas by weight; at the same time, import existing marine protected area (MPA) or no-fishing zone boundaries and assign them extremely low resistance values to simulate protected ecological safe havens.

Next, perform Least Cost Path (LCP) analysis. After establishing the directional resistance raster, the toolkit calls the Cost Path spatial analysis module of GIS software or the distance package in R language. Using the binarized core areas generated in the previous phase as the start and end points respectively, run the algorithm to calculate the global cumulative cost distance surface. By backtracking this surface, extract continuous vector line segments with the lowest cumulative resistance value and single-pixel width, which serve as the optimal main corridor for long-distance migratory species' transoceanic migration.

Finally, introduce circuit theory to evaluate multi-path redundancy. Operators import the above resistance raster and binarized core areas into the high-performance Circuitscape computing package reconstructed based on the Julia language. Set the core habitats as nodes injected with unit current (1 Ampere). After the calculation is completed, extract the global current density output layer.

4.3 Stage 3 — Ecological Corridor Identification and Network Optimization

After integrating the above data, use GIS technology and graph theory methods to finally construct a set of marine ecological corridor network solutions. This stage includes the drawing of corridor spatial distribution maps, the identification of key nodes, and dynamic simulations under different scenarios. Thus, providing clear and scientifically sound management recommendations for decision-makers to guide protected area planning and policy formulation.

After generating the underlying path vectors and current matrices, this stage converts them into management strategies through topological operations and scenario resetting. The operation steps are as follows:

First, it is necessary to integrate the two connectivity results. The reason for integrating these two algorithms is that they complement each other in ecological management: the Least Cost Path (LCP) can outline the "optimal migration main

axis" with the lowest energy consumption, while circuit theory (Circuitscape) can show all alternative paths and "network redundancy" when species deviate from the main axis. In the GIS environment, operators perform buffer analysis on the linear main axis output by LCP, rasterize it, and then overlay it with the Circuitscape current density layer that has undergone 0-1 normalization processing using map algebra (e.g., setting a 1:1 weight addition). From the overlay results, continuous polygons with pixel scores higher than a preset threshold (such as the top 20% quantile) are extracted. These overlapping areas are identified as buffer zones and key stepping stations that both have the advantage of the lowest cost and high accessibility redundancy.

Next comes the step of identifying key corridors and hub nodes. The above continuous raster patches are converted into network topology objects of nodes and edges. A network analysis package (such as igraph) is called to calculate the betweenness centrality of each node and corridor segment for the entire network, that is, to count the number of times the shortest paths in the entire network pass through specific areas. The geographic blocks with betweenness centrality scores ranking in the top 5% are separately rendered and marked in the layer, clearly defined as ecological pinch points that would cause network paralysis once blocked.

Finally, scenario simulation and protection strategy formulation are completed. To support management decisions, the operation process requires reconfiguring the resistance surface at the bottom layer for deduction. For example, manually increase the resistance value of specific pixel areas representing extreme heatwaves or high-intensity ship routes by 10 times, and re-run the entire set of pathfinding algorithms mentioned above. Calculate the attenuation percentage of network betweenness centrality indicators before and after interference. Ultimately, the toolkit packages and outputs this attenuation comparison report along with the core polygon boundaries, guiding management departments to directly delineate the exact longitude and latitude coordinate red lines for seasonal speed limit zones or mobile no-fishing zones on nautical charts based on these boundaries.

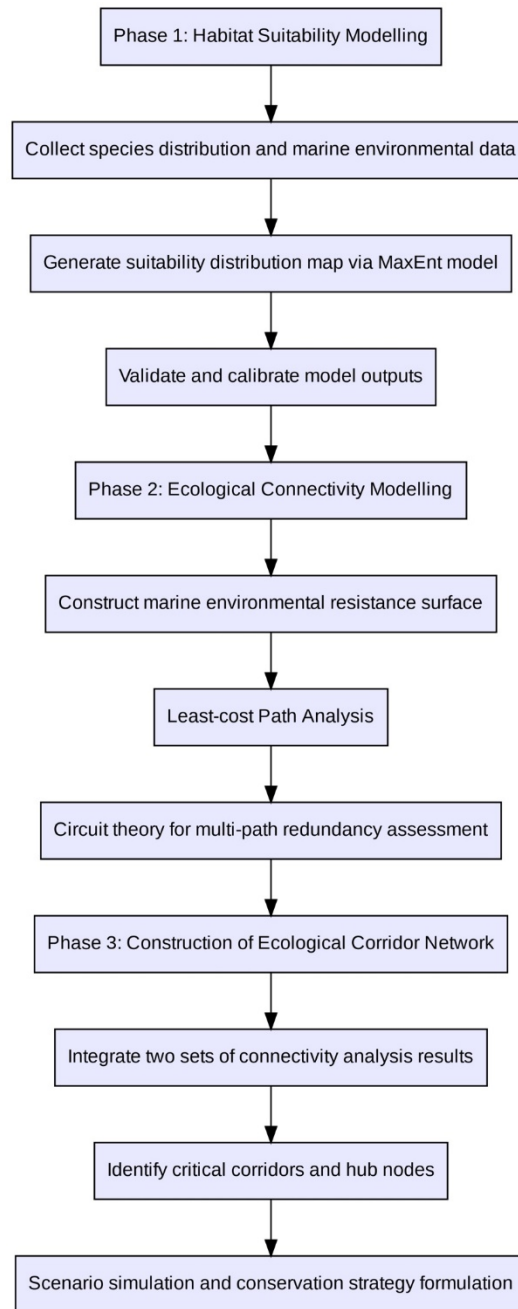


Figure 6: Three-stage workflow diagram of the marine long-distance migratory species conservation management toolkit

4.4 High-fidelity marine environmental dynamic base supporting ecological computing

Data quality and representativeness have always been the bottleneck restricting the reliability of species distribution models. To address this issue, this methodology is built based on a multi-scale, full-coverage marine dynamics coupled forecasting

system and an integrated observation base. In order to depict the dynamic habitat characteristics relied upon by long-distance migratory species at the bottom layer, the system constructs a computing engine with both high-resolution forecasting capabilities and real-time dynamic data assimilation functions by deeply coupling advanced dynamic theories and intelligent observation technologies. This base system mainly consists of three core components:

- I. Fundamentals of forecast engine based on hydrodynamic coupling
Aiming at the limitations of traditional numerical models in upper ocean simulation, a high-order forecast engine based on dynamic coupling modeling is introduced in this system. By originally implanting the dynamic mechanism of "wave-turbulence mixing", the system can accurately couple the following key physical processes in the process of operation, effectively reduce the simulation bias, improve the prediction accuracy of heat and momentum exchange in the upper ocean, and thus more realistically restore the extreme thermodynamic and dynamic environment faced by large-scale species during migration:
 - o Wave-induced mixing parameterization: Considering the controlling role of non-breaking ocean waves in turbulence mixing in the upper ocean, the structural simulation of the ocean mixed layer is significantly optimized, reducing the systematic biases in traditional simulations.
 - o Air-sea flux dynamic coupling: Introducing the influence of Stokes drift on air-sea fluxes (momentum exchange) and the nonlinear modulation effect of sea spray on heat fluxes (latent and sensible heat transfer). This scheme significantly improves the ability to simulate air-sea heat exchange under complex weather processes (such as typhoons and other severe disturbances).
 - o High temporal resolution coupling: Incorporating the diurnal variation process of sea surface temperature, enabling the model to capture sub-daily scale thermodynamic responses dominated by solar radiation and ocean mixing. The above dynamic coupling mechanism, through constructing a nested framework of ocean

numerical forecasting, typhoon dynamic simulation, and climate evolution models, realizes seamless forecasting from weather scale to climate scale, and from the ocean interior to the air-sea interface, providing the possibility for the underlying habitat driving field that conforms to the laws of physical conservation.

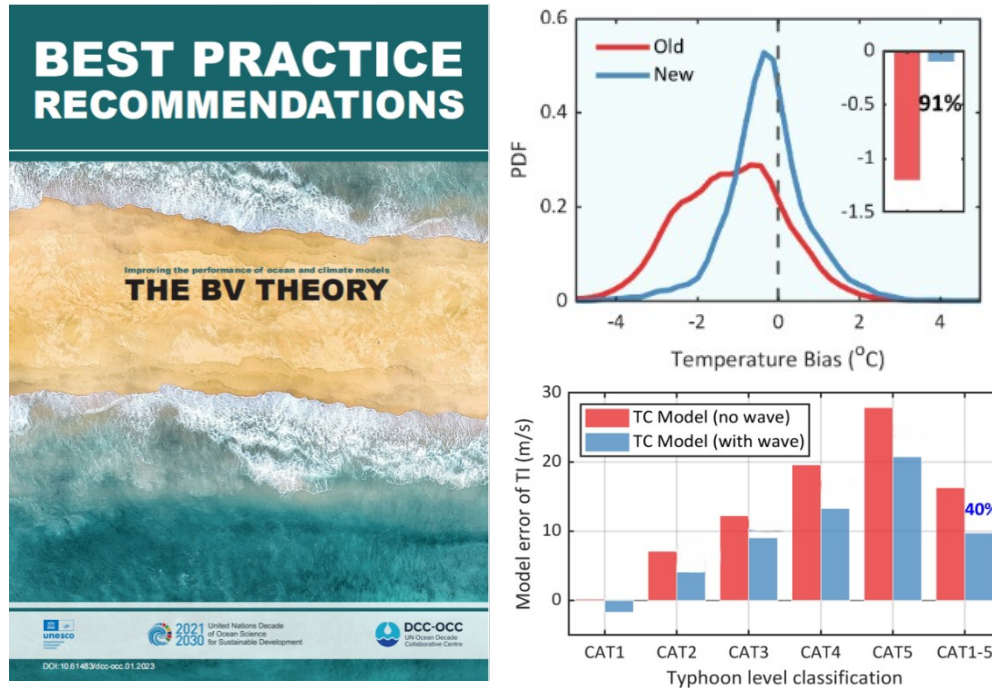


Figure 7 Theory of wave-induced mixing and its improvement effect on ocean and typhoon forecasting

- II. New Multi-parameter Intelligent Observation Base At the observation input end, to solve the technical bottlenecks of high cost and low precision in oceanic and deep-sea observation, the system integrates a new generation of multi-parameter intelligent buoy network based on GNSS satellite navigation technology. Through interdisciplinary technological innovation, this observation base constructs a low-cost and high-efficiency environmental information perception system, ensuring the integrity of habitat parameter acquisition:
 - o Multi-parameter synchronous extraction technology: Abandoning the traditional single sensor stacking mode, through independently designed signal processing algorithms, deeply mining GNSS satellite original data, realizing the synchronous acquisition of key

environmental elements such as ocean waves, water level, ocean surface current velocity, and atmospheric water vapor content by a single buoy, fundamentally overcoming the worldwide problem of multi-parameter synchronous acquisition.

- o Lightweight and large-scale observation system: Significantly reducing the manufacturing and operation and maintenance costs of individual observation equipment through miniaturization design, making large-scale and high-density buoy array deployment possible, providing a practical solution to make up for the lack of real-time on-site observation data in the global far-reaching sea areas.
 - o Multi-source data assimilation and fusion: This observation base, together with satellite remote sensing large-area coverage data and shipborne section observation data, constitutes a multi-source data input stream. Using a parallel ensemble Kalman filter assimilation system, this toolkit realizes real-time fusion of on-site observations and numerical forecast fields, significantly correcting the spatial discrete error of the forecast initial field, and ensuring the temporal and spatial continuity of the driving matrix. This seamless temporal and spatial connection is crucial for capturing transient habitat changes on large-scale migration paths.
- III. Empirical Validation of Complex Disasters and Trajectory Forecasting To verify the robustness and extrapolation prediction capability of the dynamic model, the forecasting core of this system has undergone empirical validation and systematic iteration in multiple complex marine dynamic scenarios. Relying on a mature physical drift tracking algorithm, the system is capable of inverting the dynamic trajectories of various particles in complex sea areas. In actual operational processes, these core algorithms, which have been tested in real disaster scenarios such as oil spill diffusion, floating object drift, and search and rescue trajectory prediction, have undergone ecological transformation: the system can combine atmospheric background fields to simulate the spatiotemporal distribution characteristics of marine organisms (such as

passive transport of larvae) and human activity pollutants (such as ship oil spills) in complex flow fields.

This empirical validation process not only ensures that the system can output prediction results with high spatiotemporal consistency when facing sudden marine environmental disturbances but also provides a decisive underlying validation basis for the aforementioned species spatiotemporal distribution patterns and corridor connectivity analysis. At this point, the complete methodological system composed of the front-end ecological spatial analysis algorithm and the underlying high-fidelity marine dynamic base has laid a solid scientific foundation for addressing cross-border protection and adaptive management of long-distance migratory species.

5. Application Cases and Toolkit Implementation Recommendations

To better illustrate the application of this toolkit in actual marine conservation management, the following takes cetacean conservation as an example to discuss how to use this toolkit to achieve conservation management of long-distance migratory species.

5.1 Distribution and Suitability Prediction of Cetacean Habitats

This section of the report aims to explore the actual construction process and output performance of habitat suitability models for species with complex ecological habits in large-scale spaces through specific flagship species empirical analysis. Considering the important role of the APEC region and the Pacific Ocean in maintaining global marine biodiversity, this study selected a typical oceanic long-distance migratory species - the humpback whale (*Megaptera novaeangliae*) - as the core research object. By combining its long-term accumulated on-site observation points with multi-dimensional spatial remote sensing environmental data, the study attempts to comprehensively evaluate the potential habitat distribution pattern of this species from a more macroscopic Pacific-centered perspective, thereby demonstrating the application potential of multi-algorithm combination models in ecological spatial analysis.

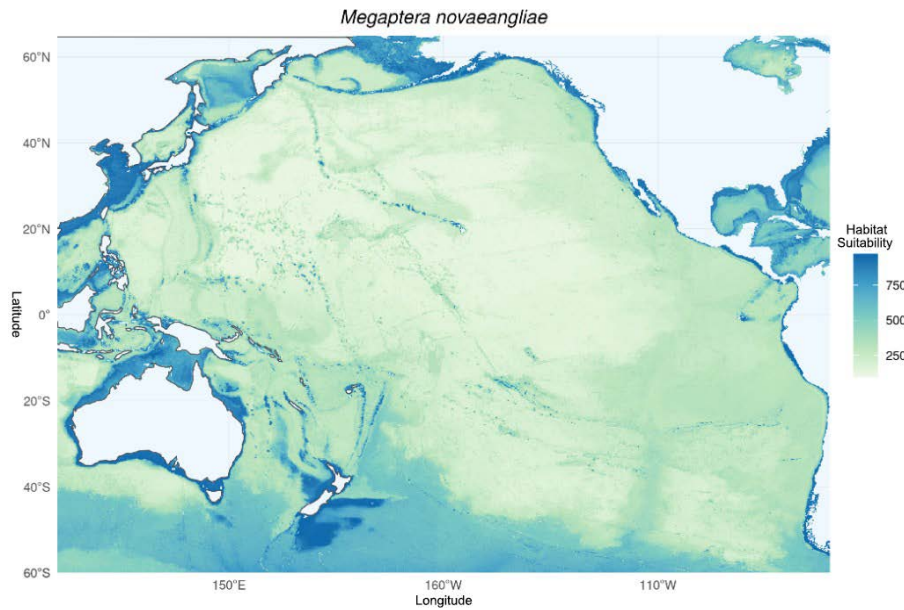


Figure 8: Humpback Whale Habitat Suitability Prediction Map in the APEC Region

First, through the combination of on-site monitoring data and satellite remote sensing data, collect cetacean distribution information and marine environmental parameters (sea surface temperature, substrate, current velocity, etc.). Use the MaxEnt model to construct a cetacean habitat suitability map, clarifying their main activity areas, foraging areas, and breeding areas. Model validation can use historical data and cross-validation methods to improve prediction accuracy.

In the initial preparation stage of building the model, the research team carefully considered the quality and ecological representativeness of the input data. In the selection of environmental variables, not only the sea surface temperature (SST), which can reflect the thermodynamic characteristics of water body, but also the chlorophyll concentration, which represents the primary productivity level, the topographic characteristics, which reflect the local undulation of the seabed, and the real physical water depth of the ocean are introduced. The comprehensive consideration of these dimensions is mainly to meet the complex environmental needs faced by humpback whales at different life cycle stages. For example, surface water temperature is directly related to its physiological heat tolerance limit, chlorophyll concentration can be used as an indicator of potential food abundance, while water depth and topographic undulation are often closely related to the formation of upwelling and the hidden haven demand during breeding period.

At the same time, considering that large-scale observation data of global species often have spatially sampling biases with regional concentration (for example, records in coastal waters or specific scientific research routes are relatively redundant), this case implemented relatively spatial gridding thinning and data cleaning work before modeling. This step performs deduplication screening based on the spatial resolution of environmental data to ensure that only valid representative points are retained within the same habitat grid. This preprocessing method has weakened the spatial autocorrelation problem caused by clustered observation points to a certain extent, attempting to avoid excessive fitting of the model to high-frequency observation areas as much as possible, thereby helping to improve the objectivity and spatial generalization ability of subsequent model learning.

In the construction of the algorithm framework, this case implements the single model technical route advocated by this toolkit, and takes the fine-tuned maximum entropy model (MaxEnt) as the core deduction algorithm. In order to overcome the overfitting limitation and prediction bias of traditional single model under default parameters, we introduce a systematic Grid Search and parameter traversal mechanism in practice. On the basis of multi-round K-fold cross-validation, the model optimizes the Regularization Multiplier (RM) and different Feature Classes (such as linear, quadratic and fragmented features), and selects the global optimal parameter set according to the corrected Akaike Information Criterion (AICc). The probability spatial distribution map of habitat suitability finally output by this optimization framework retains the high ecological interpretability of a single model (it can clearly show the response curve of humpback whales to specific environmental gradients such as temperature and chlorophyll), and also shows smooth and relatively robust spatial gradient changes on the map, thus providing highly objective and rigorous data support for subsequent ecological corridor identification and macro management interpretation.

Observing the final output of the APEC regional humpback whale habitat suitability prediction map, it can be found that its spatial distribution exhibits obvious regional heterogeneity characteristics, which is in good agreement with the biological observation records of the species' long-distance migration. First, in the high-latitude zones of the Northern Hemisphere as shown on the map (such as the Bering Sea and the coastal areas around the Gulf of Alaska) and the margins of the Southern Ocean in

the Southern Hemisphere, the model has fed back contiguous areas with high suitability (represented by dark blue patches in the map). From the perspective of marine ecosystem operation, these areas are comprehensively influenced by polar cold water masses and ocean current convergence, and usually have high primary productivity, which can nurture abundant krill and small fish resources. Therefore, the high suitability evaluation of the model reasonably reflects the potential ecological value of these sea areas as places for humpback whales to forage intensively and store energy in summer.

Secondly, in the low-to-mid latitude coastal and island reef waters on both the eastern and western sides of the Pacific Ocean (such as along Central America, the Hawaiian Islands, the east and west coasts of Australia, and around New Zealand), the model also identifies patches with relatively high suitability. This distribution pattern well reflects the specific habitat preferences of humpback whale mothers during the winter breeding period. The relatively warm sea surface water temperature can help newborn calves, which lack a thick fat layer, maintain a relatively stable body temperature, while the relatively shallow continental shelf water depth and complex seabed topography provide them with natural shelters to a certain extent, helping to reduce the ecological risk of encountering large deep-sea predators. The high suitability assigned by the model to these shallow warm water areas reflects the weight shift of environmental variables in different life history stages of the species.

