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Overlooked discrepancies in protocols undermine coastal restoration practices in China

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To improve the success of expanding ecosystem restoration efforts, technical guiding-standards are being developed in many nations. Whether these protocols have been well adopted to guide restoration practices remains unknown, especially in developing countries where policies evolve rapidly to balance socioeconomic development with ecosystem restoration. By conducting text semantic mining analyses, we reveal widespread discrepancies between China's coastal restoration practices and protocols over the past four decades. Over 60% of executed restoration projects had no detailed technical standards to guide implementation, especially for severely degraded ecosystems. Development of these standards lagged significantly behind project implementation, was poorly enforced, and focused more on monitoring than guiding good restoration designs and adaptive management, likely undermining restoration performance. Nevertheless, current policies toward prioritizing ecosystem restoration offer opportunities to remedy this issue. Enforcing policies to ensure that practices are guided by protocols is necessary to promote coastal restoration success in China and globally as nations strive to achieve ambitious restoration targets.

Coastal wetlands are among the most productive zones on earth, providing a variety of services, but are economically over-exploited to support the increasing global population^{1,2}. In the United Nations (UN) Decade on Ecosystem Restoration and the coming decades under global changes, ecological restoration is increasingly regarded as an essential strategy to reverse the degradation of coastal ecosystems globally^{3–5}. For example, the Kunming-Montreal Global Biodiversity Framework (GBF) aimed to ensure that at least 30% of degraded ecosystems are under effective restoration by 2030. The 2025–2030 Global Strategic Framework for Wetland Conservation encourages priority restoration of vulnerable coastal wetlands. As the world's most populous nation with a rapidly expanding economy, China is also committed to systematically protecting and restoring the diverse coastal ecosystems such as salt marshes, mangroves, coral reefs, and seagrasses, ensuring that no less than 35% of the coastlines will be restored to its natural state by 2035. Fulfilling such ambitious restoration commitments necessitates developing effective restoration approaches^{6,7}. Improving restoration outcomes depends on highly integrated knowledge drawn from practitioner experiences, ecological theory, local or traditional ecological knowledge, and socioeconomic cognition^{8,9}. Therefore, effective ecological restoration requires a framework or guiding principle, implemented by domestic

policies and laws that guide restoration practices with state-of-the-art restoration science^{10,11}.

As the world enters the new era of ecosystem restoration¹², many countries and organizations worldwide are expected to increase efforts in developing technical standards across various ecosystems, including coastal wetlands, to ensure that ecological restoration achieves its full potential^{11,13–16}. Both mandatory standards enforced by government regulations or policies and recommended standards based on common acceptance of long-term practical experience can guide practitioners through the four restoration stages: designing, implementation, monitoring, and management^{17–19}. These standards contain technical guidelines, details, and procedures that should be used to improve restoration success²⁰. Surprisingly, however, little is known about how such technical guiding standards translate into practical methodologies that eventually match the operating protocols for various coastal restoration projects^{21–23}. Few organizations or countries have analyzed how many of their restoration projects the operating protocols are actually implemented under the guidance of well-defined technical standards. Deviation from established technical standards in restoration practices can not only hinder the attainment of anticipated ecological outcomes but also give rise to pseudo-ecological

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interventions²⁴. For example, afforestation was carried out in mudflats or salt marshes, which transformed the structure and even the type of existing ecosystems. Such misguided efforts may, in turn, undermine the ecosystem's resilience and compromise its long-term sustainability, further exacerbating degradation rather than fostering recovery. This question is most pressing in developing countries such as China, where the field of ecosystem restoration is still relatively young and emerging²⁵.

Over the past few decades, China has been striving to improve ecological restoration to reverse the degradation caused by the overexploitation of coastal wetlands. Since 2015 (China's 13th Five-Year Plan), the concept of ecological civilization has been included as an essential element of sustainable development in China, and coastal protection and restoration have rapidly become mainstream in national and local management²⁶. China is an ideal system for studying the alignment between technical guiding standards and operational practices²⁷, also because its centralized government uses a "top-down" system (e.g., from the national to local level) to implement these protocols, and technical standards are formulated by related governmental departments at three primary implementation levels: national, professional and local standards^{27,28}. This offers a unique opportunity to evaluate the effect of shifting policy priorities on both technical standards and operational practices for coastal restoration²⁶, thereby assessing the effectiveness of these standards in guiding practices.

In this study, we investigated the guidance of coastal restoration practices with technical standards in China. To do so, we constructed a comprehensive dataset that includes detailed information on restoration projects, technical guiding standards, and related policies by screening and compiling from multiple data sources (e.g., official documents, published literature, yearbooks, and commercial search websites) and traced their development process. Then, we examined the extent to which implemented practices, including their restoration processes and techniques, are guided by China's existing restoration standards. To further explain the matching relationship between restoration practices and standards, the distribution of clustering themes and structural network characteristics of protocol documents in different coastal ecosystems, as well as the development trajectory of ecological policy focus, were explored by conducting quantitative semantic mining, spectral clustering, and network analysis based on machine learning algorithms. After highlighting the presence of overlooked discrepancies, we concluded by offering recommendations for matching practices and protocols to advance coastal wetland restoration. The development trajectory of China's coastal restoration policies, techniques, and guiding standards will be a reference for countries that are currently facing rapid economic development while being committed to coastal wetland conservation. Our findings have general implications for enhancing restoration practices in coastal ecosystems globally.