In addition, it is worth focusing on the vast deep-sea hinterland of the Pacific Ocean. In the forecast map, this vast ocean heartland generally presents low fitness levels (dominated by large areas of light green tones). This result reflects more intuitively the spatial distribution limitation of marine food web. Because the central area of the deep ocean often lacks strong vertical upwelling and relatively scarce nutrients, it is difficult to support the huge energy consumption of humpback whales, a giant filter feeder, for a long time. As a result, humpback whales usually have fewer long-term residencies in these areas. Relatively speaking, these low-fitness deep vast waters are more ecologically used as transition zones for species to travel long distances between feeding grounds and breeding grounds in the northern and southern hemispheres.

Overall, the above suitability prediction model based on multi-dimensional environmental variables and the MaxEnt algorithm vividly and robustly presents the

potential macro-distribution trend of humpback whales at the Pacific scale. The prediction results well reflect the species' habitat selection tendencies under different latitudes and water depth gradients, and clarify the spatial distribution characteristics of potential feeding areas and breeding areas. This not only provides a spatial reference for large-scale marine species protection, but also prepares detailed spatial bases and analysis conditions for the next stage of exploring the potential connections between these core distribution patches and constructing spatial connectivity and ecological network corridors across the ocean.

5.2 Application of Ecological Corridor Identification in Cetacean Conservation

Considering the macro-ecological characteristics of long-distance migration in large baleen whales, their migration routes often span multiple economies' exclusive economic zones and vast open ocean areas. Although traditional Species Distribution Models (SDMs) can effectively identify static suitable habitat patches (such as high-latitude feeding areas in summer and mid-low latitude breeding areas in winter), they often struggle to directly reveal the dynamic spatial connections between these core habitat patches. Therefore, this section of the report attempts to introduce the connectivity analysis framework from landscape ecology based on habitat suitability assessment. By constructing complex resistance surfaces and migration networks covering multi-dimensional environmental variables, this study aims to identify potential transoceanic ecological corridors and geographical bottlenecks for humpback whales, thereby providing a more coherent scientific basis for formulating multi-level, cross-regional marine spatial conservation measures.

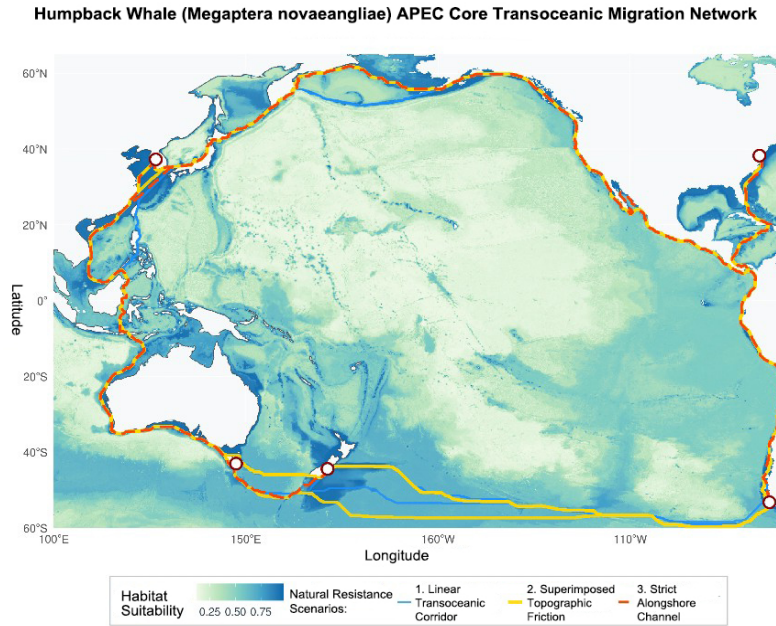


Figure 9: Predicted Map of Humpback Whale APEC Transoceanic Migration Network

In the initial stage of conducting spatial connectivity simulations, the extraction of core nodes and the objective construction of spatial matrices are prerequisites for ensuring the rationality of the analysis. Based on the suitability probability distribution extracted by the aforementioned combined model, this case preliminarily identified multiple representative core habitat patches in the APEC and surrounding waters by setting relative suitability thresholds and connectivity area thresholds, designating them as potential "sources" and "sinks" for simulating migration paths. It is important to note that for spatial simulations of transoceanic migrations of pelagic ocean species, traditional global geographic coordinate systems often result in artificial geographical discontinuities and visual distortions in spatial algorithms within the central Pacific due to the rigid division by the International Date Line (180° meridian). To address this, this study implemented coordinate reconstruction in the underlying spatial operations, converting the analysis matrix to a native Pacific-centered perspective. This spatial translation and seamless stitching of the underlying matrix enable the model to more objectively assess the true geographical distances and environmental connectivity costs across the entire Pacific basin while minimizing boundary effects.

Regarding the construction logic of the Resistance Surface—a core component in ecological corridor identification—this case did not limit itself to a simple "inversion

of suitability" algorithm but instead attempted to reconstruct multiple natural scenarios by incorporating the complex three-dimensional space utilization characteristics of humpback whales. Typically, relying solely on the reciprocal of suitability would assign extremely high exponential resistance to the deep ocean, causing model paths to overly adhere to coastlines and fail to simulate realistic transoceanic behavior. To address this, the study designed progressive resistance constraint scenarios. In the basic transoceanic scenario, the model converts suitability into a relatively gentle linear resistance. This setting aims to reflect the ecological reality that while the deep ocean lacks sufficient food resources, it possesses potential as a rapid transit corridor at the macro scale, thereby partially releasing the computational tendency of species to cross oceans in search of the shortest geographical path.

On this basis, in order to more objectively simulate the energy loss process of large-bodied cetaceans in complex marine fluid environments, the advanced resistance surface further incorporates fluid friction variables derived from seabed topographic undulations and local hydrodynamic characteristics. This spatially heterogeneous environmental penalty mechanism attempts to reproduce the migratory cost trade-offs that species face when passively avoiding areas with drastic seabed topographic changes or turbulent ocean currents during long-distance migrations.

Additionally, the model retains a stringent suitability trunk scenario constrained by extremely high environmental resistance for comparative analysis. Through multi-scenario simulations using pathfinding algorithms such as the Least Cost Path, the simulation results interweave to form a relatively complex ecological network corridor across the Pacific basin. This network not only demonstrates potential transoceanic linear pathways connecting the Northern and Southern Hemispheres but also outlines secondary wandering routes that are more influenced by local environmental heterogeneity and relatively close to the edge of continental shelves. It effectively reconstructs the species' trade-off strategy between "pursuing lower time costs (shortest distance)" and "seeking lower environmental pressure (high-suitability detour)".

Through spatial superposition and comparison of corridor networks under different natural constraint scenarios, the system identified several potential ecological choke points or spatial bottlenecks (Pinch points) at the macro scale. These

potential bottleneck areas are typically located at the intersections of island chains and basin edges where the geographical space is relatively narrow or the deep-sea environmental resistance on both sides rises sharply, forcing multiple theoretical migration routes to highly overlap and converge here. From the perspective of conservation biology, these naturally formed convergence nodes often represent vulnerable spaces where species experience relatively high energy consumption during migration and are more sensitive to external environmental changes. Although this empirical simulation primarily focuses on exploring the baseline constraints of the natural environment dimension, these clearly identified natural spatial bottlenecks provide basic spatial anchors for subsequent superimposition of human activity disturbances. In future in-depth studies, if high-density commercial shipping's dynamic underwater acoustic interference or fishing operation hotspots can be spatially intersected with these natural choke points, it will help further reveal high-risk areas for ship strikes and noise masking. Clarifying the geographical distribution of these natural corridors and spatial bottlenecks not only supplements empirical evidence for transoceanic connectivity theory but also prepares a macro decision-making base map with certain reference value for future discussions with relevant APEC regional institutions on the design of transboundary dynamic marine protected area (MPA) networks.

5.3 Connectivity Evaluation and Conservation Decision-Making

Using graph theory methods to analyze cetacean ecological networks, connectivity indicators (such as node degree centrality, path redundancy rate, etc.) are calculated to identify node regions that play a key role in improving the stability and connectivity of the overall ecological network. Once these regions are confirmed, decision-makers can implement special protection measures based on their importance, such as restricting ship navigation, enhancing monitoring, and providing ecological compensation.

For key hub areas with high node degree centrality (such as deep-sea seamounts or persistent upwelling zones that serve as intersections of multiple migration routes), single static enclosure protection often conflicts with traditional shipping networks in the area. Therefore, measures restricting ship navigation should develop towards

dynamization and refinement. Management departments can delimit Dynamic Speed Reduction Zones in these hub areas based on model-output seasonal suitability probabilities. During hydrological windows when cetaceans frequently pass through, large merchant ships are required to reduce their speed to a specific safety threshold (e.g., below 10 knots). This measure can not only significantly reduce the probability of fatal ship strikes but also effectively reduce low-frequency underwater noise caused by propeller cavitation, thereby providing an acoustic shelter corridor for cetaceans that are highly dependent on echolocation.

Secondly, for vulnerable connectivity bottlenecks with low path redundancy (i.e., narrow water areas lacking alternative migration routes), enhancing monitoring measures requires the introduction of three-dimensional technical means. In such high-risk areas, coastal states can deploy an integrated early warning network including Passive Acoustic Monitoring (PAM) arrays, Unmanned Surface Vehicles (USVs), and high-frequency coastal radars. These monitoring facilities can capture transient cetacean transit signals in real-time and synchronously transmit the data back to the maritime traffic management center, thereby triggering temporary Route Deviation or pilot warnings. At the practical level of ecological compensation, for regional stakeholders who suffer losses in fishery output or shipping efficiency due to protection implementation, the connectivity quantification indicators provided by the toolkit serve as the basis for scientifically calculating compensation standards. Decision-making departments can establish a stepped ecological compensation fund distribution standard based on the marginal contribution rate of a protected node to maintaining the connectivity of the entire macro-network, ensuring that limited protection funds can be precisely allocated to communities and industries that play a core supporting role in maintaining the stability of regional ecosystems, thus ensuring the ecological bottom line while taking into account the stable operation of the blue economy.

The following table shows the comparison of terrestrial ecological corridor methodology and marine ecological corridor tools in terms of key parameter weighting:

Table 5: Application Evaluation Comparison of Marine Ecological Corridor Tools

APPLICATION FREQUENCY RANKING	ALGORITHM NAME AND ABBREVIATION	CORE FEATURES	TYPICAL APPLICATION SPECIES	MAIN APPLICATION SCENARIOS
1	Random Forest (RF)	Ensemble learning, anti-overfitting, variable importance output	<i>Scomber</i> , <i>Thunnus</i> , <i>Salmo</i>	Widely applicable to various groups, especially commercial economic fish with large data volumes
2	Artificial Neural Network (ANN)	Nonlinear fitting, black-box model	<i>Salmo</i> , <i>Oncorhynchus</i>	High-precision prediction in complex marine environments, especially for anadromous fish
3	Generalized Additive Model (GAM)	Semi-parametric model, smoothing function	<i>Thunnus</i>	Traditional fishery-environment relationship analysis, often used to explain environmental thresholds
4	Maximum Entropy Model (MaxEnt)	Only requires occurrence point data	<i>Leatherback/leatherback turtle hatchlings</i> , some <i>Salmo species</i>	Data-scarce species, benthic invertebrates, polar species
5	Boosted Regression Tree BRT/GBM	Gradient Boosting, Ensemble Learning	<i>Scomber</i>	As a supplement to RF, it is often used in model performance comparison studies

For example, Generalized Additive Models (GAM), due to their excellent ability to fit smooth functions, are often used to explain the threshold response curves of species to single environmental variables (such as water temperature steps, salinity fronts). When formulating adaptive conservation strategies for global warming,

management departments can rely on the temperature tolerance inflection points output by GAM to identify in advance vulnerable marine areas that may lose corridor functions due to warming in the next decade. For areas with serious observation data gaps such as the high seas and deep seas, the Maximum Entropy Model (MaxEnt), with its robust performance under the condition of only presence data, can outline the potential connectivity baseline map for data-scarce species (such as deep-diving cetaceans or deep-sea corals), providing a basic basis for preventive spatial planning.

When dealing with highly complex modern marine multi-source data, ensemble learning algorithms such as Random Forest (RF) and Boosted Regression Tree (BRT) show core advantages. They not only have excellent anti-interference and anti-overfitting capabilities, but also can output intuitive Variable Importance evaluation indicators. Based on these indicators, decision-makers can clearly determine whether natural hydrological factors (such as eddy kinetic energy) or human disturbance factors (such as high-intensity bottom trawling operations) play a dominant role in blocking ecological corridors in a specific sea area. This attribution analysis based on algorithm characteristics enables the formulation of protection measures to be targeted, avoiding resource waste caused by one-size-fits-all management.

In addition, to address issues such as insufficient data, dynamic marine environment changes, and cross-regional management that may be encountered during implementation, this toolkit also recommends cooperating with a scenario simulation module to predict connectivity under future marine environment changes and assist managers in formulating flexible emergency protection strategies.

In long-term management practices, static planning schemes are difficult to effectively respond to complex and changeable natural and human disturbances. The introduction of the Scenario Simulation Module endows the protection decision-making system with strategic depth for predicting the future. This module allows policymakers to deduce the macro ecological impacts brought by various hypothetical premises in the background sandbox, thereby reserving a flexible policy toolbox to deal with unknown risks.

To address the normalization challenge of insufficient data, the scenario simulation module can adopt the strategy of Surrogate Species migration or knowledge graph transfer learning. In the sea area lacking a continuous observation

trajectory of a certain migratory species, the model can generate probabilistic distribution hotspots by simulating the activity laws of species with similar ecological niches or trophic levels, and add artificially set confidence interval error bands on this basis. This simulation not only fills the cognitive gap in management, but also provides guiding spatial guidance for the sampling route design of subsequent scientific expedition voyages.

Facing dynamic changes in the marine environment, especially frequent extreme climate events (such as widespread marine heatwaves triggered by strong El Niño years), the scenario module can couple high-resolution climate prediction data. For example, the system can simulate the polar-ward migration trajectories of the main prey organism clusters of cetaceans under scenarios of abnormal increases in sea surface temperature or expansion of bottom dissolved oxygen depletion zones. Through quantitative prediction of the evolution trend of connectivity networks over the next 10 to 30 years, managers can proactively anticipate whether existing fixed marine protected areas will face the risk of Ecological Emptying in the future, thereby initiating the dynamic adjustment procedure for protected area boundaries in a timely manner.

In the complex cross-regional management dimension, flexible emergency protection strategies are the key to defuse multilateral conflicts of interest. Scenario simulations can prospectively quantify the cascading impact of increasing human activity intensity in different regions (such as the increase in navigability of an emerging economy-wide port or the delineation of deep-sea polymetallic nodule mining areas) on the overall ecological corridor resistance. By deducing the composite scenario of multiple human activities superposition and increased ecological resistance, it assists managers to formulate threshold-based Rolling Closures or maneuvering no-navigation mechanisms. This emergency intervention plan, which verifies its effectiveness through simulation rehearsal, not only enhances the scientific persuasiveness of transboundary management, but also provides a solid and prudent decision-making basis for maintaining the long-term balance between marine space development and long-distance migratory species conservation.

5.4 Transboundary Policy Coordination and Adaptive Management Practices

In the actual transboundary protection of cetaceans, traditional marine protected areas with fixed boundaries often struggle to match their migration routes that shift due to climate anomalies. Therefore, based on the adaptive management module of this toolkit, management authorities can jointly implement dynamic marine protected area strategies. For instance, when species distribution models, combined with seasonal abnormal sea temperature data, predict a spatial shift in cetacean foraging grounds, the connectivity evaluation module will recalculate the optimal ecological corridors. Subsequently, through regional multilateral cooperation mechanisms, economies along the route can quickly initiate emergency responses and implement temporary speed limits or acoustic disturbance restrictions in the newly designated key corridor waters. This data-driven joint adaptive management can minimize the risks of bycatch and ship strikes and also provide a successful practical paradigm for dynamic coordination of marine space across economies and sectors.

In the practical implementation of the above adaptive management paradigm, how to transform the macro theoretical framework into specific action guidelines that can guide domestic-level or even regional-level transboundary joint law enforcement is the core issue that this toolkit strives to address. This case has carried out technical and policy extensions in the aspects of transboundary data integration, multilateral interest coordination, and automated decision-making response, with detailed explanations as follows:

To support the delineation and real-time displacement of Dynamic Marine Protected Areas (dMPAs), the toolkit has restructured the data flow method in its underlying architecture and introduced a dynamic ensemble forecasting system.

Traditional marine ecological management often relies on retrospective analysis, which evaluates the distribution status of species through the aggregation and statistical fitting of historical data after the conclusion of annual or quarterly scientific expeditions. This rearview mirror-based management model inevitably results in significant policy lag when facing sudden environmental changes caused by climate change. To break this time barrier, this system can interface with real-time marine observation networks and satellite remote sensing cloud nodes in major ocean regions worldwide for real-time forecasting. Under this architecture, frequently updated oceanographic parameters can better drive model operations. The system can nearly real-time capture the anomalous fluctuation values of sea surface temperature (SST

Anomalies), reveal the chlorophyll concentration gradients of primary productivity blooms, and track the generation and dissipation trajectories of mesoscale eddies that dominate energy transport in oceanic waters. By dynamically injecting real-time physical fields into pre-trained and cross-validated Ensemble Species Distribution Models (Ensemble SDMs), dynamic real-time predictions are formed.

Therefore, the system has the ability to output the probability drift surface of cetacean core foraging hotspots and migration corridors on a rolling basis with days or even hours as time steps.