Results

Developing trajectory of policies for China's coastal wetlands

Since China's economic reforms in 1978, 158 policies have been enacted to develop a regulatory framework for protecting and managing coastal wetlands, including laws, administrative regulations, departmental rules, regulatory documents, and government programs. Over time, there has been a shift from policies focusing on economic development to those addressing ecological attributes, including restoration (Fig. 1). Tracing the timeline, its developing trajectory has chiefly gone through the following stage. (i) Although fisheries development has been the primary goal since the Economic Reforms, coastal environments, natural resources, and ecological conservation were gradually included as the reform progressed. Coastal fisheries development (offshore fishing) was given the highest policy priority before 1996 (focus 1, Fig. 1C). As such, marine catch and related coastal gross domestic product (GDP) increased rapidly until 2000 (Fig. 1A). (ii) The "China Ocean Agenda" made sustainable marine and coastal development an essential strategy in 1995. Since then, a series of "Five-Year Plans" with greater emphasis on resource conservation, environmental protection, and ecological restoration (focus 2–5, Fig. 1C; the slope of lines become steeper over time) have been implemented by the government. As a

result, marine catches have gradually stabilized or even declined since about 2000, while the coastal human population has grown with flourishing GDP (Fig. 1A). (iii) Since China's 10th Five-Year Plan started in 2000, ecological protection (focus 4, Fig. 1C) has gradually received increasing attention from the government. (iv) After "ecological civilization" was adopted as a national development strategy in 2012, more actions (e.g., establishing protected areas) were taken to protect vulnerable coastal ecosystems, resulting in a sharp increase in policies focused on ecological protection. Meanwhile, more investments were made to restore damaged coastal wetlands, reversing the trend of loss (Fig. 1B). Only the recovery of mangroves had started much earlier, having been initiated as early as 2000, possibly due to policies encouraging coastal reforestation for storm protection in the 1980s (Fig. 1B). (v) At the end of the 12th Five-Year Plan, policies focused on coastal restoration (focus 5, Fig. 1C) also had increased dramatically and for the first time exceeded those related to fisheries development.

Increasing emphasis on coastal restoration practices and related standards

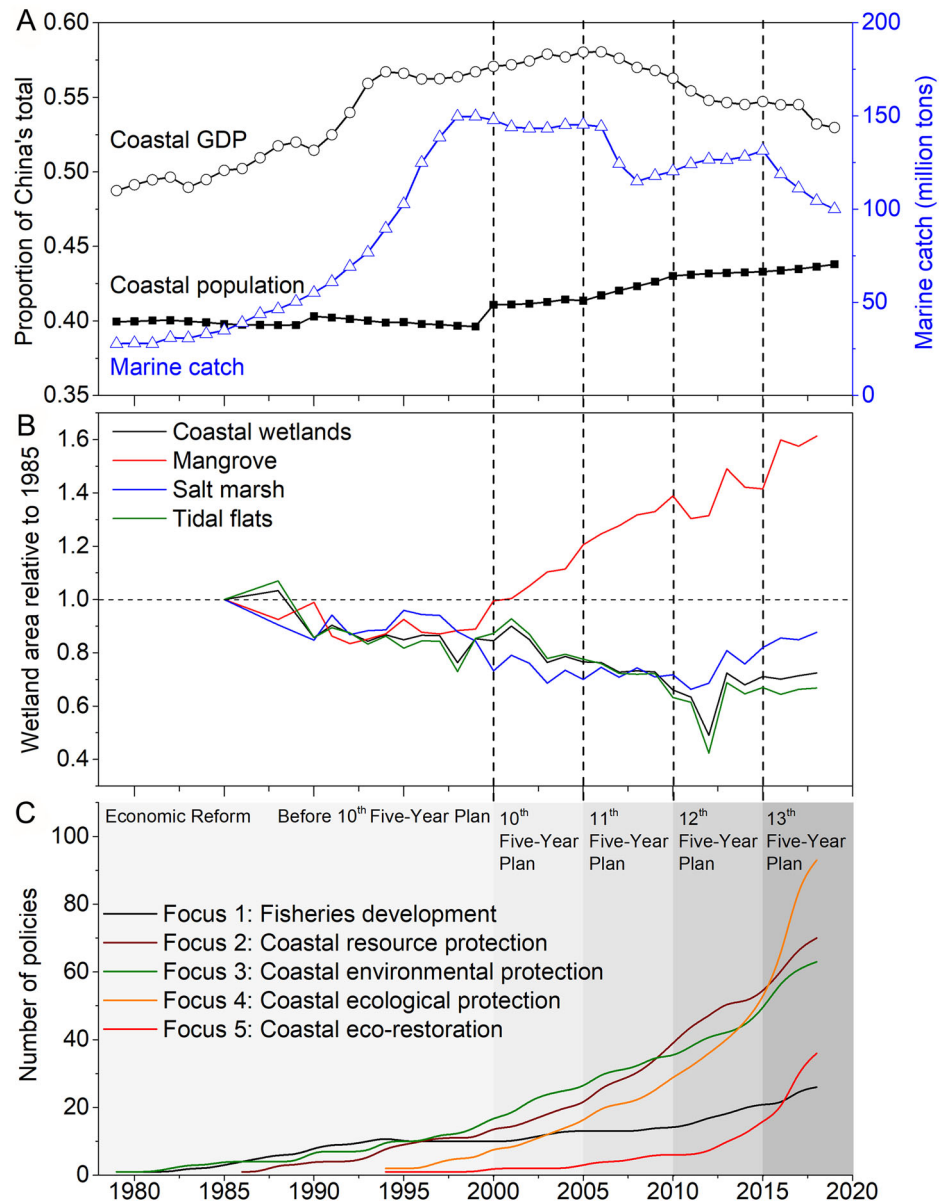
An increasing number of restoration projects have been carried out year by year across various coastal ecosystems, including mangroves, salt marshes, coastal waters, seagrasses, coral reefs, and beaches (Fig. 2 and Fig. S1). Before the 1980s, coastal restoration received limited attention and was generally not implemented, except for some mangrove planting projects. Since the late 1980s, but especially in the early 2000s, restoration projects in different coastal wetlands have been accelerating, facilitated by implementing related policies and technical standards (Fig. 2). Although technical standards have also been increasingly implemented to guide restoration practices across multiple types of coastal wetlands over time, there was a significant time lag between the practical implementation of coastal restoration projects and the development of corresponding technical standards (Fig. 2B–G). It was not until the early 1990s that technical restoration standards were gradually established, which also accelerated from the 2000s onwards (Fig. 2A). Restoration projects on mangroves and coastal waters were implemented earlier than others, followed by salt marshes and coral reefs, with development of restoration standards typically lagging behind restoration projects by around a decade (Fig. 2B–G). Restoration projects and technical standards appeared simultaneously only for beaches and seagrasses (Fig. 2B–G). This might reflect learning from the earlier delays, as these projects and standards were all developed after 2000 (Fig. 2E, G).