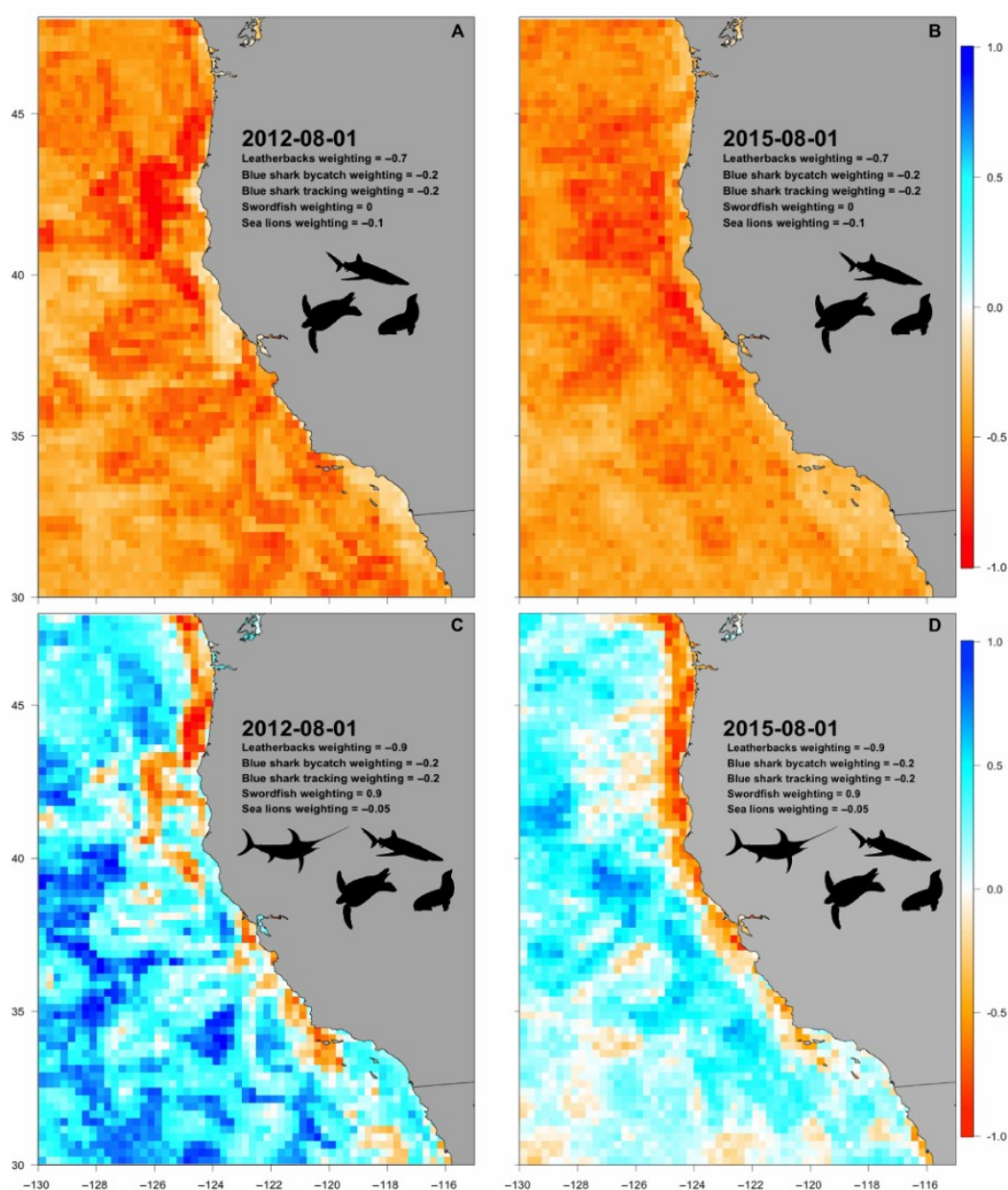


Figure 10. Predicted risk surfaces of bycatch species and integrated EcoCast products on 1 August 2012 and 2015 (Hazen et al., 2018)

As shown in the practice of the EcoCast tool developed by Hazen et al. (2018) in the California ocean current system (Fig. 10), the spatial distribution of high-risk pixels underwent a drastic restructuring when the marine environment changed from normal conditions in 2012 to an unusually warm water event in 2015. Specifically, a comparison of Figure 10A with Figure 10B (risk prediction surface for bycatch sensitive species only) shows that high-risk areas for leatherback turtles, blue sharks, and California sea lions were distributed from mesoscale structures primarily around offshore in 2012 to sharply contraction and shift to nearshore in 2015; Figures 10 C and 10D (comprehensive prediction surface after integrating the target species swordfish) further show that this prediction surface driven by real-time ocean variables (such as sea surface temperature anomalies) not only captures the habitat drift under climate forcing, but also integrates and quantifies the ecological red line (red high-risk area) and the economic blue ocean (blue high-value catch area) on the same spatial explicit plane through continuous color mapping from -1 (high side-catch/low target catch) to 1 (low side-catch/high target catch), which intuitively presents the spatial reconstruction of ecological and economic "win-win" areas and "conflict" areas under different climate forcing. This provides a visual decision base for the cross-sectoral dynamic early warning and bioeconomic game described below. Combined with Hidden Markov Model (HMM) behavioral decoding techniques for existing satellite tracking individuals, this near real-time response can be pushed to a more forward-looking predictive height. Hidden Markov models can keenly capture geometric features in the tracking trajectory (such as instantaneous changes in steering angle and moving step size), characterizing the current activity of the whale group as resident foraging or directional transoceanic. Through this, the management department can not only know the current geographical coordinates of the whale group, but also predict its swimming trend and potential spreading boundary in the short term (such as the next 48 to 72 hours) through a lower-level probabilistic dynamic model.

This predictive capability with a clear time lead provides a crucial golden window for transboundary joint early warning and intervention. For example, when it is predicted that a whale group is moving towards a high-risk operational sea area of a certain economy, the maritime department of that economy can receive early warning several days in advance, thereby having sufficient time to complete internal approval,

issue navigation notices, and deploy maritime law enforcement forces for preventive measures, transforming ecological protection from passive accident rescue to active risk avoidance.

In the actual interest game of transboundary coordination, the pure demand for ecological protection often appears thin, and even encounters strong resistance between the competent shipping authorities of coastal states and large-scale offshore fisheries departments. The ecological corridors of long-distance migratory species inevitably traverse global maritime trade arteries or traditional high-yield fishing areas. If the management scheme merely mechanically delineates no-navigation or no-fishing zones, it may lead to a stalemate in multilateral negotiations.

To this end, this implementation proposal suggests nesting a Spatially Explicit Bioeconomic Game Model within the policy coordination module. The original intention of this model is to recognize and quantify the interests of all parties, and to find the optimal compromise between ecological protection and the blue economy. When the dynamic forecasting system triggers an early warning, predicting that cetacean migration corridors are about to spatially overlap with economy-wide golden waterways or intensively operated fishing grounds, the underlying algorithm will activate a Multi-objective Optimization function. At the mathematical level, this function incorporates two major categories of conflicting indicators into the same calculation pool: On one hand, there are economic dimension losses, including the sharp increase in fuel costs and greenhouse gas emissions caused by requiring merchant ships to detour, the network logistics delay costs resulting from requiring merchant ships to slow down, and the direct yield losses faced by fishing vessels forced to transfer fishing efforts. On the other hand, there are ecological dimension risk thresholds, including the output of the probability model for cetaceans being killed by ship strikes at specific speeds, the bycatch rate associated with high-intensity fishing due to fishing gear entanglement, and the acoustic masking effect and communication space compression caused by low-frequency underwater noise from shipping on cetaceans' echolocation systems.

Through rigorous integer linear programming and game theory derivation, the toolkit can export multiple sets of highly operational compromise plans to the participating states parties on the premise of ensuring that the survival rate and connectivity of cetacean populations are not lower than the safety bottom line. These

proposals can provide more flexible spatial planning options while maximizing the interests of economies. For example, the system may suggest Stepped Speed Limits accurate to specific water depth gradients during specific high-risk climate windows (such as predicting that whales will cross a strait on a large scale in the next two weeks) -limiting the Speed to below 10 knots in the core high-density area and 15 knots in the edge gentle zone; Alternatively, for extremely high noise sources such as seismic exploration, the system will suggest a long and narrow acoustic silence corridor that is time-sensitive (e.g. only 72 hours), and require the relevant operating vessels to implement equipment silence during this period.

This dynamic management plan based on quantitative economic cost trade-offs presents a more detailed cost-benefit accounting ledger to various economies, which can reduce the political resistance to the implementation of multilateral policies to a certain extent. Decision-makers of various economies can choose the most cost-effective ecological intervention methods on the premise of clearly knowing the economic costs, promoting transboundary protection actions from conceptual consensus to practical cooperation.

Finally, to ensure that transboundary collaborative intervention is not only scientifically feasible but also institutionally guaranteed with rigidity, this case relies on the legal framework of regional economy-wide organizations (such as regional fisheries management organizations or multilateral marine environmental protection conventions in relevant sea areas) to design a set of data-driven transboundary dynamic trigger mechanisms. The protection of long-distance migratory species has long been plagued by delays in management measures. Traditional adjustments to economy-wide conventions often rely on lengthy annual diplomatic negotiations fraught with political uncertainty. By the time representatives from various economies finally reach an agreement on the protection boundaries of a certain sea area at the conference table, the actual state of the ecosystem may have already undergone irreversible changes.

This practical model advocates promoting consensus among economies and proposing protection plans based on consensus-based objective data. The network connectivity invulnerability indicators output by the toolkit are written into the implementation clauses of the multilateral cooperation Memorandum of Understanding (MoU). This means that when contracting parties reach a framework

agreement, they need to pre-establish legal consensus on a series of objective ecological early warning thresholds. Once the real-time monitoring platform of the toolkit, by assimilating the latest data, detects that the cumulative environmental pressure on the core corridor exceeds the pre-set critical value of ecological resilience, the system will automatically generate a high-risk early warning briefing. For waters within the Exclusive Economic Zone (EEZ), coastal states can immediately trigger the issuance of temporary speed limit recommendations through domestic Navigational Telex (NAVTEX); for high seas waters, the multilateral coordination mechanism can promptly submit Dynamic Routing Advisories to the International Maritime Organization (IMO), guiding surrounding merchant ships to voluntarily deviate their routes or slow down to avoid through maritime communication channels.

Sewing cutting-edge computing ecology algorithms with agile multilateral governance frameworks can eliminate the ecological risks caused by human-made administrative delays to the maximum extent, and enhance the credibility of transboundary law enforcement with highly transparent and objective data closed loop. If it is put into use, it can make the protection and management of long-distance migratory species in the ocean jump from a lagging and static paper agreement to a modern and dynamic defense system that can keenly adapt to global climate change and the transfer of human activities, and provide a dual-track landing scheme of technology and system for the construction of a global marine community with a shared future.

5.5 Empirical Testing of Underlying Dynamic Models and Multilateral Technical Empowerment

The prediction accuracy of any high-level niche model and connectivity algorithm is subject to the reliability of the underlying physical marine environment driving field. To verify the robustness of the toolkit's underlying "wave-tide-circulation coupling" dynamics engine, the core forecasting module of the system has undergone empirical testing in various complex marine emergency incidents, and on this basis, has exported substantial technical empowerment to globally vulnerable sea areas through multilateral mechanisms.

- I. Empirical Testing of Trajectory Drift in Complex Disaster Environments The passive diffusion of long-distance migratory organisms during their larval stage shares a high degree of physical homology with the dynamic mechanisms of marine surface floaters. The underlying oil spill and trajectory prediction modules of this toolkit have undergone practical testing in several major economy-wide marine emergencies. The system has successively conducted dynamic trajectory inversion and diffusion range prediction for the 2006 Bohai Sea Oil Spill, the 2008 large-scale *Enteromorpha prolifera* disaster in the Yellow Sea, the 2011 Fukushima Nuclear Sewage Leak in Japan, and the 2018 Donghai "Sanchi" Oil Spill Accident.

Particularly in the extreme application scenario of Search and Rescue (SAR) at sea, the model has demonstrated extremely high near-real-time forecasting accuracy. In the 2018 major cruise ship capsizing accident in Phuket, Thailand, and the 2022 maritime disaster in Cambodian waters, the technical team relied on the drift prediction technology underlying the toolkit, coupled with real-time wind field, wave, and high-resolution ocean current data, to simulate the dynamic drift trajectories of people overboard and floating objects under complex sea conditions. The high-probability search "target areas" output by the system helped frontline rescue forces significantly reduce the blind search area, and all victims and people overboard were ultimately found within the target areas predicted by the model. Such extreme search and rescue operations not only prove the accuracy of the underlying physical model but also indirectly confirm the reliable computing capability of the system in tracking the passive transport trajectories of marine organisms.

- II. Transboundary Deployment of Observation Bases and Data Reflow High-quality forecasting is inseparable from the assimilation and correction of in-situ observation data. To compensate for the lack of in-situ observation data in global oceans, especially in the waters surrounding Small Island Developing States (SIDS), the hardware observation base of this toolkit has carried out extensive transboundary deployments. At the level of integrated coastal zone management, the R&D team collaborated with the Phuket Marine Biological Center in Thailand to build a land-sea joint observation station. By delivering independently developed integrated land-sea monitoring equipment, this station has achieved long-term in-situ continuous observation of key indicators such as

seawater intrusion, coastal erosion, and coastal seasonal hypoxia, completely breaking the data bottleneck faced by nearshore ecological research in the economy.

In the broader open oceans, the new generation "Jingwei" multi-parameter marine observation buoys supporting the toolkit have been systematically deployed in the jurisdictional waters of small island economies such as Fiji, Yemen, Maldives, Antigua and Barbuda. These low-cost, high-efficiency observation nodes not only enhance the recipient economies' local perception capabilities of climate change and extreme marine weather but also their returned real-time temperature, salinity, and air-sea flux data further feed back and assimilate into the global numerical forecasting field of the toolkit, forming a positive iterative data ecological closed loop.

III. Regional Customization of Forecast Products and Multilateral Capacity Building

Facing the common challenges for the sustainable development of global ocean cities, the digital forecast products of the toolkit have been directly adopted by meteorological and oceanographic management departments in multiple economies as the basic foundation for operational implementation. For example, the system provides stable open boundary forcing conditions for the high-resolution regional operational forecast model of the South African Weather Service; assists the Nigerian Meteorological Agency in completing the historical baseline assessment of complex hydrological conditions in the sea areas under its jurisdiction; and supports academic institutions such as the University of Terengganu in Malaysia to develop a locally adapted multi-hazard early warning system (MultiEars) based on the underlying interfaces of this toolkit.

By combining technological empowerment with data sharing, the capacity building module supporting the toolkit has trained nearly 800 professionals in marine science and spatial management for 18 economies worldwide (such as Egypt, Nigeria, etc.). This full-link economy-wide collaboration, ranging from underlying hardware deployment, forecast product distribution to personnel technical training, not only verifies the universality of the toolkit as a global public good but also provides a replicable regional technical empowerment model for solving the dual dilemma of "technical barriers and data silos" in transboundary ocean governance.

6. Economy-wide Cooperation under the

APEC Mechanism: Data Sharing and Collaborative Protection

The activity range of long-distance migratory marine species often spans the jurisdictional waters and high seas of multiple APEC economies, making it difficult for the conservation measures of a single economy to cover the needs of their complete life cycle. As an important multilateral cooperation platform in the region, the Asia-Pacific Economic Cooperation (APEC) has potential institutional advantages in promoting data sharing, collaborative protection, and capacity building. This chapter focuses on elaborating how the APEC mechanism can provide institutional support for the toolkit proposed in this paper, mainly including the data sharing framework, collaborative protection directions, and a simplified cooperation roadmap.

6.1 Data Sharing Mechanism

- **Standardized Data Interface:** Relying on the marine data metadata standards advocated by APEC, the heterogeneous environmental and biological data provided by various economies are uniformly preprocessed and directly connected to the data input module of the toolkit.

To achieve this goal, the toolkit will build a semantic ontology-based cross-source data alignment engine at the data ingestion layer, implementing the data interoperability principles advocated by the APEC Ocean and Fisheries Working Group (OFWG). In specific implementation, the so-called "relying on marine data metadata standards" means forcing the fragmented local data in various formats from different economies to be mapped to economy-widely recognized metadata specifications. For example, for biological survey data such as species occurrence points, the engine has a built-in automatic conversion dictionary to the Darwin Core (DwC) standard, which uniformly standardizes taxonomic ranks, observation time (uniformly converted to ISO 8601 format), and spatial coordinate fields; for physical oceanographic raster data such as sea temperature and current fields, it strictly follows the Climate and Forecast Metadata Conventions (CF Conventions) and ISO 19115 geospatial metadata standards for label alignment.

Due to significant differences in measurement accuracy, time span, and spatial resolution of parameters such as ocean currents, temperature, and sediment among

different participating economies, the engine will use multi-dimensional tensor interpolation and spatio-temporal resampling algorithms under the unified framework of the above metadata standards to force discrete heterogeneous data into standard matrices directly readable by the model. At the same time, the built-in automated quality control pipeline can real-time eliminate abnormal outliers caused by sensor drift or transmission packet loss, ensuring that the data base entering the prediction center has high physical consistency and statistical purity.

On top of this technical foundation, the promotion of standardized interfaces will also align with the APEC regional data governance framework. By establishing a multilateral recognized data mapping dictionary, the engine can automatically identify and convert proprietary data formats from different jurisdictions, effectively reducing the technical threshold for each economy to participate in joint modeling. The standardized operations at the data ingestion end enable the stitching of cross-ocean basin-scale environmental layers and fundamentally ensure the comparability and scientific credibility of species distribution model output results at the regional level. As standardized interfaces are regularly opened to more Asia-Pacific coastal economies, the system's ability to characterize the spatio-temporal heterogeneity of environmental covariates will be substantially enhanced.

- Cross-border observation network: Within the framework of the APEC Ocean and Fisheries Working Group, encourage economies to share occurrence records of long-distance migratory species (such as observation data, satellite beacon trajectories, etc.) to fill data gaps in high seas areas.

Under the policy guidance of APEC multilateral cooperation, such collaborative protection requires economies to establish a normalized sharing system of "observation mutual recognition and data intercommunication". A single economy relying on limited scientific research vessels and monitoring networks within its exclusive economic zone cannot cover the complete life cycle of migratory species across several ocean basins. Therefore, the key to solving the lack of data in high seas and deep seas lies in promoting coastal economies to break the administrative boundary thinking at the policy level and establish a regional cooperation mechanism of active collaboration, mutual trust and sharing.

Specifically, multilateral policies encourage cross-border administrative

integration of Member States' decentralized scientific research resources, monitoring platforms and even opportunistic sensors mounted on commercial ships. Through effective coordination of policies within the region, all economies can jointly establish unified data collection standards and error compensation agreements, so that those observation data originally scattered at the edge of the sea areas under the jurisdiction of various economies can be imported into the data bus jointly built by APEC region without any political and technical obstacles. This type of resource pooling, based on mutual trust in policy, can not only greatly expand the sample repository for deep-sea regions at an extremely low marginal administrative cost, but also foster regional synergy, correct extrapolation biases in species distribution models for undersampled sea areas, and fill geographical data gaps through transboundary data sharing.

Furthermore, in terms of substantially filling the cognitive gap between three-dimensional and hidden species, multilateral coordination at the policy level has also paved the way for the transboundary implementation of high-precision observation technologies. For rare migratory populations that are difficult to directly observe in the deep and high seas, APEC economies are no longer fighting alone, but can jointly launch regional special actions for frontier observation. For example, with the support of multilateral policy authorization and regional funds, scientific research voyages of various economies can share the task of collecting water samples for environmental DNA (eDNA) analysis, and jointly build a regional marine DNA barcode database; at the same time, through bilateral or multilateral agreements, bioacoustic monitoring array interfaces within jurisdictional sea areas are shared for cross-validation across domestic boundaries. This brand-new collaborative model, which breaks the situation with mutual trust in policies and drives the convergence of technologies, will fill the systematic cognitive gap left by traditional unilateral fishery-dependent data in the wide ocean. It will promote the Asia-Pacific economies to truly move from conservative data defense to open data co-construction, and jointly draw a three-dimensional map of marine life activities with no dead ends and high dynamic resolution.

- **Dynamic Data Exchange:** For near-real-time environmental data such as ocean currents and temperature, reference can be made to existing bilateral or multilateral data exchange arrangements in the region to provide dynamic input for the adaptive management module of the toolkit.

In order to ensure low latency and high fidelity of near real-time input, the data exchange base needs to integrate edge computing and low-orbit satellite communication technology. When ocean buoys or beacons carried by animals capture sudden ocean heat waves or abnormal temperature fronts, the edge computing nodes can complete the preliminary filtering and feature extraction of data in situ, and then push the highly compressed key environmental variation signals to the central collaboration server in seconds through satellite broadband. This high-frequency dynamic injection mechanism enables the adaptive management module of the toolkit to get rid of the lag dependence on historical meteorological reanalysis data, and effectively realize the computational response and transboundary early warning of synchronously triggering the potential distribution shift of long-distance migratory species at the moment when the physical marine environment changes drastically.