Lagged and incomplete development of restoration standards for practices

The greatest challenge facing China's coastal restoration is the misalignment between restoration practices in actual projects and the corresponding technical standards associated with designing, implementation, monitoring, and management. Only 42% of the coastal restoration project techniques had corresponding technical guiding standards, and the majority of them were centered on coastal waters and mangroves (Fig. 3A). In practice, these technical standards target only a few restoration techniques, in particular mangrove planting, artificial reef construction, and artificial release of juveniles. In contrast, in many other coastal wetlands, such as beaches, salt marshes, and seagrasses, the coverage of standards for restoration techniques was comparatively lower (Fig. 3A). Surprisingly, there were no corresponding standards to guide appropriate restoration techniques for coral reefs, and only 12 restoration projects have been reported. This emphasizes the need to develop restoration standards more rapidly while implementing restoration practices.

Not all stages (i.e., designing, implementation, monitoring, and management) of restoration practices were considered comprehensively by technical guiding standards in different coastal ecosystems (Fig. 3B). Most of the technical standards (55%) focused on the monitoring and assessment stage, with much less emphasis on designing (~14%), implementation (~23%), and adaptive management (~8%), although these latter three may be most critical to successful outcomes. Furthermore, most restoration techniques applied to coral reefs, seagrass, and salt marshes were

Fig. 1 | China's increasing coastal economy and population are accompanied by wetland losses, while policy focuses have gradually shifted from economic development to ecological priorities over the past four decades. Time-trending of coastal GDP, population, marine catch (A), coastal wetland area (B), and number of policies for five different focuses during policy transition (C). The GDP and population data were from China's National Database of Statistics (<http://www.stats.gov.cn/>). Marine catch data was obtained from the China Fishery Statistical Yearbook. The areas of total coastal wetlands, salt marshes, mangroves, and tidal flats were derived from Wang et al.¹¹.



implemented without the guidance of technical standards (Fig. 3B). Overall, this emphasizes the need to refocus technical standards for coastal restoration to including pre-design, implementation, and adaptive management.

The current discrepancies between restoration techniques and their designing, implementation, monitoring, and management protocols were partly caused by redundancy and inefficiency in the content of standards that guide restorations (Fig. 4). To facilitate this, we analyzed the text of current standards. The text similarity between standards was reflected by the cluster structure of the technical standard system, where each cluster unit has a specific topic. Most clusters focused on monitoring and assessment (yellow blocks; Fig. 4), traditionally the most achievable. Few thematic clusters, however, dealt with the pre-design of restoration practices (purple blocks; Fig. 4), which might be the most challenging aspect, especially in beaches and seagrasses. The national standards (N-labelled circles) issued by the China National Standards Committee or the professional standards (P-labelled circles) issued by the Departments of China State Council were the central nodes of the standard networks (Fig. 4). Local standards (L-labelled circles) were developed around national standards and formed clusters with independent topics. Moreover, complex standard networks existed in coastal waters (including coastal water mariculture and quality), general

categories, and mangroves (Fig. S2). In comparison, simple networks in salt marshes, beaches, seagrasses, and coral reefs indicated a lack of adequate guidance and overall design regarding the standard system. This emphasizes the need to optimize the structure of restoration standard networks by reducing those related to monitoring with high text-similarity, and by increasing the quantity and linkages between the standards on pre-designs, techniques, and post-management, particularly for those ecosystems with incomplete restoration standard systems like coral reef, seagrass and salt marsh.

Development of restoration standards linked to national policies

There was an imbalance in government-formulated policies across different types of coastal wetlands, which largely explained the discrepancies between restoration practices and their corresponding standards. Statistics derived from the text-mining analysis showed that over 41.6% of the policies focused on coastal waters (Fig. 5A). This intense focus makes sense in that good water quality is a prerequisite for the restoration of many specific ecosystems (e.g., seagrasses and corals). The percentages of restoration related-policies focused on beaches, mangroves, and coral reefs were about 17.7%, 16.7%, and 13.2%, respectively (Fig. 5A). Policies related to seagrasses and salt marshes were minimal, accounting for 7.6% and 3.2%, respectively

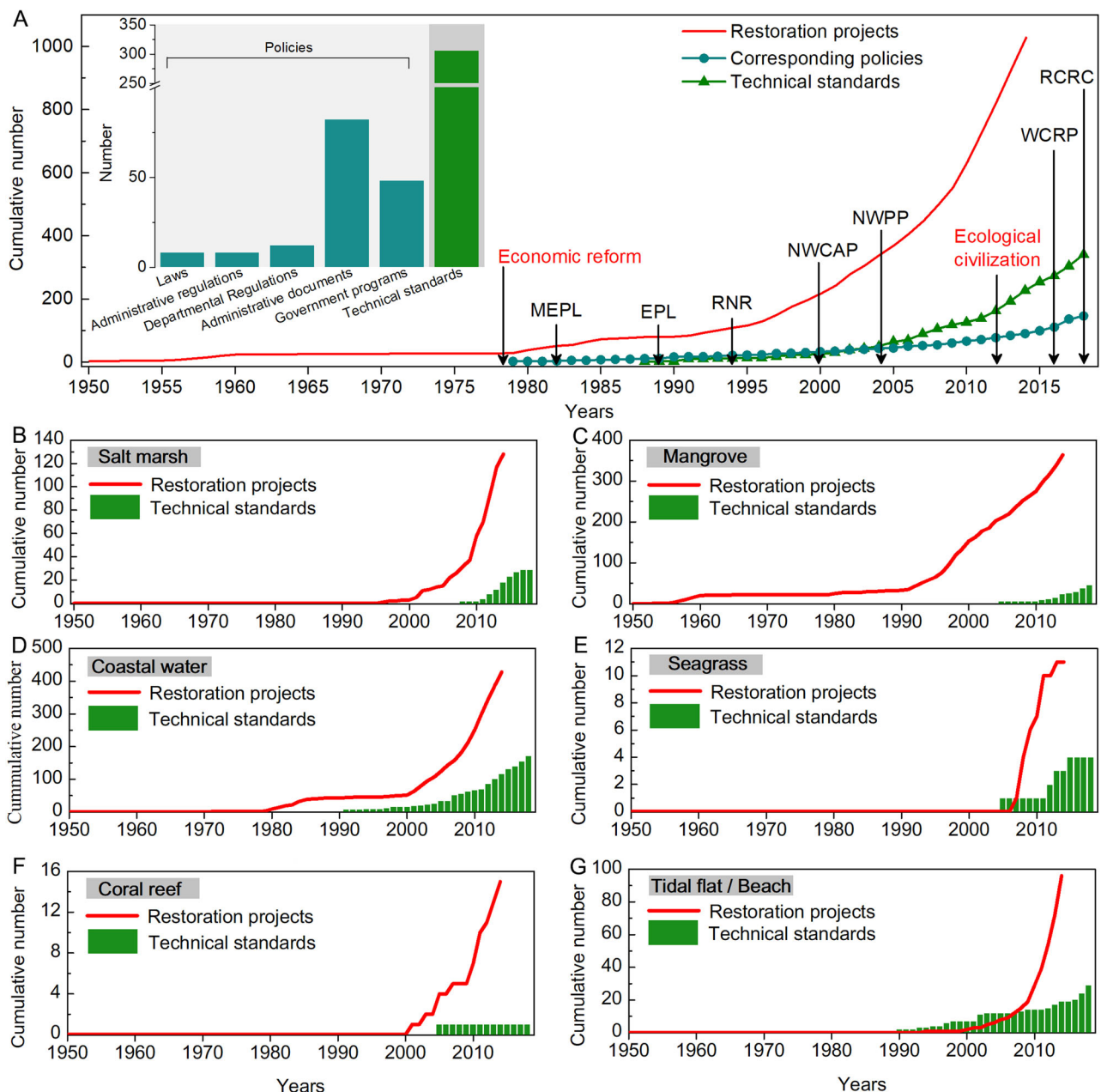


Fig. 2 | Increasing emphasis on coastal restoration practices and related protocols, but time lags exist between implemented restoration projects and formulated corresponding technical standards. A Trends in China's coastal restoration projects, related policies, and technical standards. **B–G** Restoration projects and technical standards for salt marshes, mangroves, coastal waters, seagrass, coral reefs, and beaches, respectively. Major policies in (A): Marine

Environmental Protection Law (MEPL, 1982), Environmental Protection Law (EPL, 1989), Regulations on Nature Reserves (RNR, 1994), National Wetland Conservation Action Plan (NWCAP, 2000), National Wetland Protection Plan (NWPP, 2004), Wetland Conservation and Restoration Plan (WCRP, 2016), and Notice of the State Council on Strengthening the Protection of Coastal Wetlands and Reclamation Control (RCRC, 2018).