In institutional practices at the regional level, dynamic data exchange is not limited to meteorological and hydrological parameters but will gradually incorporate spatial intensity indicators of human activities. For example, by accessing regional Automatic Identification System (AIS) data and fishing effort grid data, the system can monitor real-time fluctuations in the artificial resistance surface within potential corridors. When deviations in natural habitats overlap with high-intensity human activities within short temporal and spatial domains, the dynamic data exchange hub can issue early warning signals to maritime regulatory and fisheries authorities of relevant economies, thereby gaining valuable scheduling cycles for implementing adaptive interventions with higher temporal and spatial precision.

The above mechanism must respect the data sovereignty and confidentiality requirements of each economy and be promoted on the principle of voluntary reciprocity.

On the basis of the aforementioned data sharing framework, to effectively address economies' concerns about sensitive data sharing and break down information barriers, future data cooperation needs to introduce a collaborative network based on the principle of "usable but invisible", such as federated learning mechanisms. The core of federated learning lies in allowing statistical models to be trained on remote devices or isolated data centers (such as local marine monitoring systems of various economies) while keeping data localized (McMahan et al., 2017; Li et al., 2019). In the past, requiring economies to centrally share underlying raw data such as

hydrological and topographical data involving domestic interests often faced significant policy resistance due to domestic security concerns. However, under this new mechanism, each participating economy only needs to analyze data in its local network to ensure that original observation records never leave the economy. During cross-border joint evaluations, instead of transmitting raw data, the systems of all parties only submit desensitized and encrypted model updates (such as gradient information or feature weights) to the central server, avoiding the transmission of specific original spatiotemporal coordinates (Li et al., 2019). This model eliminates the risk of outflow of strategic marine data to a certain extent. Although mere model updates may still face potential privacy leakage challenges (Li et al., 2019), by combining technologies such as differential privacy or secure multi-party computation, it not only ensures the core information security of each economy but also successfully integrates scattered regional data into an ecological connectivity model covering the entire ocean, substantially enhancing political mutual trust in multilateral cooperation. The core of this new mechanism lies in its network topology, which is shifting from the traditional data aggregation center model (star network) to a cross-node decentralized collaborative network, which is an effective alternative to overcome the communication bottlenecks and single-point trust risks of central servers (Li et al.).



Figure 11: Comparison of Centralized and Decentralized Network Topologies (Li et al., 2019)

As shown in Figure 11, the decentralized topology (right diagram) allows each economy to act as an equal node, exchanging model parameters or features only with trusted peers, without needing to aggregate raw data to a single center. This eliminates the technical root cause of data silos from an engineering architecture perspective, achieving the unity of data sovereignty and cooperation efficiency.

Furthermore, to ensure the long-term and fair operation of cross-border data

exchange, the design of the top-level architecture also needs to introduce tamper-proof digital records and rights confirmation systems (such as distributed ledger technology). In the oceanic environment, obtaining high-precision continuous observation data often requires huge capital investment and a long operation cycle. Through digital rights confirmation technology, data-contributing economies can attach clear digital property rights labels to their uploaded precious satellite tracking records or deep-sea buoy detection data. When the management toolkit uses these high-value environmental data for delineating cross-border ecological corridors or formulating adaptive policies, the system will automatically and highly transparently quantify and display the specific contribution of each party. This institutional innovation that integrates data usage and digital trust has completely changed the previous one-way and unpaid scientific data assistance model, steadily establishing a mutually beneficial and win-win virtuous cycle, and providing a strong institutional guarantee for long-term collaborative protection under the APEC framework.

6.2 Three-Dimensional Operational Mechanism to Overcome Barriers to Transboundary Data Sharing

While cutting-edge technologies have explored the possibilities of transboundary data interaction, practical implementation within multilateral frameworks still requires a mechanism with a high-level macro-management perspective and operational feasibility. This is necessary to resolve the three major pain points—security concerns, format barriers, and insufficient willingness—commonly faced by economies, particularly developing ones, when sharing survey data. To this end, in the design of the data sharing mechanism, this toolkit constructs the following three-dimensional operational paths:

1. Implementing "Data Classification Management" and "Distributed Collaboration" Architecture to Address Data Sovereignty Security Concerns

The primary policy resistance to transboundary data sharing stems from deep-seated concerns among coastal economies regarding the leakage of sensitive geographic information within their Exclusive Economic Zones (EEZs), such as specific coordinates of key economic species or detailed seabed bathymetry.

Therefore, in its architectural planning, this mechanism moves away from the traditional model of "centralized submission of raw data" and instead advocates for the implementation of strict data classification and distributed processing strategies:

Public Circulation of Basic Data: The mechanism suggests that non-sensitive large-scale environmental background parameters (such as standard water temperature and current characteristics) or historical public records should be integrated and shared openly within the APEC regional network to establish a regional baseline.

Local Retention of Sensitive Data and Model Deployment: For sensitive survey records involving domestic sovereignty and ecological security, the mechanism recommends that they be permanently retained within the local management systems of the respective economies. When multilateral cooperation requires the identification of transboundary ecological corridors, a "distributed collaboration" logic is adopted—meaning the platform or lead economy sends "analysis models and algorithmic instructions" to the local nodes where the data resides for computation. Upon completion, only de-identified macro-assessment results (such as species distribution probability maps or gridded connectivity indices) are transmitted back for aggregation. This institutional design of "moving the model, not the data" effectively addresses the data security concerns of participating economies while ensuring the smooth implementation of regional-level macro-spatial planning.

2. Establishing Regional Unified Data Submission Protocols and Basic Templates to Break Down Underlying Format Barriers

Historical survey data in many developing economies often lacks unified standards and varies in format, and local management departments typically lack the capacity for complex data engineering processing. This results in significant difficulties in seamlessly integrating valuable local data with economy-wide standards. Therefore, in the design of the sharing mechanism, the toolkit proposes the establishment of a standardized data mapping and submission protocol.

This protocol aims to lower technical barriers through administrative means. The mechanism suggests that relevant APEC working groups take the lead in translating complex economy-wide biodiversity information standards (such as the Darwin Core standard) into a set of universal basic data recording templates (such as standardized spreadsheet specifications and filling manuals). Local research institutions or fisheries

departments in various economies do not need to incur significant costs to learn complex database technologies; instead, they need only follow these universal norms to perform basic field organization and entry of existing raw records to meet the access requirements for the subsequent regional large database. By unifying the standards for front-end data collection and organization, a low-cost, easy-to-operate access channel is provided for all economies, ensuring the efficient integration of multi-source heterogeneous data.

3. Establishing a "Contribution for Empowerment" Reciprocal Compensation Mechanism to Drive Incentives for Active Sharing

Transboundary data sharing must be built upon a foundation of fair benefit compensation and capacity building. Traditional sharing models often leave coastal data-contributing economies bearing the management costs without sharing equivalent benefits. To change this one-way "data extraction," the mechanism introduces a set of positive reciprocal incentive logics in its top-level design:

Regional Technical Resource Feedback: For developing economies with limited marine forecasting and spatial analysis capabilities, the mechanism advocates for the coordination of superior technical resources within the region under the APEC multilateral framework. For economies that actively contribute survey data from key waters (such as important migratory bottlenecks), the cooperation network should prioritize providing them with detailed marine environmental forecasts, extreme climate warning data, or spatial planning technical assistance. This uses substantive technical benefits to support their domestic coastal management and disaster reduction efforts.

Priority Alignment with Economy-wide Conservation Resources: An objective data contribution assessment system should be established within multilateral cooperation. The mechanism suggests that when coastal economies apply for special funds for biodiversity conservation from the Global Environment Facility (GEF) or relevant APEC specialized agencies, their active participation records and contribution weights in regional data sharing should be incorporated into the assessment system as important scoring factors. This institutional arrangement aims to transform "passive demands for sharing" into an "active strategic demand" for developing economies to obtain economy-wide support through the allocation of

economy-wide resources, thereby ensuring the long-term stability of the transboundary data sharing ecosystem.

6.3 Collaborative Protection Directions

Based on the ecological network diagrams and key node identification results output by the toolkit, the following collaborative protection directions can be explored under the APEC mechanism:

- **Joint Focus on Corridor Priority Areas:** When the toolkit identifies important migration corridors connecting multiple economies, relevant members can issue non-binding joint focus areas through APEC-related working groups and coordinate the adoption of temporary and voluntary protection measures (such as speed limits, avoidance, etc.).

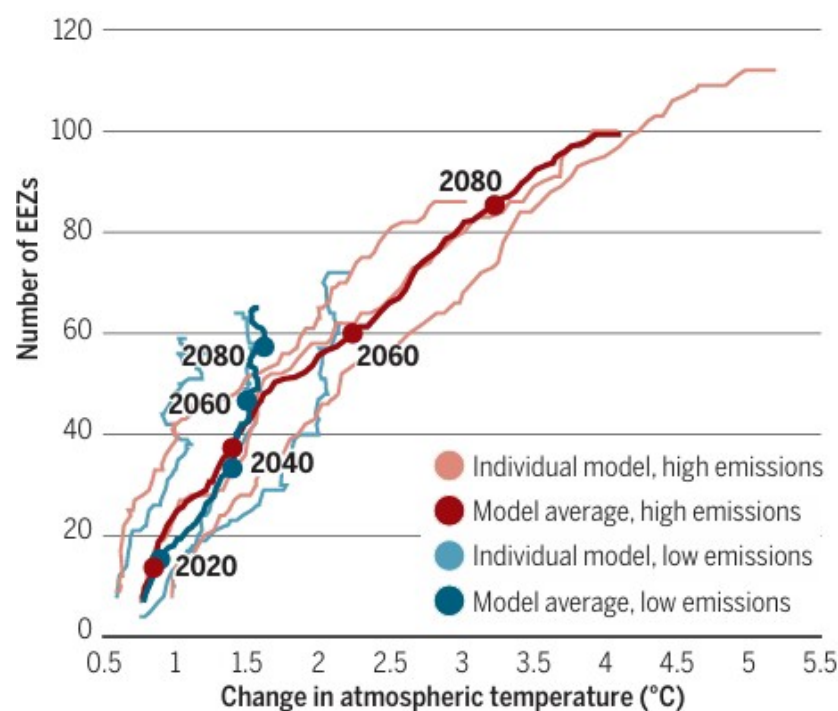


Figure 12: Prediction Diagram of the Relationship between Global Warming and the Number of New Cross-Boundary Species in Exclusive Economic Zones (Pinsky et al., 2018)

Climate change is accelerating the geographical migration of marine species distribution, leading to a sharp increase in potential conflicts over transboundary shared resources. As shown in Figure 12, global warming will significantly increase

the number of new cross-boundary species in Exclusive Economic Zones (EEZs), and under high-emission scenarios, nearly 90% of EEZs may face cross-boundary species issues by 2080 (Pinsky et al., 2018). This trend requires economies to proactively address the ecological risks of migration corridors through a joint focus mechanism.

To make the joint focus mechanism more scientific and operable in practice, it is necessary to shift the protection strategy from the traditional passive response to data-driven active threshold management. The dynamic habitat suitability probability surfaces and temporal connectivity networks generated by the toolkit can identify transient ecological bottlenecks caused by specific marine environmental changes (such as abnormal warming or ocean current fluctuations). Under the coordination of multilateral frameworks such as APEC, economies can jointly set quantitative early warning indicators based on the environmental pressures faced by species. When the background data assimilation system detects that a connectivity corridor spanning multiple jurisdictions is facing high ecological risks, the system can automatically generate early warning information and trigger joint focus within a specific time and space range. This proactive response strategy helps to improve the spatial matching and temporal effectiveness of voluntary protection measures in responding to environmental anomalies.

In the practical operation of multilateral cooperation, non-binding joint attention mechanisms help reduce the complexity of member economies in the decision-making process and enable more rapid technical-level responses. Specifically, when the toolkit warns that a high-density commercial waterway is about to spatially overlap with a large-scale species migration route, the maritime management departments of relevant economies can cooperate with regional industry associations to issue flexible navigation avoidance guidelines. These guidelines are based on model-calculated multi-dimensional resistance surfaces and economic costs, providing merchant ships with recommended alternative routes that balance fuel consumption and ecological avoidance, thereby balancing the needs of economic activities and ecological protection.

Research indicates that climate change-driven species shifts are breaking the static resource allocation patterns based on historical data. The asymmetry of resource allocation driven by climate change means that fixed quotas will inevitably lead to disputes, highlighting the urgent need for a dynamic replacement mechanism.

Specifically, the gain in the share of shared fish stocks in one economy's Exclusive Economic Zone is often accompanied by the loss of shares in neighboring economies, which constitutes the core of interest conflicts that must be directly addressed and quantified in transboundary policy coordination (Palacios-Abrantes et al., 2022). Such an objective data-based coordination mechanism helps all parties seek an effective path to enhance overall ecological network benefits and balance economic interests of all parties in multilateral cooperation (Craig & Link, 2023).

In addition to spatial route avoidance, voluntary protection measures can be further refined into hierarchical management of operational intensity. For example, in navigation segments that need to cross joint attention areas, guidelines can recommend implementing stepped speed limit measures (such as reducing speed in core activity areas and maintaining moderate speed in buffer zones), or suggest that specific types of operating vessels implement acoustic silence in these areas. To encourage shipping and fishing enterprises to actively comply with these voluntary guidelines, APEC can explore the establishment of positive incentive mechanisms, such as incorporating enterprises' compliance performance into their Environmental, Social, and Governance (ESG) evaluation systems, or providing berthing convenience at major regional ports for vessels that implement avoidance measures. This flexible management approach based on scientific consensus and market incentives provides a pragmatic path for ecological protection in sensitive sea areas with complex jurisdictions.

- Policy coordination for spatial planning: Encourage economies to incorporate the ecological corridor layers output by the toolkit into their respective marine spatial planning or protected area network design, and exchange best practices at the APEC level.

In the process of implementing transboundary policy coordination, it is necessary to go beyond simple superimposition of geographical information and achieve an organic integration of systematic protection planning and interest coordination. The ecological networks of long-distance migratory species usually spatially overlap with traditional marine economic activities (such as commercial fisheries, shipping hubs, etc.) in the exclusive economic zones of various economies. When economies convert the dynamic corridors output by the toolkit into domestic Marine Spatial Planning (MSP), they will inevitably face trade-offs between different sectors. Therefore, at

this stage, the toolkit needs to integrate multi-objective optimization models and assist neighboring economies in conducting objective ecological compensation assessments and responsibility sharing at the regional level through cost-benefit analysis.

For example, when the analysis results of the toolkit show that a key ecological hub is located in the jurisdictional waters of a developing economy, if that economy takes protective measures, it will bear the corresponding cost of economic development transfer alone, while the ecological benefits brought by the protection may benefit a wider region. Faced with this asymmetry between costs and benefits, the multilateral coordination mechanism can, based on the connectivity contribution indicators calculated by the toolkit, guide the beneficiaries in the region to reasonably share the protection costs of the source economy through technical cooperation, financial support, or quota adjustments.

In addition, conducting Best Practices exchanges under the APEC framework helps promote members to gradually form consensus on standards and management tools for marine spatial planning. Currently, when economies plan domestic Marine Protected Areas (MPAs), they mostly focus on protecting relatively fixed benthic habitats. How to incorporate dynamic migration probability surfaces that fluctuate over time into legally binding planning frameworks is a common issue faced by regional marine governance. APEC can serve as a platform for sharing dynamic planning cases, promoting member economies to exchange experiences on how to use management tools such as flexible administrative permits and seasonal spatial controls to convert the dynamic indicators of the toolkit into operable management boundaries. Such cross-border policy coordination helps alleviate habitat fragmentation caused by administrative boundaries and enhances the overall connectivity and adaptability of regional marine ecological networks.

- **Capacity Building and Technical Assistance:** Leveraging APEC's development agenda to provide toolkit usage training, modeling technical support, and standardized methods for ecological connectivity assessment to economies in need.

For this direction, the core objective of technical assistance should focus on bridging the widening digital divide in computational ecology and marine data governance within the region. The scientific foundation of modern marine spatial

management is undergoing profound evolution. Advanced species distribution models (such as algorithms integrating hidden Markov behavior decoding), the construction of three-dimensional dynamic fluid resistance surfaces, and the calculation of omnidirectional connectivity matrices all impose strict technical thresholds on the supercomputing capabilities of underlying hardware, parameter optimization of complex algorithms, and processing capabilities of massive observation data. Although many developing economies possess rich baseline biodiversity resources and key habitats, they are limited by computing resources and data analysis capabilities, making it difficult to convert them into high-precision management plans.

To this end, technical assistance under the APEC framework should not be limited to short-term theoretical training or software operation demonstrations. Instead, it should rely on multilateral technical cooperation frameworks to build a cloud-integrated marine computing power sharing and open-source algorithm platform. By encapsulating complex underlying geographic information system calculations, multi-source data assimilation processes, and operational research optimization mechanisms into standardized, visualized, and low-code online computing modules, researchers and frontline management institutions in developing economies can bypass the onerous tasks of local hardware setup and underlying code writing. They can directly access robust regional collaborative cloud computing power, combine it with unique local benthic exploration data, nearshore fishery logs, or local acoustic observation data, and independently conduct high-precision adaptive spatial planning. This digital equity mechanism of "teaching people to fish" while providing supporting fishing tools is a key underpinning to ensure that regional macro ecological networks can achieve technical closure and practical application on a full ocean basin scale.

At the same time, the dimension of capacity building should systematically extend from single model technology transfer to the cultivation of management systems and the incubation of cross-border governance talents. The establishment of standardized methods not only involves the scientific setting of model built-in parameters but also covers the standardized operation of front-end data quality control (QA/QC) processes, the ecological definition of early warning trigger thresholds, and the correct policy interpretation of model prediction uncertainties (error margins). With the help of APEC's special development funds and regular seminars of the

Marine Working Group, economies can jointly plan medium- and long-term talent echelon construction programs, aiming to cultivate a group of compound hub talents who are proficient in both cutting-edge computational ecology logic and economy-wide maritime law as well as multilateral diplomatic negotiation rules. This continuous intellectual support and institutional empowerment can substantially promote more developing economies to transform from passive providers of raw data to core participants in formulating regional ecological governance rules, thereby comprehensively consolidating the scientific decision-making foundation and multilateral implementation effectiveness of marine conservation policies under the overall APEC framework.

These directions do not presuppose legally binding obligations but aim to gradually form soft law norms through consensus and cooperation.

This soft law development model based on scientific consensus adapts to the current practical needs of economy-wide marine environmental governance, especially the governance of areas beyond domestic jurisdiction. In the vast marine areas lacking centralized compulsory jurisdiction, reaching legally binding economy-wide treaties usually faces complex consultation processes and interest considerations. However, with the objective and neutral quantitative analysis results provided by this toolkit, member states can gradually establish governance mutual trust on a non-confrontational technical exchange platform.

With the gradual implementation of measures such as joint attention warnings and voluntary avoidance in practice, and the continuous advancement of transboundary technical cooperation, these voluntary collaborative initiatives based on scientific consensus are expected to form widely accepted codes of conduct among participating parties and the marine industry. In the long run, this soft law regulatory system, where science gradually permeates into policy, can effectively test the economic feasibility and ecological benefits of dynamic management measures. It not only provides practical space for various economies to explore new marine management tools but also helps lay a solid political and cognitive foundation for reaching more binding bilateral or multilateral environmental cooperation agreements in the future, thereby promoting the systematization and normalization of conservation efforts for long-distance migratory species in the Asia-Pacific and even global marine areas.