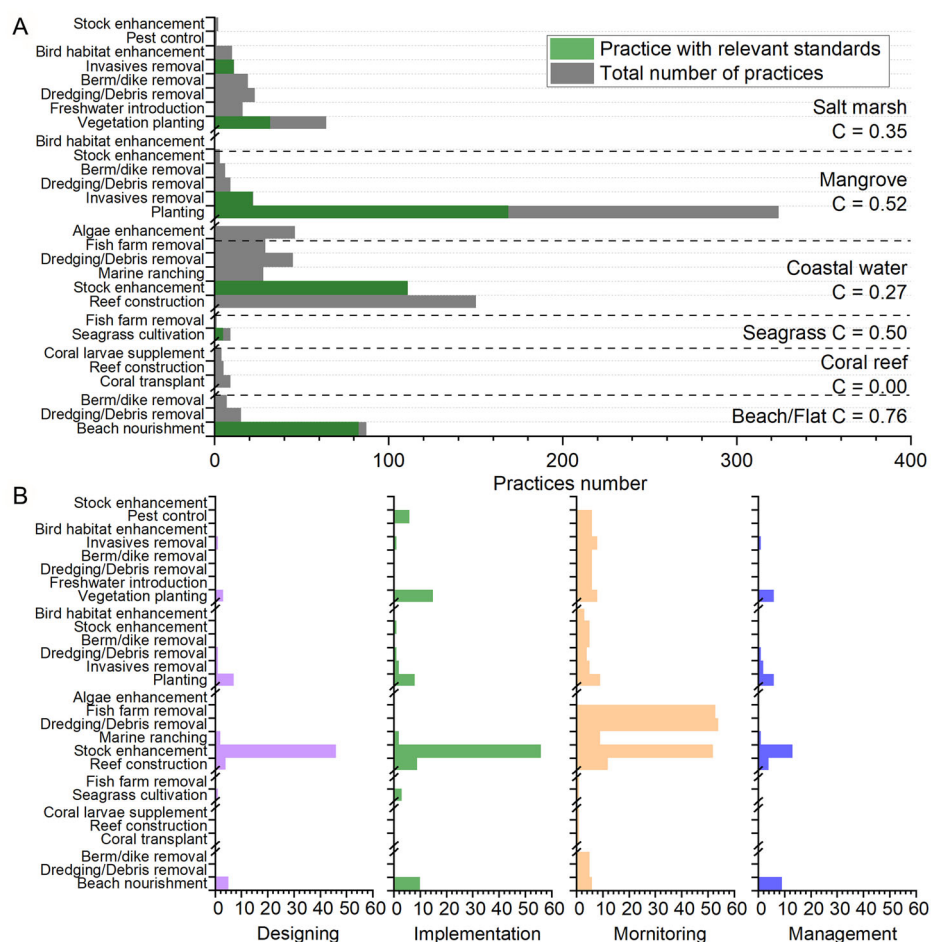
(Fig. 5A). Since 1979, a majority of the policies has been focused on coastal waters, whereas policies on beaches, mangroves, coral reefs, and seagrasses remained few until the 2000s (Fig. 5A). There were no policies addressing salt marshes until 2002 (Fig. 5A). These policies enacted at the national level may have had a substantial impact on protocols, as indicated by the positive correlation between the numbers of technical standards and restoration-related policies over time ($R^2 = 0.75$, $P < 0.001$, Fig. 5B). There were still few standards for seagrasses, coral reefs, and salt marshes because policies did not fully address these ecosystems yet. These results suggest the great need to balance the concerns of restoration-related policies among different coastal ecosystems according to their ecological conditions to effectively guide the formulation of standards.

Discussion

Lessons from the developing trajectory of China's coastal restoration

With an increase in coastal ecological restorations globally, there are concerns about the capacity of technical standards to guide restoration projects^{10,17}. This study highlights considerable discrepancies between restoration practices and protocols among coastal wetlands in a rapidly evolving policy-driving system, as mainly shown in the following aspects: (i) many restoration techniques lacked appropriate technical guiding standards, especially for severely degraded coastal ecosystems; (ii) technical standards lagged significantly behind the implementation of restoration projects, leaving most practices being carried out without guidance; (iii)

Fig. 3 | Prominent discrepancies exist between coastal restoration practices and protocols as many restoration techniques and processes lack detailed technical standards to guide implementation. A The guidance matching index of technical standards for restoration practices and the proportion of standard-guided techniques in different coastal ecosystems. **B** The standard distribution of varying restoration techniques in four stages (i.e., designing, implementation, monitoring, and management).



most standards focused on conventional monitoring, rather than coming up with good designs and adaptive management. China is making solid efforts to improve coastal restoration as current policy priorities shift from economic development to ecological conservation^{26,27,29}. The development path of coastal restoration that China has implemented can provide important lessons and references for many developing countries to optimize the existing restoration standard system from the perspective of policy guidance.

Ecological restoration standards are highly related to the macro-policy orientation for protecting, restoring, and managing coastal wetlands in China. This suggests that restoration practices and standards prioritized the coastal wetlands that received more policy attention or can generate greater economic benefits, rather than those that are ecologically important but severely degraded. As a result, some coastal wetlands have been over-exploited or destroyed due to insufficient attention from managers. These degraded ecosystems, such as seagrasses, coral reefs, and salt marshes, also deserve priority for restoration, but the reality has long been the opposite¹¹. The core reason for uncoupled restoration practices and technical standards seems to be that standard formulation was mainly driven by policies dominated by socioeconomic factors rather than the actual restoration demand of different coastal wetlands³⁰. The imbalance in restoration efforts across multiple coastal ecosystems and misalignment of restoration projects from standards are likely to be experienced in many countries with rapidly developing economies that, like China, are expanding ecological restorations, such as mangrove restoration in Southeast Asia²³, seagrass restoration in the Baltic Sea and Australia³¹, salt marsh restoration in Africa and the Middle East³², and coral reef restoration in Atlantic Sea islands³³. Restoration standards should be developed in line with the integrated design across ecosystems and in response to expanding practices, which is essential for long-term restoration success.

The profound effect of restoration standards on improving practices

Although technical standard systems of ecological restorations vary significantly in different countries, either aligned or divergent from the macro-orientation of policies^{34,35}, the existing standards are typically based on the initial trial, successful paradigms, and unsuccessful experiences, which can reduce the failure risk and uncertainty of restoration projects^{12,17}. The problem, however, is that not all coastal restoration projects follow these standards, mainly due to the lack of policy guidance and systematic evaluation of the effectiveness of the technical standard system²². Government departments, standardization organizations, or international associations as protocol agencies need to pay greater attention to whether there are gaps in the current technical standards for restoration practices^{6,36}. Importantly, formulating good technical standards requires mature restoration techniques, which can be determined by technology readiness levels (TRLs), a method for estimating the maturity of technologies during the acquisition phase of a program.