6.4 Toolkit Usage, Community Participation, and Regional Cooperation Roadmap

It is recommended to promote the transboundary application of the toolkit and community participation in three phases under the APEC framework:

- Phase I (approximately 1-2 years): Conduct small-scale joint testing, select a small number of typical transboundary migratory species and several interested economies to trial the core modules of the toolkit, and organize technical training activities. Carry out science popularization education in communities to enhance residents' awareness of conservation, provide relevant policy recommendations to local governments in habitats, breeding grounds, etc. of long-distance migratory species, and strive to establish corresponding ecological compensation mechanisms while strengthening the protection of migratory species. Develop knowledge products to guide ecotourism and the transformation of ecological value.

In order to deepen the implementation effect of the joint testing stage, the promotion of the toolkit needs to integrate Participatory Geographic Information System (PGIS) and Traditional Ecological Knowledge (TEK) in the underlying logic. For a long time, high-end computational ecology models tend to be outside the actual perception of local communities, resulting in a lack of solid mass base for conservation policies. When carrying out small-scale joint tests, we should not only rely on high-precision satellite telemetry and acoustic arrays, but also build a standardized mobile data acquisition interface to transform the empirical observations accumulated by coastal indigenous peoples and artisanal fishermen for generations (such as fish group gathering patterns in specific seasons and rare stranding event records) into spatial prior probability parameters that can be read by the model. This bottom-up data Crowdsourcing model can not only perform low-cost and efficient Ground-truthing on hidden breeding farms and migration paths predicted by algorithms, but also significantly enhance the sense of subject participation and identity of local communities in the process of conservation decision-making.

In the preliminary exploration of constructing an ecological compensation mechanism, it is recommended to simultaneously introduce Spatially Explicit

Ecosystem Services Valuation Models (such as the InVEST system). Traditional ecological compensation often falls into a deadlock of bargaining due to the lack of quantitative basis. Through this toolkit, management departments can transform abstract species connectivity contributions into specific natural capital accounting indicators. For example, the model can quantify the ecological support capacity of a specific nearshore seagrass bed or mangrove as a key nursery ground for flagship migratory species and convert it into the economic value of supplementing fishery resources in the entire region. This scientific and quantitative accounting system provides a rigorous and uncontroversial benchmark for local governments to issue Transfer Payments to communities located in core habitats, ensuring that the priority allocation of economy-wide climate and biodiversity funds (such as GEF) can be precisely directed to stakeholders who have made actual sacrifices for protection.

In terms of the development of knowledge products and the transformation of ecological value, the first stage should focus on digital empowerment and community co-construction. The three-dimensional seabed topography, hydrodynamic evolution, and species migration dynamic probability surfaces generated by the toolkit can be transformed into immersive virtual reality (VR) science popularization materials or Digital Twin display platforms. These high-end technological knowledge products can inject high-value-added scientific connotations into community-led ecotourism projects. In this process, scientific research teams and non-governmental organizations (NGOs) should assist local residents in developing ecotourism routes themed on non-destructive observation and scientific research, guiding communities to transform from traditional resource-consuming livelihoods (such as overfishing) to service and knowledge-intensive livelihoods, thereby bringing visible and sustainable economic benefits to communities at the initial stage of protection actions.

- Phase II (approximately 2-4 years): Based on pilot experience, collect species data and resistance surface parameters from various economies to form the initial version of a regional ecological corridor map, which will be shared internally in the form of dynamic maps. Communities and local governments that have performed outstandingly in the field of protection and sustainable development will share their experiences and knowledge products, guiding tourists from developed APEC economies to relevant communities in developing APEC economies, and driving the improvement of protection

levels and community development in the entire APEC region through economic cycles.

With the formation of the initial version of the regional ecological corridor map, the strategic focus of transboundary collaboration should be systematically shifted to the management of spatial spillover effects of natural capital and the inter-regional circulation of the Payment for Ecosystem Services (PES) mechanism. On the basis of realizing secure sharing within APEC through dynamic maps, the architecture of the toolkit should be further expanded to develop spatial deduction and dynamic control modules for ecotourism Carrying Capacity.

There are objective differences in natural resource endowments and economic development stages within the region. Core sanctuaries for long-distance migratory species, such as undamaged coral reef breeding grounds and natural deep-water safe havens, are often concentrated in the jurisdictional waters and surrounding communities of some developing economies. By overlaying ocean cruise routes, diving and whale-watching hotspots with model-predicted migration corridors, multilateral cooperation mechanisms can leverage precise data to guide ecotourism capital and high-end tourist groups from developed economies to flow towards communities in developing economies with high ecological resilience and strong conservation willingness. Macroscopically, this mechanism constructs a transboundary blue economic micro-circulation where developed regions export capital and demand, and developing regions export high-quality ecological products.

However, to prevent the blind influx of foreign tourism capital from causing secondary damage to original ecological habitats, the carrying capacity deduction module will play a key gatekeeping role. The system can use Agent-based Modeling to simulate the stress effects of tourist activities of different scales and frequencies on sensitive species, and systematically set strict avoidance thresholds for acoustic and physical interference. For example, based on the animal auditory thresholds and breeding period sensitivity output by the toolkit, the system can automatically calculate the maximum number of whale-watching boats allowed to operate simultaneously in a specific sea area, mandatory safe observation distances, and the upper limit of ship engine noise emission standards.

In this transboundary economic cycle based on high-precision spatial planning

and dynamic threshold control, a reasonable proportion of ecotourism revenue will be designated to support local monitoring network maintenance and livelihood alternative projects. It successfully transforms the sunk costs of pure ecological protection into regional industrial green increments with endogenous motivation, truly realizing the interest binding and mutual promotion between the construction of transboundary sanctuary networks for flagship species and poverty alleviation in coastal communities.

- Phase III (approximately 4-6 years): Promote economies to voluntarily incorporate corridor identification results into relevant local government plans and explore incentive and recognition mechanisms in the APEC forum to ensure the sustainable impact of project outcomes.

To ensure that project outcomes can achieve long-term institutionalized operation beyond the short funding cycle, the top-level design of Phase III needs to focus on stabilizing adaptive governance paths and integrating market-oriented incentive tools. Promoting the voluntary incorporation of multilateral recognized corridor identification results into domestic and local-level Marine Spatial Planning (MSP) of various economies essentially promotes the institutional isomorphism of scientific consensus formed by cutting-edge algorithms into multilateral administrative jurisprudence. This process requires the APEC mechanism to provide a continuous policy coordination platform to assist member states in digesting and transforming technical indicators into zoning regulations that comply with their domestic legal frameworks.

In this institutionalization process, mere administrative advocacy often lacks lasting binding force. Therefore, it is particularly crucial to explore and implement a series of market-oriented incentive and recognition mechanisms in the APEC forum. The connectivity hotspot maps and dynamic resistance surfaces output by the toolkit can serve not only as a basis for management but also directly as the core spatial evidence baseline for issuing regionally recognized Eco-labeling and sustainability certifications.

Specifically, multilateral mechanisms can collaborate with the International Maritime Organization and authoritative third-party certification bodies to establish a data-driven blue supply chain traceability system. For instance, for ocean-going

merchant shipping enterprises that commit to fully utilizing the early warning functions of the toolkit in voyage route planning and proactively adopting measures such as slowing down, detouring, or silencing equipment in dynamically predicted high-risk migration bottleneck areas, the APEC mechanism can play the role of a multilateral platform connector. It can join hands with existing economy-wide authoritative certification bodies (such as the Marine Stewardship Council, MSC) or global Environmental, Social, and Governance (ESG) rating systems to take the dynamic compliance records of the toolkit (such as actively slowing down or silencing in high-risk migration areas) as an important evaluation indicator for enterprises to obtain economy-wide green certification and green financial credit, thereby indirectly endowing the seafood they catch with green premium advantages in the terminal market and priority customs clearance convenience.

This mechanism innovation that directly connects the computing power of underlying computational ecology with the terminal consumer market of the global supply chain reshapes the driving logic of marine conservation. It enables compliance enterprises' ecological responsibility behaviors to receive substantial financial returns through market premiums and brand appreciation. By constructing this positive business feedback loop based on the Environmental, Social, and Governance (ESG) framework, the roadmap will provide a long-term, stable, and resilient external market driving force for the transboundary sanctuary network of long-distance migratory marine species, thereby thoroughly consolidating the big data-based collaborative governance paradigm within the Asia-Pacific region and ensuring the intergenerational inheritance and continuous influence of multilateral ecological conservation achievements.

6.5 Policy Implementation, Community Empowerment, and Adaptive Management

When pushing the marine conservation blueprint constructed by cutting-edge computational ecology algorithms into reality, spatial planners often face severe grassroots implementation barriers. As a core ecological hub connecting the Pacific and Indian Oceans, Indonesia's waters constitute a critical strategic passage for numerous long-distance migratory species such as marine mammals, whale sharks, and sea turtles. In the face of global ecological stressors such as climate change, high-

intensity commercial shipping, fisheries bycatch, and plastic pollution, Indonesia highly aligns with economy-wide frameworks such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) at the domestic level, and has achieved deep integration of technological tools, local regulations, and traditional ecological knowledge at the micro operational level. The economy's diverse practices across multiple cultural contexts provide a valuable real-world model for transboundary marine spatial management.

In terms of legal theory integration and institutional isomorphism, the sea turtle conservation practices in Bali demonstrate the strong binding force of customary law. Sea turtles have long been widely used in local Hindu religious rituals and traditional dietary systems. Initially, relying solely on domestic-level mandatory protection regulations failed to effectively curb illegal fishing, as the external legal framework encountered an enforcement vacuum at the grassroots community level. To break this deadlock, the local government and non-governmental organizations collaborated to formally incorporate the core demands of sea turtle conservation into the traditional village customary law (Perarem), which holds strong social deterrence. In the specific implementation phase, the community spontaneously established a village self-governing protection group called KOMPAK, which is specifically responsible for the rescue excavation of sea turtle eggs and the efficient management of hatcheries. When the protection clauses were accompanied by traditional social sanction mechanisms based on local culture and received substantial support from provincial government and corporate social responsibility (CSR) funds of state-owned enterprises, the community compliance rate saw a substantial leap. This initiative strongly proves that transboundary conservation networks need to provide flexible legal interfaces to transform ecologically calculated red lines into social rules supported by local cultural contracts.

When reconciling traditional wisdom with modern conservation concepts, the adaptive management model of Lamalera Village in East Nusa Tenggara Province (NTT) offers a novel solution. The local residents' custom of hunting sperm whales and spinner dolphins dates back to 3000 BCE. Facing the impact of modern animal protectionism, the Indonesian government adopted an inclusive strategy of indigenous exemption and adaptive spatial management. In-depth field investigations show that the local traditional whaling activities are completely different from the excessive

exploitation of modern industrialization. The annual whaling season (Lewa, usually from May to September) is highly constrained by the ancient Leva Nuang ritual. Participants are required to use inefficient traditional tools such as wooden sailing boats and handcrafted steel harpoons. Hunting of economy-widely protected critically endangered species is strictly prohibited, and catches must be fairly distributed among all villagers on a non-commercial basis. This self-quota management based on traditional ecological knowledge has objectively maintained long-term ecological balance. Policy makers have thus legally recognized this tradition as a sustainable customary practice, preserving a legitimate survival buffer for indigenous peoples with sustainable attributes and preventing ecological conservation from becoming a negative means of depriving marginalized communities of their right to subsistence.

In the field of cutting-edge technology empowerment and non-consumptive value conversion, the whale shark ecotourism project in Botubarani Village, Gorontalo region, has achieved a win-win situation for conservation and livelihoods. Whale sharks have evolved into an important cultural symbol in the region, with local authorities even introducing whale shark mascots named "Dago" and "Dangi," which are actively used in regional elections, traditional Batik design competitions, and prison art rehabilitation projects. To understand the population base, the University of Indonesia, the Indonesian Ministry of Marine Affairs and Fisheries (KKP), and several non-governmental organizations collaborated to equip 70 whale sharks with high-precision satellite telemetry beacons over a ten-year period across four core sea areas: Cenderawasih Bay, Kaimana, Saleh Bay, and Tomini Bay. Massive tracking data has revealed that these whale sharks are dynamic marine wanderers crossing the exclusive economic zones of 13 economies. The project team then integrated multi-dimensional monitoring methods, including five newly deployed real-time satellite tags in April 2025, artificial intelligence (AI)-based body spot image recognition technology, geographic information system (GIS)-mapped bycatch hotspot maps, hydrophone acoustic monitoring networks for assessing ship noise impacts, and drone platforms for sea surface observation.

Relying on these high-precision scientific forecasting data and the digital citizen science reporting platform, the local community has successfully developed standardized ecotourism routes. Clear economic accounting has made local fishermen deeply aware that the long-tail ecotourism benefits created by live whale sharks far

exceed the value of one-time hunting. With funding support from multiple departments, traditional fishermen have transitioned to eco-guides on a large scale, driving the prosperity of supporting service industries such as surrounding micro, small, and medium enterprises (MSMEs) and parking management.

In conjunction with the regular marine mammal stranding rapid response training carried out in coastal areas such as Sorong and West Sulawesi, grassroots personnel have proficiently mastered morphometric recording, stretcher handling techniques, and management norms for mass stranding events. This series of empowerment actions has significantly reduced the abnormal mortality rate of species caused by improper handling by well-meaning but unprofessional members of the public, completing a grassroots blue economy industrial upgrading driven by in-depth collaboration between the government, academia (such as Diponegoro University), non-governmental organizations (such as Konservasi Indonesia), and indigenous peoples.

7. Challenges and Future Outlook

Although the proposed toolkit theoretically integrates the methodological approaches of both terrestrial and marine ecological connectivity and provides relatively complete technical support for the conservation of long-distance migratory species, it still faces several challenges and future improvement directions in practical application:

● Complexity of Data Acquisition and Processing

The discontinuity and variability of data in the marine environment pose significant challenges to species distribution modeling and resistance surface construction. In the future, more long-term, continuous, high-resolution marine environmental data and accurate species observation data will be needed to support model construction.

A thorough analysis of the complexity of this acquisition and processing reveals that while surface satellite remote sensing can provide ocean-scale surface water temperature and chlorophyll dynamics, the core ecological niches of long-distance migratory species (such as deep-diving foraging whales or sea turtles) often lie in the mesopelagic and bathypelagic waters beyond the reach of optical remote sensing. This

extreme scarcity of three-dimensional vertical environmental data inevitably introduces significant extrapolation and interpolation errors when models construct three-dimensional water column resistance surfaces. The breakthrough in future technologies lies in the assimilation of multi-source heterogeneous data. There is an urgent need to perform three-dimensional spatial topological alignment and mathematical assimilation of continuous in-situ profile measurement data obtained by deep-sea autonomous profiling float arrays and underwater autonomous gliders with surface satellite remote sensing layers, thereby constructing a truly full-water-depth, high-fidelity physical oceanography input base for connectivity algorithms.

At the computational ecology level of data processing, with the evolution of marine environment layer to high spatiotemporal resolution, the traditional desktop-level stand-alone computing architecture has faced serious computing power bottleneck. The construction of dynamic time-series resistance surfaces and omnidirectional connectivity networks covering the whole ocean basin scale is essentially to solve huge multi-dimensional tensor equations. The future evolution direction to break through this bottleneck lies in the comprehensive migration to cloud native space parallel computing architecture. By developing the underlying driving engine based on distributed graph computing, the real-time streaming fusion processing of massive ocean climate model datasets and high-frequency animal tracking trajectories is realized, thus compressing the computing cycle of macro-spatial planning from month level to near real-time level.

Furthermore, to address the inherent spatiotemporal discontinuity problem of marine observation data (such as large-area data gaps in satellite images caused by complex weather and cloud cover), advanced preprocessing techniques need to abandon traditional linear interpolation methods. Cutting-edge artificial intelligence algorithms such as physics-informed neural networks show disruptive application potential. By incorporating the fluid dynamics governing equations of ocean circulation as hard physical constraints into the iterative loss function of the learning model, researchers can intelligently reconstruct continuous environmental factor fields that fully conform to the objective conservation laws of physics in sparse or even severely missing marine ecological observation fields. This algorithmic leap from pure statistical fitting to physical mechanism deduction will provide a coherent and logically rigorous underlying habitat driving matrix for future species distribution

dynamic models.

● **Cross-boundary Management and Regional Collaboration**

The migration of long-distance migratory species often involves multiple marine areas and domestic boundaries, and the lack of unified planning among different management entities can easily lead to fragmented conservation measures. Therefore, it is necessary to strengthen economy-wide cooperation and the construction of cross-regional ecological connectivity management mechanisms.

The root cause of this fragmentation lies in the severe institutional spatial mismatch between the ecological macroscale of marine species and the current administrative jurisdiction scale of humans. Long-distance migratory species have developed hydrodynamic adaptability across multiple ocean basins during evolution, while the modern economy-wide law of the sea system mechanically divides the vast ocean into discrete exclusive economic zones and high seas patches. Future transboundary management research needs to break this traditional governance paradigm centered on static geographical boundaries and move towards dynamic transboundary marine spatial planning based on ecosystem connectivity. This requires future algorithmic tools not only to output pure biological habitats but also to have the ability to generate fluid jurisdiction boundaries across economy borders, enabling the geometric form of conservation planning to flexibly expand and contract across borders with seasonal oscillations in marine climate variability and species migration rhythms.

From the perspective of future challenges in policy implementation, overcoming the fragmentation of management entities requires not only diplomatic consultations but also the urgent integration of computational ecology and environmental economics. In the complex pattern of transboundary interests, the cost of fishery concessions or shipping speed limits paid by an economy to maintain key ecological corridors often translates into ecological dividends in the waters under the jurisdiction of neighboring economies. This transboundary mismatch between costs and benefits is the core inducement leading to the breakdown of cooperation. Therefore, the future development of toolkits needs to proactively integrate spatially explicit social-ecological system coupling models. By quantifying the spatial flow process of ecosystem services within the mathematical framework of multi-economy games,

researchers can calculate the ecological compensation threshold required to maintain specific transboundary connectivity networks. This transboundary benefit distribution algorithm based on objective mathematical deduction will provide the core technical intermediary for resolving resource disputes between sovereign states.

Finally, the collaborative extension to areas beyond domestic jurisdiction is the ultimate frontier of future marine connectivity management. With the gradual establishment of global frameworks such as the Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction, the high seas are no longer an ecological lawless zone lacking regulation. However, how to delineate protection boundaries in the vast ocean without a single sovereign endorsement still faces a huge scientific basis vacuum. Future toolkits need to assume the role of scientific empowerment in global ocean governance, using omnidirectional connectivity analysis and temporal network invulnerability assessment to identify crucial deep-sea seamount stepping stones and upwelling convergent corridors in the high seas. By transforming these spatial topological evidence outputs based on hardcore hydrodynamic algorithms into scientific benchmarks recognized by economy-wide multilateral tribunals, we can truly promote the trans-regional ecological connectivity management mechanism from a soft regional cooperation initiative to a hard marine legal practice with global binding force.

● Model Dynamics and Scenario Simulation

Due to global climate change and the increasing intensity of human activities, the dynamic changes in the marine environment will affect the long-term stability of ecological corridors. Future toolkits need to integrate dynamic scenario simulation tools to monitor and adjust conservation strategies in real-time, ensuring the ability to respond to short-term and long-term changes.