While there is a global consensus that restoration can reverse losses and conserve coastal wetlands, the degradation of global coastal ecosystems underlying climate change and human activities is not well mitigated, and degradation continues to exceed restoration^{9,37}. This failure is in part due to the absence of uniform policies and practices for implementing restoration, as well as a lack of post-restoration monitoring and adaptive management²³. Most projects are limited in performance metrics to assess whether they meet their goals, and many lack clear, measurable goals to determine success^{12,21}. Significantly, some sort of metrics are urgently developed to examine whether degraded ecosystems are under effective restoration after various types of restoration projects have been implemented, as adopted by the Kunming-Montreal GBF Target 2. The number and type of restoration projects were

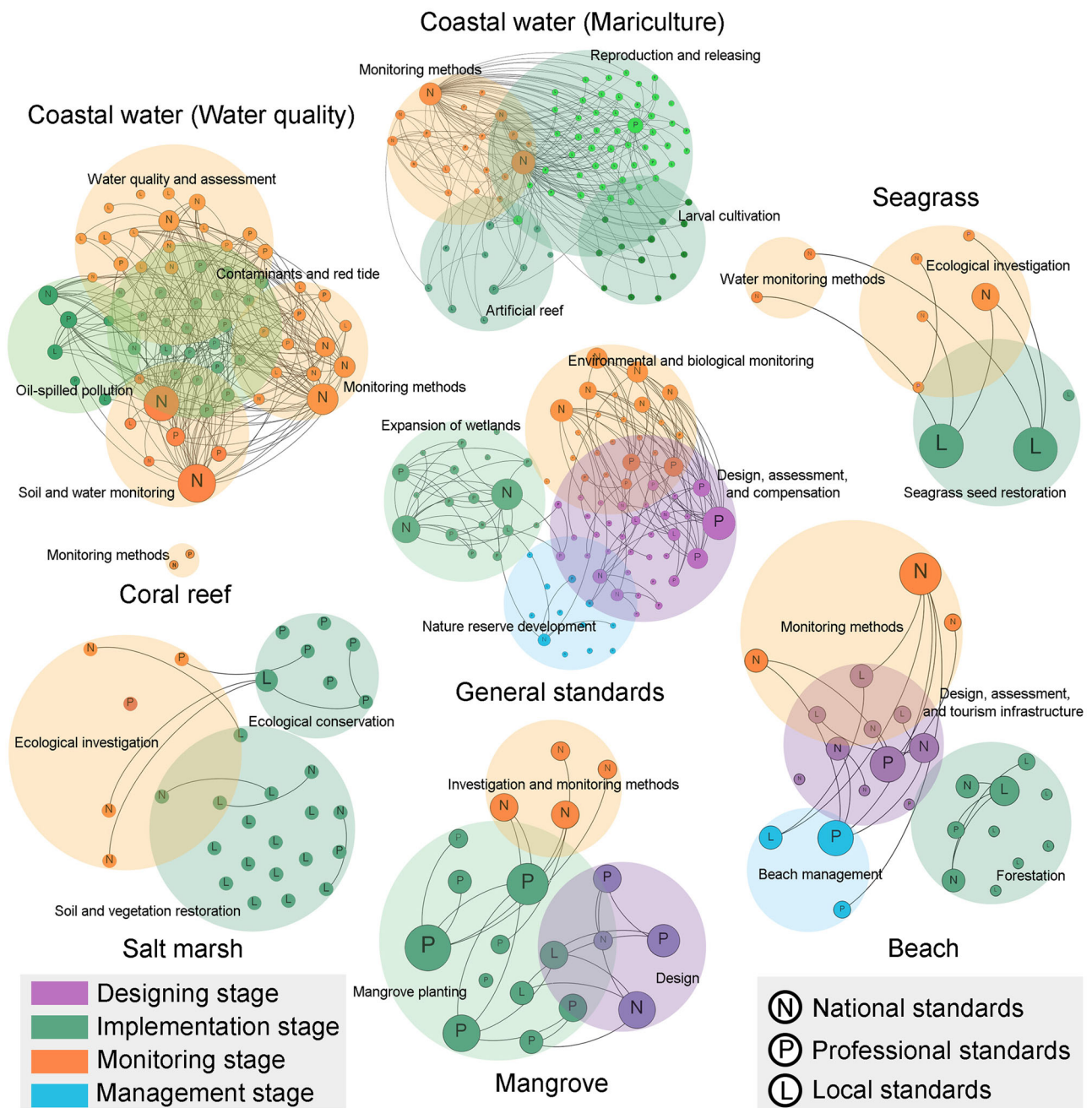


Fig. 4 | Clustering distribution and structural network characteristics of China's formulated restoration standards in different types of coastal ecosystems. The nodes are standard documents, and the similarity value between every two standards determines the distance of the node pairs. The linkage connecting two nodes indicates that a co-citation was presented between the two standards. The size of nodes reflects the total citation number. The letters within nodes represent the hierarchy of

standards: N-national, P-professional, and L-local. These restoration standards were grouped by the spectral clustering method. Documents with more than 30% similarity were clustered into a group with a common theme. The purple, green, yellow, and blue circles represent the design, implementation, monitoring, and management theme, respectively.

identified in the present study, but as no such criteria have been developed or implemented, the overall restoration effectiveness of China's coastal wetlands cannot be assessed, as is likely to happen in most countries worldwide. Such post-assessment could be of great significance for the dynamic adjustment of national or regional restoration actions.