Delving into the dynamic evolution of the marine environment, global climate change is not a linear translation of a single variable, but a nonlinear superposition of multiple extreme events such as marine heatwaves, ocean acidification, and intensified stratification. Traditional static correlation models are often built on the assumption of stable relationships between species and the environment, which can easily lead to prediction failures in the context of drastic climate change. Therefore,

the scenario simulation module of future toolkits needs to transition to mechanism-driven ecophysiological models. By rigidly embedding the thermal tolerance thresholds, basal metabolic rates, and energy budget equations of long-distance migratory species into spatial distribution algorithms, researchers can more accurately simulate the transient dynamic responses of species when facing extreme hydrological oscillations, thereby identifying future ecological bottlenecks and highly connected climate refuges that cannot be predicted solely by historical distribution data.

For scenario deduction of long-term evolution trends, future prediction frameworks need to be decoupled and downscaled from the latest generation Earth system models. The existing macro-climate scenario layers tend to have coarse spatial resolution, which makes it difficult to capture mesoscale vortices and local upwelling anomalies that are crucial to migration trajectories. The future breakthrough direction lies in using dynamic downscaling technology to seamlessly nest global climate prediction under the shared socio-economic path into a high-resolution regional fluid dynamics grid. This high-precision spatiotemporal projection enables the connectivity network to deduce the far-reaching influence of ocean circulation reorganization on ecological network topology frame by frame with interdecadal time scale, and provides solid physical boundary conditions for cross-generational long-term protected area site selection and dynamic corridor reservation.

In terms of coping with short-term high-frequency changes and real-time strategy adjustment, ocean digital twin technology represents the ultimate evolution form of dynamic space management. By constructing a virtual mapping space running parallel to the real physical ocean, the advanced toolkit can seamlessly throw back data from multi-source satellite remote sensing and deep-sea anchor buoys around the clock. In this virtual digital space, managers can carry out advanced ecological resistance calculations and stress tests for hypothetical offshore wind farm construction, route changes of very large ships or sudden environmental disasters. This immersive and highly interactive scenario deduction system will completely subvert the lagging management mode of destruction first and remediation later in traditional marine spatial planning, and truly give multilateral economy-wide organizations and regional management institutions the digital decision-making power to plan for a rainy day in the face of complex ocean changes.

● Integration of Conservation Policies and Regulations

Currently, marine spatial planning and conservation policies in many economies do not fully consider ecological connectivity issues. To realize the practical application of the toolkit, it is necessary to promote the update of policies and legal systems, clarify the protection status of ecological corridors in MPA and OECM networks, and thus provide legal guarantees for protection measures.

In-depth analysis of the lag of current policies and regulations, the core contradiction lies in the natural conflict between the static solidification of spatial jurisdiction and the dynamic migration attribute of species in the current law of the sea system. The traditional legal framework of marine protected areas is highly dependent on the geographical boundary defined by fixed coordinates, which leads to the dynamic ecological corridor drifting with seasons and ocean currents predicted by frontier algorithms, which often faces the embarrassing situation that there is no reliance in the current legal provisions. Therefore, the renewal of the legal system in the future requires the introduction of a completely new legal concept of dynamic marine space management at the legislative level. This means that the legislature needs to authorize the management department to give specific waters a temporary legal protection status with time attributes and conditional triggering mechanism based on the output of ecological algorithms of real-time assimilation, so as to completely break the rigid shackles of traditional static demarcation at the bottom of law.

In advancing the legal practice of protecting ecological networks, the operational breakthrough lies in fully integrating ecological corridors into the network of other effective area-based conservation measures. Unlike the exclusive control of traditional marine protected areas, the legal connotation of such protection measures is more inclusive, allowing specific sea areas to achieve long-term biodiversity conservation while conducting sustainable marine economic activities. Future regulatory integration should focus on clarifying that when the connectivity evaluation module of this toolkit identifies a key migration bottleneck area, there is no need to initiate the lengthy and highly resistant legislative process for permanent nature reserves. Instead, a more flexible regulatory framework can be used to set special constraint clauses such as seasonal acoustic silence, fishing restrictions on specific gear types, or dynamic ship speed limits based on high-frequency environmental data. This legal innovation that balances blue economic development and ecological connectivity

maintenance can greatly reduce the socioeconomic resistance to the implementation of cross-departmental policies.

Furthermore, to ensure the authority of the toolkit's output results in administrative law enforcement and transboundary collaboration, it is urgent to establish statutory standards for computational ecology evidence in domestic and regional marine environmental protection laws. The transboundary protection of long-distance migratory species not only requires macro guidance from multilateral treaties but also needs to transform the habitat suitability probability surfaces and network invulnerability thresholds generated by the toolkit into statutory scientific bases in domestic law for determining environmental damage compensation, delineating ecological red lines, and implementing ecological compensation. As global biodiversity goals advance, directly anchoring highly quantifiable ecological connectivity network indicators into the mandatory technical standards for marine spatial planning of coastal states is the inevitable path to fundamentally eliminate the fragmentation of conservation policies and achieve the modernization of marine rule of law based on hard scientific data.

● **Technology Integration and Multidisciplinary Collaboration**

Building a management toolkit for the protection of marine long-distance migratory species requires multidisciplinary technological integration, including ecology, marine science, remote sensing and GIS technology, data science, and policy research. In the future, interdisciplinary collaboration should be strengthened to build a unified technical platform and data sharing mechanism.

In-depth analysis of the deep connotation of multidisciplinary integration, future interdisciplinary cooperation needs to break the simple data platter mode and move towards the algorithm-level integration of the underlying cognitive ontology. Faced with the huge disciplinary barriers between ecology, marine fluid mechanics and environmental law, the advanced toolkit needs to introduce marine ecological knowledge map technology urgently. By constructing a unified semantic network, discrete species physiological characteristics, complex mesoscale physical ocean processes and highly textualized economy-wide ocean bills are structurally anchored, so as to establish a logical mapping relationship between heterogeneous subject knowledge bases that can be jointly retrieved and computed by machines. This

underlying semantic alignment is the core cornerstone of realizing the jump from multi-dimensional data hybridization to interdisciplinary collaborative deduction.

In the specific construction of technical platforms, traditional isolated desktop-level geographic information systems can no longer carry the joint solution of massive multi-source data and complex Earth system models. There is an urgent need to build ubiquitous computational ecology infrastructure based on cloud-native architecture in the future. This platform will integrate high-performance computing clusters, edge computing nodes, and advanced artificial intelligence development frameworks to provide a decentralized digital collaboration hub for marine scientists, data analysts, and policy makers. By encapsulating complex mathematical optimization algorithms and fluid dynamics simulations into underlying microservices, this cross-domain integrated technical foundation can completely eliminate the computing power and code thresholds for non-computer professional researchers when calling cutting-edge machine learning models, truly realizing the seamless empowerment of modern data science for marine ecological conservation.

Finally, to bridge natural sciences and policy research, it is necessary to embed a science-policy interface mechanism in the top-level design of the toolkit. Due to the fundamental contradiction between the nonlinear feedback of marine ecosystems and the profit-seeking nature of human marine economic activities, future interdisciplinary cooperation needs to build a spatially explicit social-ecological coupling assessment module. This module will serve as a public digital object for multiple stakeholders to conduct quantitative games, enabling the connectivity damage resistance thresholds predicted by ecologists to be real-time converted into the opportunity costs of fisheries in the eyes of environmental economists, and further translated into legal constraint clauses when jurists draft transboundary marine spatial planning. This interdisciplinary dialogue mediated by a unified computing power platform will ultimately promote the protection of marine long-distance migratory species from a single ecological scientific exploration to a global systematic governance project that takes into account both natural ecological resilience and long-term human well-being.

8. Conclusion

Combining previous studies, this paper proposes a toolkit framework for the conservation and management of marine long-distance migratory species. The main

conclusions are as follows:

● **Habitat suitability prediction is the basis of conservation management**

By integrating species distribution data with marine environmental variables (such as sea temperature, salinity, ocean currents, etc.) and using methods such as the MaxEnt model, the core activity areas of long-distance migratory species can be accurately predicted, providing a scientific basis for subsequent ecological connectivity analysis.

Reviewing the methodological construction and empirical deduction in the previous text, this study shows that suitability prediction plays a fundamental anchoring role in modern marine spatial governance. Traditional distribution prediction often relies on static layers and single-step processes, while the toolkit proposed in this paper enhances the scientific nature and logical rigor of prediction through systematic algorithm upgrades. First, in the data preprocessing stage, the introduction of point process models and target taxon background sampling method fundamentally corrects the quantitative errors caused by the scarcity of ocean survey data and spatial bias; second, in the core modeling stage, overcoming the limitations of a single statistical algorithm, a cross-algorithm combined prediction framework is constructed, which effectively smooths the overfitting interference caused by environmental extreme values and simultaneously outputs the uncertainty boundaries of spatial prediction; finally, in the dynamic feature analysis, by coupling long-term satellite tracking trajectories and using hidden Markov models for behavioral state decoding, this study transforms habitat suitability from a single geographical probability into a dynamic ecological boundary that fits the physiological needs of species (such as residence foraging and directional migration).

This habitat suitability surface with temporal attributes and high statistical confidence restores the lag dynamic mechanism of long-distance migratory species following mesoscale eddies and water temperature fronts, transcending the scope of simple species census. Only with reliable data support, objectively stripping out the core feeding hotspots and hidden spawning areas of species' dynamic swimming, the subsequent corridor identification has real deduction value. In other words, the suitability probability surface output by this toolkit is an important prerequisite for transforming the micro animal environmental selection preferences into the

construction of hydrodynamic resistance surfaces and the design of transboundary protected area networks on the macro ocean scale.

● Ecological corridor identification technology plays a key role in marine protection

Using the least cost path method and circuit theory to construct marine resistance surfaces can quantitatively identify marine ecological corridors and key connection nodes, thereby building a scientific ecological network to ensure efficient migration and gene exchange of species between protected and non-protected areas.

In traditional marine spatial planning, the construction of resistance surfaces often relies on subjective expert scoring and has long been limited by the isotropic two-dimensional assumption. The progress of this study lies in integrating high-resolution three-dimensional ocean circulation models to transform hydrodynamic elements into directional anisotropic resistance. This makes the identification of ecological corridors no longer simply finding the shortest connection in geographical space, but calculating the asymmetric physiological cost of species' downstream leveraging and upstream energy consumption, reproducing the hydrodynamic relatively optimal path at the physical oceanography level.

On the other hand, aiming at the characteristics of open ocean water lacking physical landmarks and clear boundaries, this toolkit realizes the transformation from determinism to probability in network search algorithms. By introducing the theory of stochastic shortest paths and the framework of omnidirectional connectivity analysis, it overcomes the systematic limitation of traditional models relying on preset sources and sinks. This global solution method can objectively strip out the potential diffuse ecological network skeleton from the continuous deep sea and effectively capture the secondary wandering paths under ocean current interference, providing solid spatial quantitative support for delineating protection boundaries in the vast high seas lacking prior observation data.

● Connectivity evaluation and key node identification help optimize conservation strategies

Evaluating connectivity indicators and key nodes of ecological networks through methods such as graph theory and sensitivity analysis helps decision-makers concentrate resources on protecting areas that act as hubs in the overall ecosystem and

provides quantitative support for scenario simulation.

Reviewing the connectivity evaluation module in this paper, its main contribution lies in breaking the limitations of undirected graph theory in traditional terrestrial ecology. In response to the directionality of ocean current fields, this study constructed a complex network analysis framework based on asymmetric adjacency matrices. By introducing current closeness centrality and directed betweenness centrality based on random walks, the toolkit can separate nodes that merely serve as passive transit channels in the network, thereby identifying core source areas with radiation capabilities in maintaining trans-oceanic basin gene flow and population diffusion. This application of graph theory combined with fluid mechanics principles makes the weight ranking of key nodes more consistent with the real ecological mechanisms of marine long-distance migratory species.

In addition, regarding the vulnerability assessment of key nodes, this study realizes the transformation from static single-node removal to systematic cascading invulnerability testing. With the help of percolation theory in complex network science, the toolkit can dynamically simulate the structural changes of connectivity networks when facing abrupt climate warming or increased human fishing pressure. More importantly, by constructing a spatiotemporally coupled multi-layer complex network model, the system topologically aggregates maritime shipping noise pollution, commercial fishing effort, and future abnormal warming areas as independent disturbance layers. This quantitative simulation under multi-dimensional pressures identifies cornerstone node clusters facing higher risks, providing a mathematical basis for decision-makers to formulate spatially explicit dynamic no-fishing zones and adaptive conservation strategies in multilateral coordination.

● Toolkit design should integrate dynamic scenario simulation and cross-regional collaborative management

As global climate change and human activities continue to change, conservation management toolkits need to have dynamic adjustment functions and form synergy in economy-wide cooperation and cross-regional management to achieve long-term and effective ecological conservation.

The toolkit constructed in this study goes beyond the traditional a posteriori environmental assessment, with dynamic scenario simulation as the core driving

module. Faced with nonlinear climate change such as global warming and frequent ocean heat waves, the toolkit gives ecological networks long-term time deduction capability by decoupling and assimilating dynamic downscaling prediction of Earth system models. Combined with the physiological and ecological tolerance thresholds of long-distance migratory species, the simulation framework can measure the potential impact of extreme weather events on key corridors in advance in virtual space, which provides algorithm support for building an ocean management platform with early warning and adaptive feedback capabilities in the future.

At the level of cross-regional collaborative management, the output results of this toolkit help alleviate the contradiction between static spatial jurisdiction and dynamic ecosystems in the current economy-wide marine law system. The dynamic connectivity map generated based on high-frequency data assimilation makes it possible to establish protected areas that are flexibly adjusted according to species migration rhythms. More importantly, by integrating a spatially explicit social-ecological multi-objective game model, the toolkit transforms abstract ecological protection needs into economic opportunity costs and ecological compensation reference standards that can be quantitatively weighed by contracting parties in multilateral negotiations. This shift from subjective political consultation to a data-driven threshold triggering mechanism provides a practical path for improving the governance of the high seas and areas beyond domestic jurisdiction and building a collaborative protection model based on scientific data.

Summary of Key Findings:

● Establish a marine species distribution prediction system based on the MaxEnt model

This system integrates multi-source marine environmental variables and species observation records, and effectively corrects spatial sampling biases in pelagic surveys by introducing point process models and target taxon background sampling methods. Combined with an ensemble prediction framework, the system can smooth out disturbances caused by environmental extremes and output habitat suitability probability surfaces with uncertainty boundaries, providing a scientific basis for identifying core areas of dynamic species movement.

● Construct resistance surfaces and ecological corridor identification models

using least-cost paths and circuit theory

By incorporating a high-resolution three-dimensional ocean circulation model, the model transforms the hydrodynamic elements into anisotropic resistance with directionality, which objectively reflects the asymmetric physiological consumption of species downstream and countercurrent. Combining stochastic shortest path theory and omnidirectional connectivity analysis, this method overcomes the limitation of relying on preset source and sink nodes, and can identify multiple potential migration corridors and vulnerable ecological bottlenecks from the vast sea area.

● Apply graph theory and scenario simulation methods to evaluate ecological network connectivity and key nodes

In response to the directional characteristics of ocean current fields, this study adopted a complex network analysis framework based on asymmetric adjacency matrices to identify core source areas that play a radiative role in transoceanic basin gene flow. Meanwhile, using percolation theory and multi-layer complex network models, the study systematically deduced structural changes in connectivity networks under the pressure of climate anomalies or human activities, and identified keystone node clusters requiring priority protection.

● Integrate a multi-data, multi-disciplinary comprehensive technology platform to promote economy-wide collaboration in ecological protection

The toolkit integrates data assimilation technology and spatially explicit social-ecological multi-objective game models, enabling the near real-time conversion of multi-source observation data into dynamic early warning indicators. This mechanism for quantitatively weighing economic opportunity costs and ecological protection needs provides an objective standard for transboundary data sharing and benefit distribution, facilitating cross-border and cross-sectoral joint adaptive management under regional multilateral frameworks such as APEC.

● Emphasize the improvement of policies and regulations to ensure the implementation of ecological corridors in marine spatial planning

Studies have shown that traditional static geographical demarcation struggles to adapt to the dynamic spatial characteristics of long-distance migratory species. It is recommended to introduce flexible protection tools with temporal attributes and trigger mechanisms in marine spatial planning, and explore market-based incentive

measures through multilateral mechanisms to transform scientific connectivity network indicators into operational transboundary governance norms.

Appendix: Information on Migratory Species and Their Habitats in the APEC Region

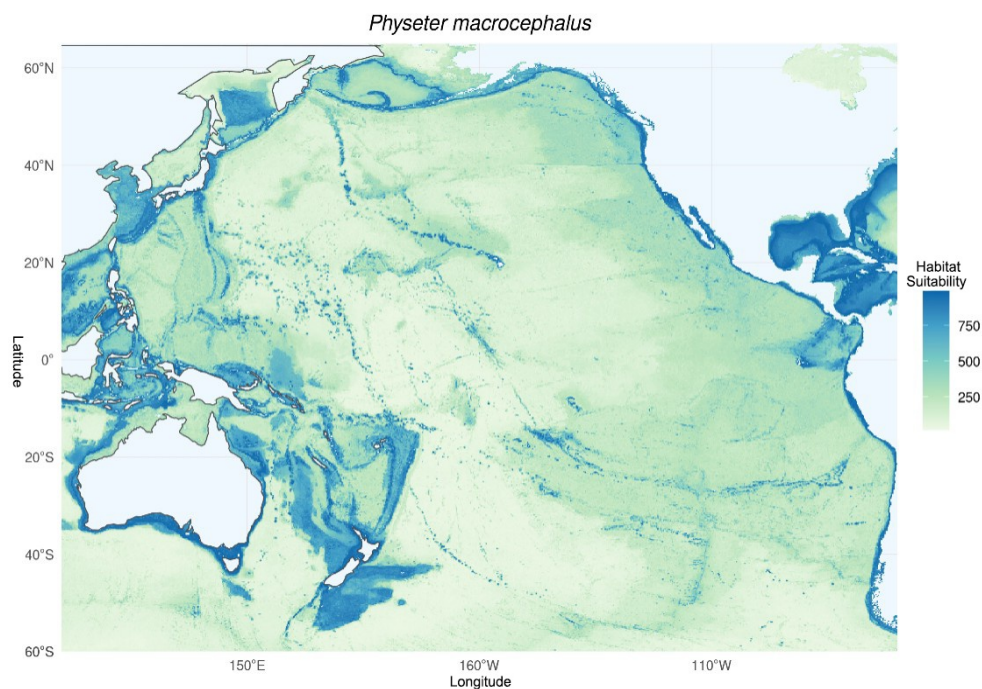
Member economies of the Asia-Pacific Economic Cooperation (APEC) surround the Pacific Ocean and possess rich marine biodiversity. The vast Pacific basin and marginal seas constitute key habitats and migration corridors for numerous long-distance marine migratory species. To provide basic biological references for the species distribution prediction models and ecological corridor identification in this report, this appendix further expands the list of representative migratory species in the APEC region, covering marine mammals, reptiles, cartilaginous and bony fishes, and pelagic seabirds, and sorts out their macrohabitat characteristics.

I. Marine Mammals (Cetaceans)

1. Sperm Whale (*Physeter macrocephalus*)

- **Habitat Preference:** Inhabits deep open oceans, continental slope edges, and deep-sea canyon zones. It has requirements for vertical water structure and benthic topography, mainly diving to feed in deep waters, preying on mesopelagic and bathypelagic cephalopods (such as giant squid).
- **Distribution Characteristics in APEC Region:** Widely distributed in the Kuroshio Extension in the northwest Pacific, the Indo-Pacific convergence zone (such as deep-water straits in Indonesia and Papua New Guinea), and upwelling regions along the west coast of the Americas. Deep-water canyons in the Indo-Pacific convergence zone serve as important ecological bridges maintaining population exchange between different ocean basins. Maternal groups show strong residency around these hotspots, while males undertake long-distance wanderings across ocean regions.
- **SDM Map Interpretation:** Intense dark blue signals concentrate on continental slope edges and deep-sea trenches. Key areas include the northwest Pacific (eastern coast of Japan), the Indo-Pacific convergence zone (gaps between Indonesian islands), waters around New Zealand, and the west coast of the Americas (extending southward from California to the coasts of Chile and Peru).

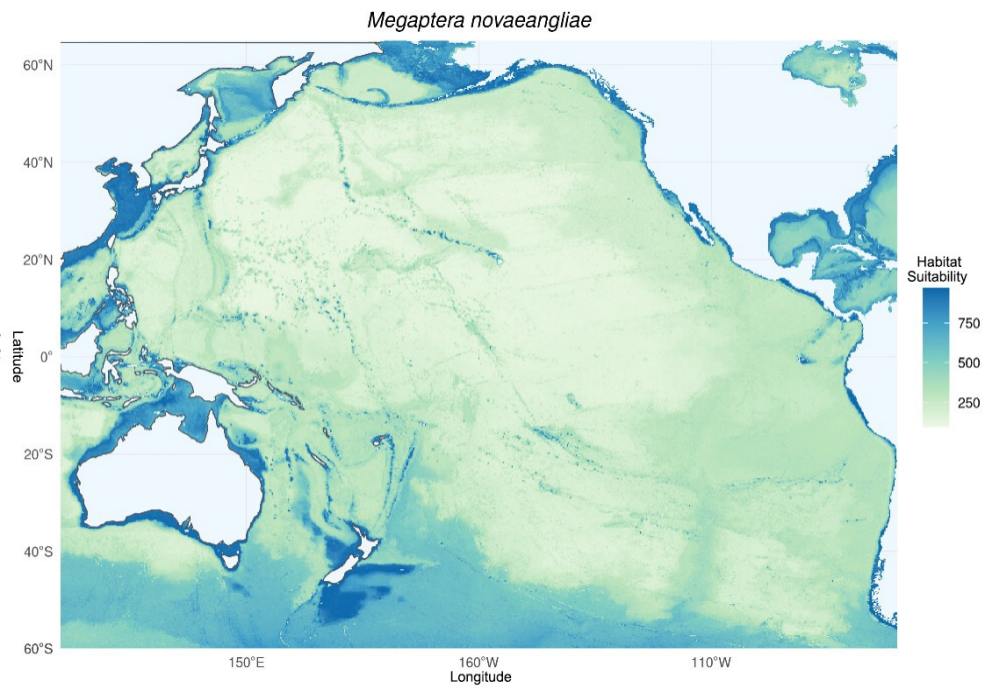
- Economies Requiring Joint Protection: Chile; Indonesia; Japan; Mexico; New Zealand; Papua New Guinea; Peru; United States.
- Recommended Key Organizations:
 - o IWC (International Whaling Commission): Responsible for overall population assessment and conservation coordination.
 - o IMO (International Maritime Organization): Coordinates transoceanic shipping routes to reduce ship strikes and underwater noise pollution in deep-water channels.
 - o IUCN SSC Cetacean Specialist Group: Provides scientific assessment of deep-sea habitats and technical support for conservation.
 - o APEC Marine and Fisheries Working Group: Promotes policy connectivity for deep-water ecological corridors within the region.



2. Humpback Whale (*Megaptera novaeangliae*)

- Habitat preference: It showed obvious seasonal habitat transition patterns. In summer, they forage in cold waters at high latitudes (bait grounds), and in winter, they travel long distances to shallow tropical and subtropical waters at low latitudes (breeding grounds) for mating and nurturing.

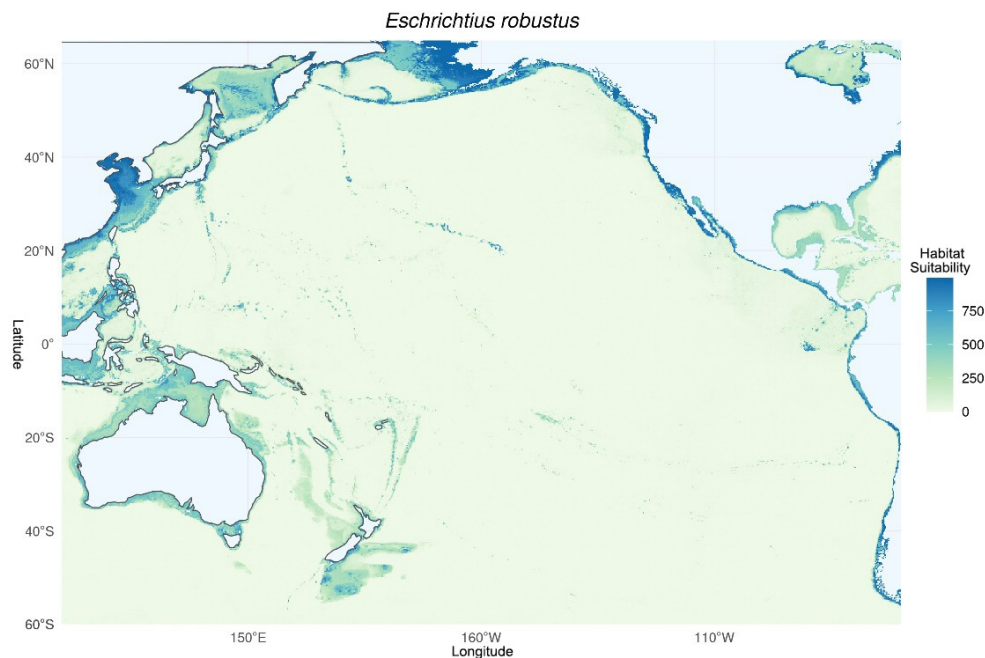
- APEC regional distribution characteristics: North Pacific populations mainly forage in Bering Sea, Gulf of Alaska and other waters with strong primary productivity, and migrate to Hawaiian Islands, the coast of Okinawa, Japan, the Philippines and the coast of Baja California Peninsula in Mexico in winter. Southern hemisphere populations travel between the surrounding waters of Antarctica and the east coast of Australia (such as the Great Barrier Reef) or the west coast of the Americas, forming an iconic north-south ecological corridor in the Pacific Basin.
- Interpretation of SDM diagram: Presenting obvious polarization high suitable zone. The Bering Sea, the Gulf of Alaska to the north, and the Antarctic perimeter to the south are deep blue high-frequency foraging areas; The Hawaiian Islands, Okinawa in Japan, Baja California in Mexico and the Great Barrier Reef in Australia are dark blue winter breeding hotspots.
- Economies in Need of Joint Protection: Australia; Canada; Japan; Mexico; the Russian Federation; United States (Alaska and Hawaii).
- Recommended Key Organizations:
 - o IWC (International Whaling Commission): Regulate and prevent the resurgence of commercial whaling.
 - o CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources): Protect its krill foraging grounds in the Southern Ocean during summer.
 - o WWF (World Wide Fund for Nature): Commit to the transboundary joint protection of its long migration corridors (blue ocean corridors).
 - o SPREP (Secretariat of the Pacific Regional Environment Programme): Coordinate the protection of breeding grounds and sustainable whale watching norms in the Pacific island economies region.



3. Gray Whale (*Eschrichtius robustus*)

- **Habitat Preference:** A typical nearshore shallow-water migratory species, often foraging benthically along the edge of the continental shelf, feeding on small crustaceans in the seabed sediment through filter feeding.
- **APEC Regional Distribution Characteristics:** The Eastern Pacific population maintains one of the longest known migration routes among mammals. They migrate annually between the summer feeding grounds in the Bering Sea and Chukchi Sea and the winter breeding lagoons in the Baja California Peninsula, Mexico, traveling tens of thousands of kilometers along the coast, and their trajectory highly overlaps with the exclusive economic zones of APEC economies on the west coast of North America.
- **SDM map interpretation:** The distribution map is special, and the dark blue area is close to the coastline, forming a slender nearshore contour. It is mainly concentrated along the west coast of North America (stretching from the Bering Strait to the shallow lagoons of Mexico) and along the northwest Pacific coast.
- **Economies in Need of Joint Protection:** Canada; Japan; Republic of Korea (endangered Western Pacific population); Mexico (Eastern Pacific population); the Russian Federation; United States.

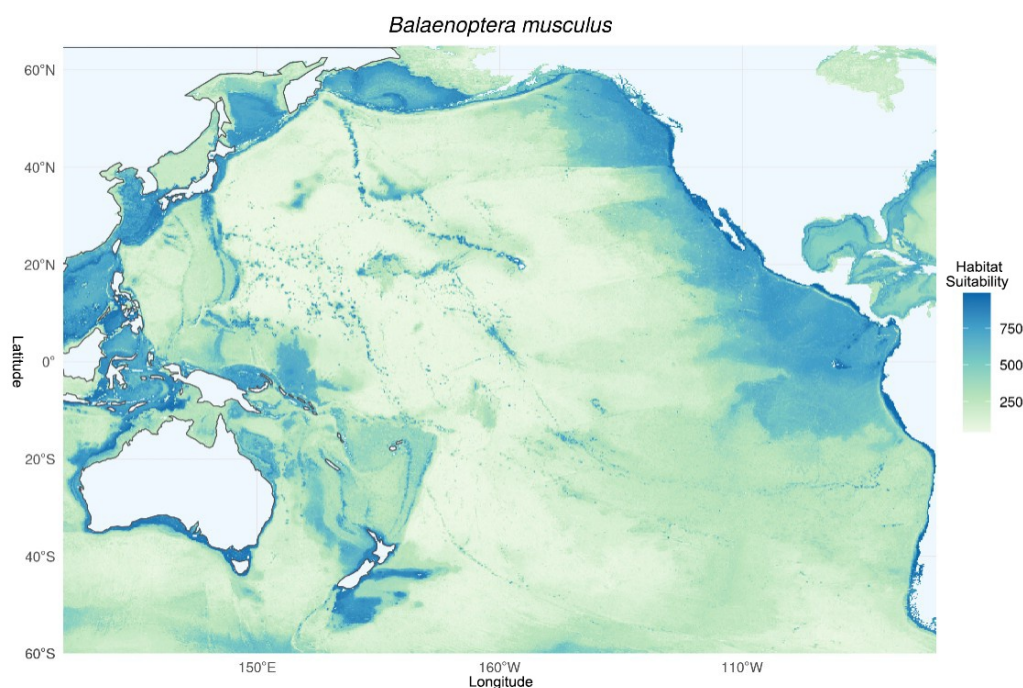
- Recommended Key Organizations:
 - o IUCN Western Gray Whale Advisory Panel (WGWAP): Specialized in providing industrial development avoidance plans for the critically endangered Western Pacific population.
 - o PICES (North Pacific Marine Science Organization): Conduct joint monitoring of nearshore ecosystems and benthic foraging environments.
 - o UNEP (United Nations Environment Programme): Promote solutions to plastic pollution and water quality degradation in nearshore habitats.



4. Blue Whale (*Balaenoptera musculus*)

- Habitat Preference: Highly dependent on large-scale krill aggregations, often occurring in areas with topographic upwelling and cold water fronts.
- Characteristics of APEC Regional Distribution: The Northeast Pacific population often forages in the Gulf of Alaska or the California Current system, and migrates south to coastal areas of Central America (such as the Costa Rica Dome region or the Gulf of California, Mexico) for breeding during cold seasons. Due to their large size and strict requirements for food density, they are sensitive to interannual abnormal changes in the marine environment (such as El Niño events).

- Interpretation of SDM Map: Dark blue areas are mainly controlled by cold water and upwelling currents, with large areas in the California Current region, the Gulf of Alaska, the Costa Rica Dome region, and the high-latitude open ocean in the Southern Hemisphere.
- Economies in Need of Joint Protection: Canada; Chile; Mexico; United States; Costa Rica.
- Recommended Key Organizations:
 - IWC (International Whaling Commission).
 - IMO (International Maritime Organization): Blue whales are highly vulnerable to collisions with large commercial ships; IMO is required to mandate or recommend changes to shipping routes and speeds in key sea areas.
 - SPRFMO (South Pacific Regional Fisheries Management Organization): Coordinate the protection of the underlying food chain and strictly control the overfishing of key prey such as krill.
 - CI (Conservation International): Promote the establishment of large Marine Protected Areas (MPAs) in key breeding areas such as the Costa Rica Dome.



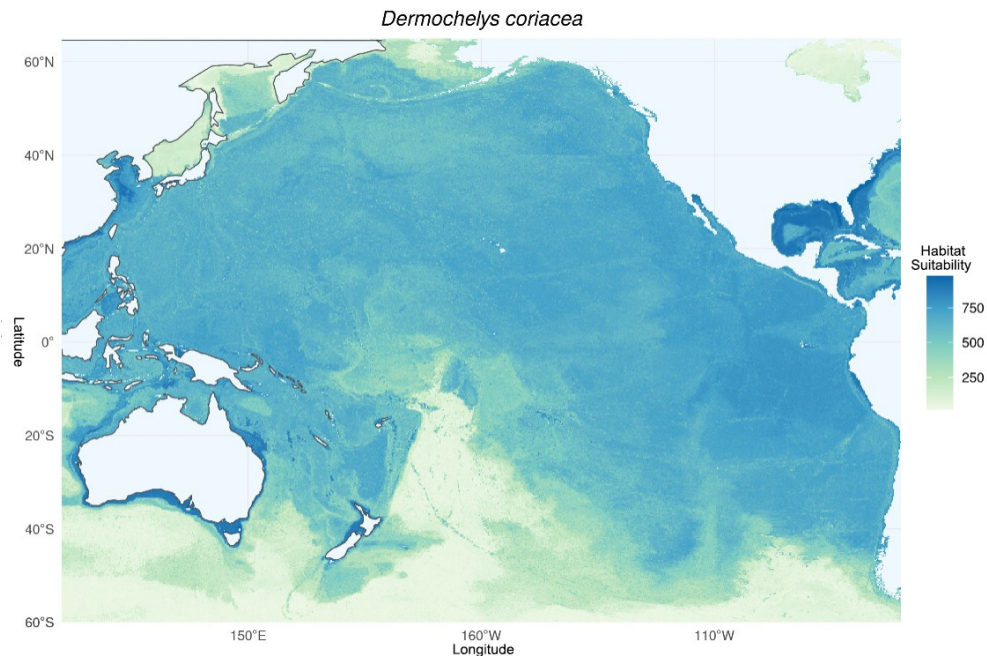
II. Marine Reptiles (Sea Turtles)

1. Leatherback Turtle (*Dermochelys coriacea*)

- **Habitat Preference:** A typical representative of pelagic water dwellers, with the ability to regulate body temperature to adapt to colder seawater, often active in cold-water eddies and frontal zones rich in gelatinous plankton such as jellyfish.
- **APEC Regional Distribution Characteristics:** The Pacific population has obvious transoceanic migration characteristics. The western population usually nests on beaches in Indonesia, Papua New Guinea, and the Solomon Islands. To obtain sufficient energy, adult individuals cross the entire North Pacific to forage in nutrient-rich waters off the coast of California, USA, and the west coast of South America. Their migration routes traverse the jurisdictional waters of multiple economies.
- **SDM Map Interpretation:** The pelagic dark blue belt is very broad. High-suitability areas in the west are located in nesting grounds such as Indonesia and Papua New Guinea; there is a dark blue migration belt spanning the Pacific Ocean in the middle; high-suitability areas in the east are concentrated in foraging grounds off the coast of California, USA, and the west coast of South America.
- **Economies in Need of Joint Protection:** Chile; Indonesia; Mexico; Papua New Guinea; Peru; United States.
- **Recommended Key Organizations:**
 - o **IAC (Inter-American Convention for the Protection and Conservation of Sea Turtles):** Coordinate joint protection and fisheries bycatch prevention among coastal economies in the Eastern Pacific.
 - o **IOSEA (Indian Ocean - South-East Asian Marine Turtle Memorandum of Understanding):** Coordinate the protection and habitat restoration of nesting beaches in the Indo-Pacific region.
 - o **TNC (The Nature Conservancy):** Promote beach light pollution control and community co-management projects in multiple

economies along the Pacific coast.

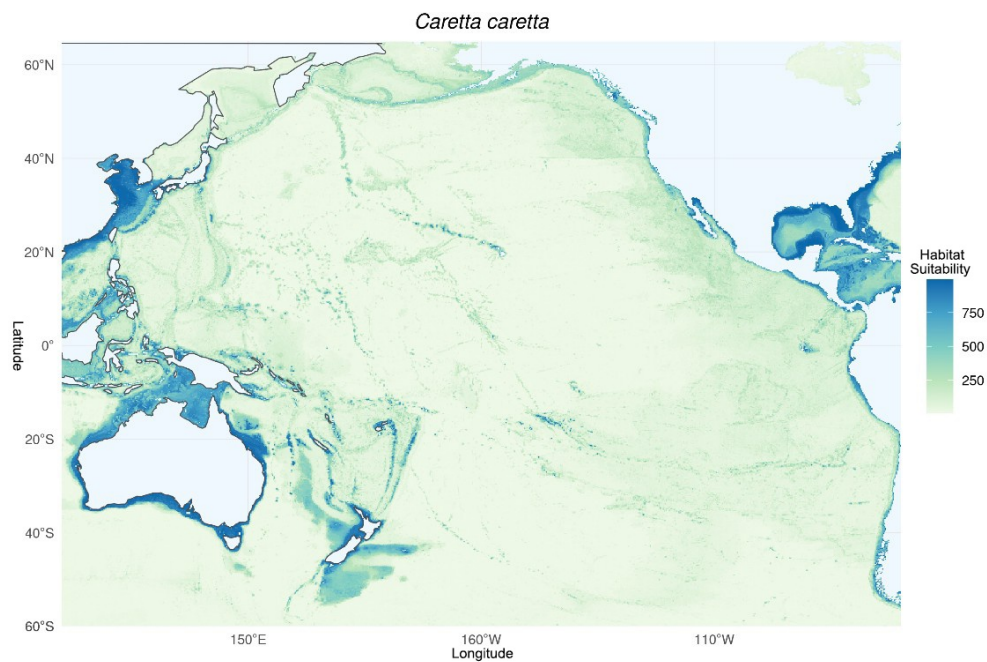
- o IUCN SSC Marine Turtle Specialist Group: Provide global monitoring support for transoceanic migration data.



2. Loggerhead Turtle (*Caretta caretta*)

- Habitat Preference: Adult individuals mostly forage benthically in shallow coastal waters, while juveniles drift passively or semi-passively in open ocean areas along with ocean currents for development.
- APEC Regional Distribution Characteristics: Nearly all North Pacific loggerhead turtles lay their eggs on the beaches along the Japanese coast. After hatching, the young turtles drift with the Kuroshio Current and its extensions, cross the South California Current, and eventually reach the coastal waters of Baja California, Mexico, where they feed and develop for several years. When they reach adulthood, they will cross the Pacific Ocean again to return to the northwestern Pacific to breed, completing a massive ecological cycle.
- SDM Map Interpretation: There is a very striking horizontal dark blue band (Kuroshio Extension) in the North Pacific, which is the "highway" for young turtles' transoceanic drift; its two ends connect Japan (spawning ground) and Baja California, Mexico (development and foraging ground). In the Southern Hemisphere, there is also a dark blue area off the eastern coast of Australia.