Furthermore, it should be emphasized that standards covering the various restoration stages of pre-designing, implementation, monitoring, and post-assessment are required and enforced by laws. In this case, the proportion of projects under effective restoration could be automatically augmented, which might lead to a great improvement in overall

restoration effectiveness, but this would also need further observation. Thus, a crucial next step may be to develop and enforce laws to ensure that (i) technical-guiding standards are adopted in large-scale restoration projects and (ii) the performance of restoration projects is assessed against a minimum outcome⁷. On 1 June 2022, the Wetland Conservation Law, China's first national law on wetlands, came into force. It emphasizes "no net loss" protection targets and nature-based solutions, providing a solid legal basis for wetland restoration and conservation³⁸. Such national action may be worthy of reference for other developing countries that are conducive to mitigating the degradation trend of global coastal wetlands.

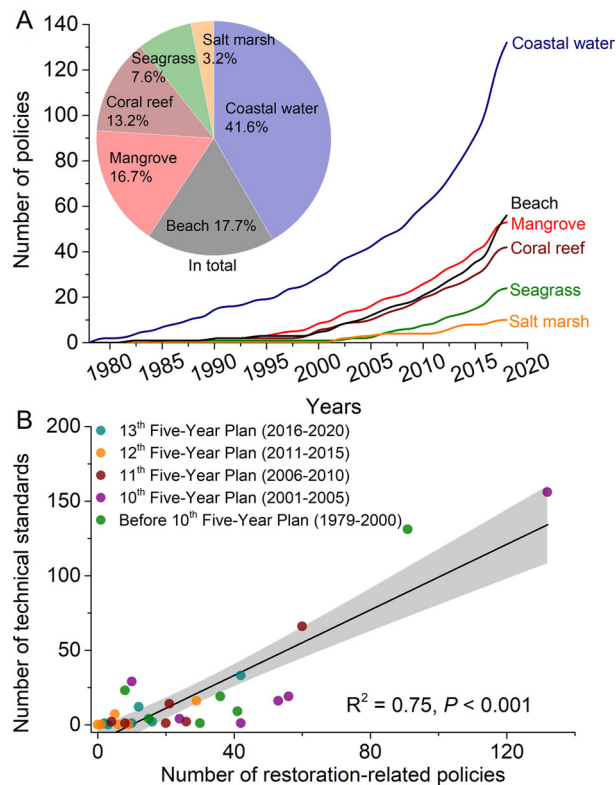


Fig. 5 | The imbalance in government-formulated policies among different coastal wetland types significantly affects the orientation of technical standards. **A** The proportion of China's restoration-related policies focused on each coastal wetland type and their changes over time. **B** The relationship between restoration-related policies and technical standards.

Towards effective and coordinated restoration of coastal wetlands

Successful restoration requires fully considering the four stages: designing, implementation, monitoring, and adaptive management¹⁶. If standards are unavailable and inappropriate at any stage of restoration processes, the risk of restoration failure increases, even potentially giving rise to pseudo-ecological interventions that not only undermine restoration objectives but also exacerbate ecosystem degradation (see examples of restoration practices with less success or pseudo-ecological engineering triggered by overlooked discrepancies; Table 1). In particular, China's coastal restoration projects lack systematic designing and long-term adaptive management at regional and national scales^{27,39}. More than half of the technical standards focused on assessing habitat characteristics (i.e., baselines) before project implementation and monitoring water, soil, and biota during and afterwards⁴⁰. However, the investigation methods for these factors are easy to standardize and exist in many ecological monitoring standards⁴¹.

This study also found differences in the standardization of different coastal restoration practices. Monoculture planting is the dominant strategy for mangrove and salt marsh restoration, while only a few projects employ multi-species planting that may promote biodiversity and ecosystem services⁴². Other comprehensive practices, such as hydrological and topographic restoration, have been widely implemented but have no clear technical guidance. Restoration practices that consider ecosystem structure and its heterogeneity represent the future development trend^{43,44}, and more such standards can be expected. The breed and release method is commonly used to rehabilitate fish populations in coastal waters²⁶. Many countries have detailed practices and technical standards, even for each species⁴⁵. This system is as expected from technical standards, with detailed guidance and comprehensive coverage of technical procedures. However, implementation after breed and release projects are seldom evaluated for their success.

Performance criteria for other coastal restoration projects, including artificial coral reefs and seagrass transplantation, do not even exist^{33,46}. Therefore, a broader application of policy is needed to cover different types of restoration practices along with performance criteria to measure restoration success.

Our findings suggest caution in enacting guidance strategies for coastal wetlands that rely on ecological restoration projects to reverse ecosystem degradation. Discrepancies between policies, protocols, and practices can lead to a “cask effect” on restoration outcomes (i.e., the weakest or shortest board among different restoration stages determines the final restoration results, as shown in Fig. 6), especially since most effort goes to the monitoring stage and much less to up-front design, implementation, and post-management. Here, we propose a feasible framework to align policies, protocols, and restoration practices optimally (Fig. 6). First, best technical practices, including a combination of feasible restoration site and technique selection⁴⁷, incorporation of pre-planning, long-term monitoring, and adaptive maintenance options, are necessary to guide restoration efforts^{8,23}. To achieve this, more comprehensive restoration protocols should be recommended to adequately match the corresponding techniques in the four restoration stages of practices and for each coastal ecosystem type. Significantly, a national database that includes technical details of restoration projects and the standards they use should be initiatively developed based on lessons from many successful and failing restoration practices to improve restoration effectiveness⁴⁸. Second, merely increasing the protocol quantity is inadequate; the quality of recovery needs to be significantly enhanced by developing policies that produce detailed and measurable performance criteria for each restoration stage. Third, an integrated quality check system (e.g., TRLs) on all stages involved in coastal restoration needs to be developed. Such a system should give instant feedback to policies on whether the protocols guide the practices well. Future protocols should integrate all restoration stages of different coastal ecosystems, significantly strengthening those related to pre-designs and post-management based on restoration effectiveness so that policies could drive restoration in a more effective way. Developing such a synergetic framework can be broadly applied to benefit other countries experiencing coastal wetland losses.