- Economies in Need of Joint Protection: Australia; Japan; Mexico; United States (especially Hawaii and the West Coast).
- Recommended Key Organizations:
 - o WCPFC / IATTC (Western and Central Pacific Fisheries Commission / Inter-American Tropical Tuna Commission): These regional fisheries organizations urgently need to promote circle hooks and turtle excluder devices to prevent bycatch.
 - o STC (Sea Turtle Conservancy): Conduct transoceanic remote sensing tracking and special protection education.
 - o BirdLife International: Although it is a bird conservation organization, it is deeply involved in sea turtle protection through the alliance against bycatch in pelagic longline fishing.

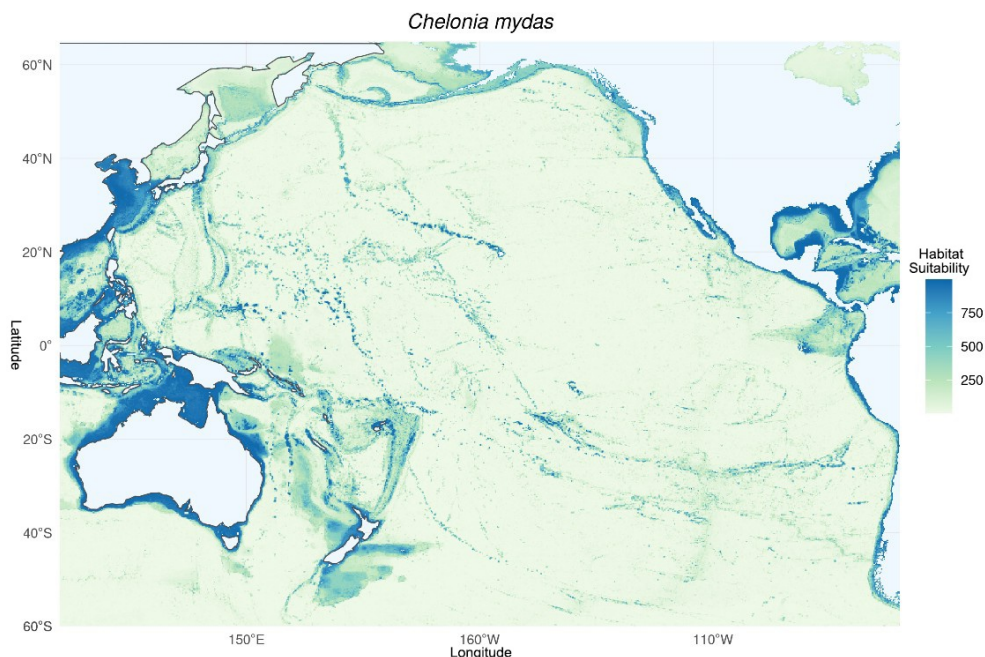


3. Green Turtle (*Chelonia mydas*)

- Habitat Preference: Adult green turtles mainly forage on benthic algae and seagrass in shallow waters of tropical and subtropical coral reefs and seagrass beds. During the nesting season, they need to return to specific beaches.
- APEC Regional Distribution Characteristics: Widely distributed in regions such as the Coral Triangle in Southeast Asia, the Great Barrier Reef, and the Hawaiian Islands. Their adult foraging grounds and nesting beaches are often

hundreds to thousands of kilometers apart, relying on complex coastal and oceanic current systems for spatial navigation.

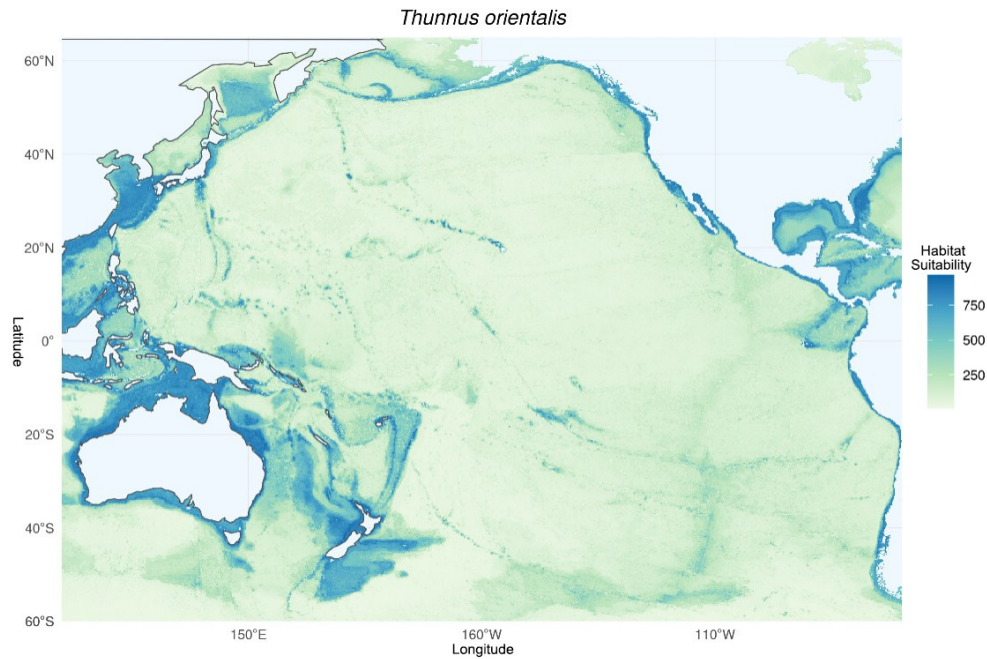
- **SDM Map Interpretation:** Dark blue areas are highly concentrated in tropical shallow waters and coral reef habitats. The Coral Triangle in Southeast Asia (Indonesia; Malaysia; the Philippines;), the area around Australia's Great Barrier Reef, and the Hawaiian Islands show dense dark blue patches.
- **Economies in Need of Joint Protection:** Australia; Indonesia; Malaysia; the Philippines, and United States.
- **Recommended Key Organizations:**
 - **CTI-CFF (Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security):** Focus on protecting seagrass beds and coral reef habitats that serve as food sources for green turtles.
 - **CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora):** Combat illegal transboundary trade in sea turtle shells, meat, and eggs.
 - **WildAid:** Reduce consumer demand for sea turtle products through public education.



III. Highly Migratory Fish and Cartilaginous Fish

1. Pacific Bluefin Tuna (*Thunnus orientalis*)

- **Habitat Preference:** Surface and subsurface waters of temperate and subtropical oceans. They are sensitive to water temperature gradients and often follow frontal zones for foraging.
- **APEC Regional Distribution Characteristics:** Breeding grounds are mainly located in the Northwest Pacific (waters from south of Japan to the Philippines and the Sea of Japan). During the juvenile development stage, some groups cross the Pacific Ocean to the eastern Pacific waters off the west coast of North America (from California, USA to Baja California, Mexico) to feed. After several years of growth and approaching maturity, they will cross the ocean again to return to the western Pacific for breeding. Their life cycle closely connects the APEC economies of Asia and the Americas.
- **Interpretation of SDM Map:** The deep blue belt is distributed in an arc shape, spanning from the Northwest Pacific (breeding areas in the Sea of Japan and the Philippine Sea) across the vast North Pacific, all the way to the west coast of North America (feeding grounds within the California Current system).
- **Economies in Need of Joint Protection:** Japan; Korea; Mexico; the Philippines; United States.
- **Recommended Key Organizations:**
 - **ISC (International Scientific Committee for Tuna and Tuna-like Species in the North Pacific):** Provides the core scientific assessment of population dynamics.
 - **WCPFC / IATTC:** The two major fishery organizations in the western and eastern Pacific need to jointly formulate and strictly implement fishing quotas.
 - **FAO (Food and Agriculture Organization of the United Nations):** Monitors and combats IUU (Illegal, Unreported and Unregulated) fishing activities.
 - **PEW Charitable Trusts:** Actively lobbies governments to reduce fishing limits and promote the recovery of bluefin tuna populations.

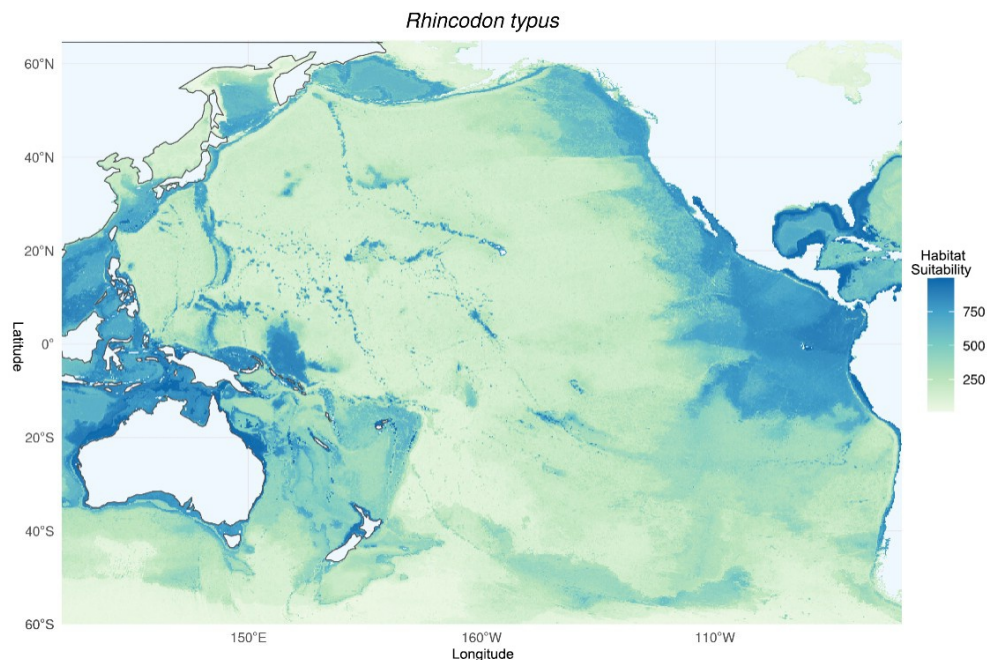


2. Whale Shark (*Rhincodon typus*)

- **Habitat Preference:** Tropical and temperate warm waters, preferring surface waters rich in primary productivity and dense with plankton, as well as areas around coastal coral reefs.
- **APEC regional distribution characteristics:** It often moves on a large scale with seasonal ocean currents and upwelling in the Indo-Pacific intersection (such as Indonesia; Malaysia; and the Philippines), the South China Sea and the surroundings of Chinese Taipei, and the coasts of Mexico and Peru in the eastern Pacific Ocean, and considerable population aggregations often form in the coastal plankton outbreak period.
- **SDM Map Interpretation:** Distributed in tropical/subtropical coastal areas and shelf edges. Deep blue hotspots are located in the Southeast Asian archipelago, the South China Sea and surrounding areas of Chinese Taipei, and the west coast of the American continent (coastal waters of Mexico and Peru).
- **Economies in Need of Joint Protection:** China; Indonesia; Malaysia; Mexico; Peru; the Philippines.
- **Recommended Key Organizations:**
 - CMS (Convention for the Protection of Migratory Species of Wild

Animals): Include it in the Key Conservation Appendix to promote the protection of migratory channels in economies along the route.

- o CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) & TRAFFIC (the Wildlife Trade Monitoring Network): Severely crack down on transboundary networks of illegal wildlife trade such as finning and discarding meat.
- o APEC Tourism Working Group: Develop and promote sustainable and eco-friendly economy-wide standards for whale shark watching tourism.

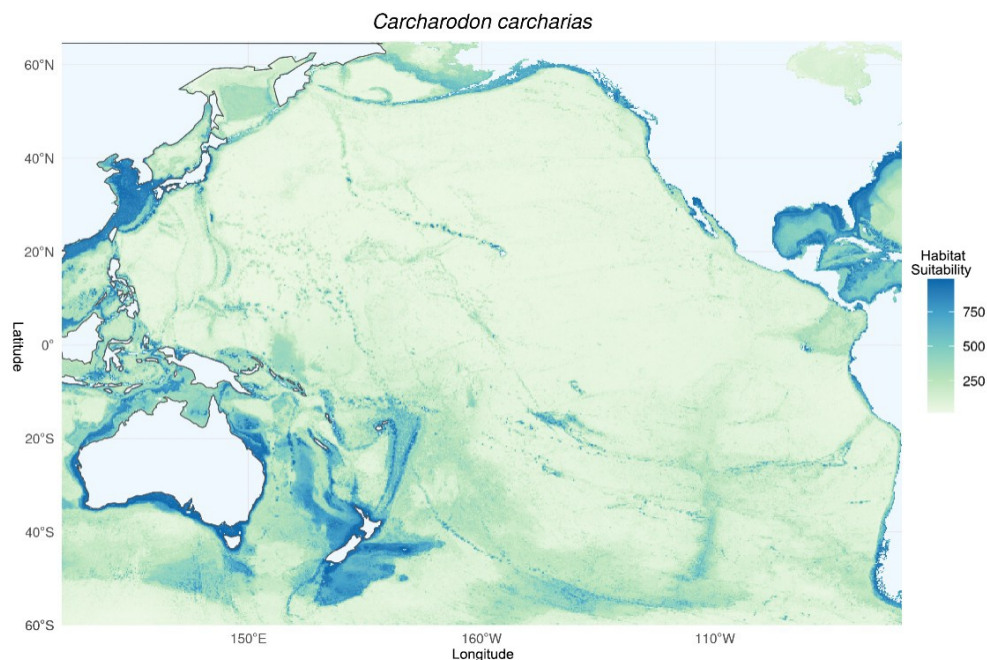


3. Great White Shark (*Carcharodon carcharias*)

- Habitat Preference: Widely distributed in temperate and subtropical marine areas. During specific seasons, they will gather in areas where marine mammals such as seals breed, and also cruise in the open ocean for long periods.
- Characteristics of APEC Regional Distribution: The Northeast Pacific population exhibits regular transoceanic behavior. Each winter and spring, they leave the west coast of North America (such as the feeding grounds near the coast of California) and migrate long distances to the vast open waters

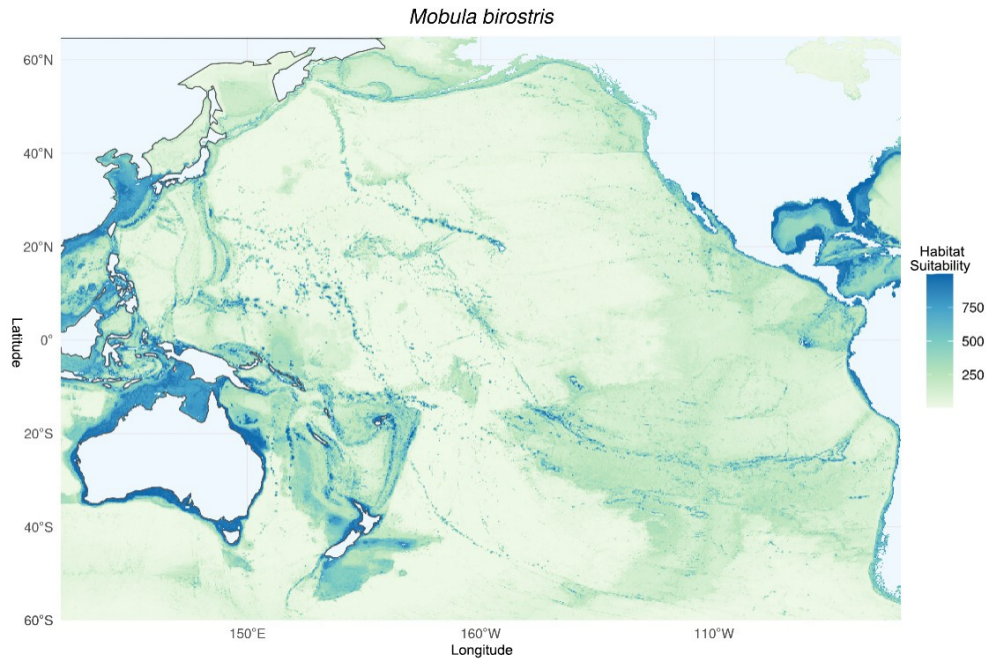
between Hawaii and North America for diving activities, returning to the coastal areas in summer and autumn.

- Interpretation of SDM Map: In addition to the traditional temperate coastal dark blue hotspots such as the North American coast, southern Australia, and New Zealand, there is also an obvious suitable area in the central Pacific (the White Shark Café) between Hawaii and North America.
- Economies in Need of Joint Protection: Australia; Mexico; New Zealand; United States.
- Recommended Key Organizations:
 - o IUCN SSC Shark Specialist Group: Coordinates the global survival status assessment and transboundary migration research of great white sharks.
 - o CMS / CITES: Protect pelagic cruising channels and prevent commercial hunting and trade targeting great white sharks.
 - o The Shark Trust: Focuses on policy lobbying and improvement of fisheries management to address the bycatch issue in pelagic fishing.



4. Oceanic Manta Ray (*Mobula birostris*)

- Habitat Preference: Mostly active in surface to mid-level waters, preferring island wake areas with dense plankton and coastal upwelling zones.
- Characteristics of APEC Regional Distribution: Distributed along the west coast of the Americas (such as the coasts of Mexico; Peru; and Ecuador), the Southeast Asian archipelago to the Australian coast, and often makes long-distance cruising along productive coastal ecological corridors.
- Interpretation of SDM Map: The dark blue areas have strong coastal and island edge attributes. The key areas are the west coast of the Americas (Mexico; Peru; Ecuador), the Southeast Asian archipelago to the northern coast of Australia.
- Economies in Need of Joint Protection: Australia; Indonesia; Mexico; Peru; the Philippines, Ecuador.
- Recommended Key Organizations:
 - o Manta Trust: A leading economy-wide scientific research and conservation non-profit organization specializing in manta rays.
 - o CITES / CMS: Severely crack down on illegal fishing and economy-wide trade targeting their gill plates (due to demand in the Chinese medicinal material market).
 - o WildAid: Carry out special public advocacy actions to reduce the consumption of gill plates.
 - o TNC (The Nature Conservancy): Assists local governments in establishing marine micro-reserves covering key upwelling areas and cleaning stations.



IV. Summary of Environment and Habitat Connectivity

Based on the distribution patterns of the above species, marine migratory species in the APEC region are highly dependent on the following major core hydrodynamic systems and ecological hotspots:

- Western Boundary Current Areas (such as the Kuroshio System and the East Australian Current): Provide strong transport channels for sea turtle juveniles and fish larvae stages. The frontal areas formed by the convergence of warm and cold water masses (such as the Oyashio Current) bring abundant food web foundations.
- Eastern Boundary Upwelling Areas (such as the California Current and the Peru Current): Cold water and nutrients from the deep seabed rise along the coast, supporting a huge plankton community, forming major global pelagic feeding grounds, and attracting a large number of baleen whales and sea turtles from across the ocean.
- Deep-water channels and shallow reef areas in tropical archipelagos (such as the Coral Triangle region): Not only are they global hotspots for benthic biodiversity, but they also serve as critical genetic exchange corridors connecting populations in the Pacific and Indian Oceans, providing shelter and transit routes for various large filter-feeding fish and cetaceans.

- Hidden oases in the open ocean: Including vast high-seas areas such as the Transition Zone Chlorophyll Front (TZCF) in the North Pacific, where hydrodynamic fronts form flowing energy supply stations on the open ocean surface.

The transboundary life history characteristics of these species objectively require close multilateral collaboration among Pacific Rim economies in data collection, spatial planning, and shipping and fisheries management, which also provides a practical ecological basis for applying the dynamic conservation management toolkit proposed in this report.

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