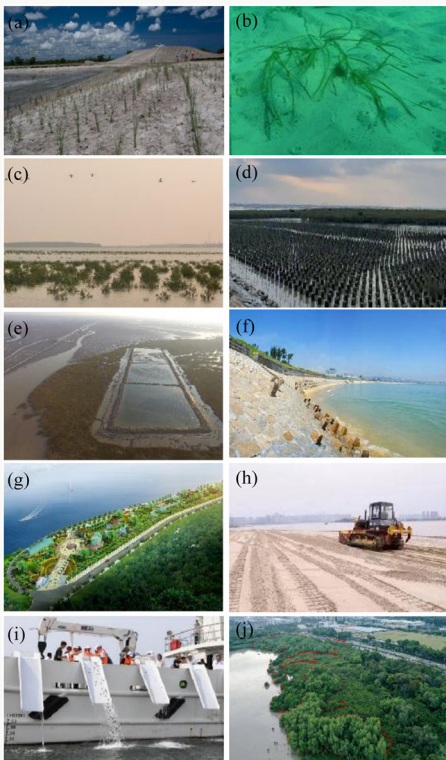
As most coastal wetlands have not yet degraded to the tipping point where restoration cannot be reversed globally, and many countries are increasingly investing in ecosystem restoration, the windows of opportunity to systematically address the discrepancies remain open. Therefore, a coordinated, comprehensive national strategy with prompt actions to strengthen policy-protocol-practice linkages and full support of international restoration communities is urgently needed to seize this opportunity before it is too late. The methods used in this study can be broadly applied to identify the discrepancies in various ecosystems worldwide and help continuously improve policy-making processes for restorations. Our findings from a coastal country facing significant development pressures can provide implications for other countries during this UN Decade of Ecosystem Restoration and Ocean Science for Sustainable Development, leading to greater opportunities to restore coastal wetlands more effectively and helping achieve UN Sustainable Development Goals.

Methods

Dataset construction

Data on China's coastal restoration projects was obtained from Liu et al.⁴⁹. The dataset integrated detailed information, including restoration name, project location, techniques, area, start year, and habitat type. Data on policies concerning coastal restorations, including laws, administrative regulations, department rules, regulatory documents, and government programs, were obtained from China's relevant official government organization websites (Table S1)⁵⁰. To compile a comprehensive dataset on China's coastal restoration standards, information was mainly obtained from four sources: (i) online news, notices, and reports, published on the official websites of China's relevant government organizations, (ii) literature from the China Knowledge Resource Integrated Database (<http://www.cnki.net/>), (iii) Commercial standard search websites (<http://www.biaozhuns.com/>).

Table 1 | Some examples of restoration interventions with less success or pseudo-ecological engineering triggered by overlooked discrepancies

Category	Interventions with less success or pseudo-ecological engineering	Representative samples
Inappropriate restoration designs and associate techniques were adopted during the implementation	• Simplifying vegetation re-establishment without consideration of the “window of opportunity” theory and habitat improvement in salt marshes (a). • Performing seagrass seeding and seedling transplantation under stresses of strong hydrodynamic disturbance and consumer control (b). • Transforming the structure and even the type of original ecosystems, such as afforestation in mudflats or salt marshes (c). • Establishing coral reefs, seagrass beds, and mangroves in places where they were historically absent (d). • Creating temporary dikes to reduce tidal disturbance to improve the survival of transplanting that fail to resist the stressful environment in the long term. • Eradicating invasive plants, such as <i>Spartina alterniflora</i> simply by plowing, mowing, and/or water flooding, while largely overlooking the damage to native (e).	
Excessive artificial engineering intervention was implemented	• Hardening the shoreline to prevent wetland erosion but reduces their biological connectivity and self-recovery capabilities (f). • Performing pseudo-ecological engineering projects, such as developing the natural salt marshes into coastal garden landscapes for tourism purposes (g). • Replacing muddy beaches with sandy beaches by dredging and sand replenishing (h). • Converting salt marshes into reed wetlands by irrigating freshwater to increase carbon sinks.	
Potential ecological risks were introduced during restorations	• Using non-native species or domesticated species for enhancement and release (i). • Introducing exotic species such as <i>Sonneratia apetala</i> for mangrove restoration (j). • Ignoring habitat heterogeneity and conducting homogenizing habitat restoration.	
Lack of pre-restoration degradation assessment and post-restoration adaptive management	• Performing excessive habitat rehabilitation for lightly degraded coastal ecosystems without evaluating the potential of the ecosystem's self-organization. • Lacking long-term substrate maintenance and management for transplanted salt marsh plants, mangroves, and seagrasses, leads to high mortality. • Neglecting reinvasion risk after eradication of invasive plants due to a lack of timely monitoring and adaptive management.	

com/; <http://www.bzfxw.org/>), and (iv) National Library of China (Table S2)⁵⁰.

The GDP and residential population (1979–2020) data was extracted from China's National Database of Statistics (<http://www.stats.gov.cn/>) for each of the 11 coastal provinces/province-level cities: Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan. The total GDP and population data were also extracted in the following sections. Taiwan, Hong Kong, and Macau were omitted because (i) governmental policies enforced in mainland China did not apply, and (ii) consistent and long-term data were unavailable. Coastal GDP and population were calculated as the sum of the coastal provinces and were defined on a provincial basis. Long-term marine catch data was obtained from the China Fishery Statistical Yearbook. Annual offshore catch data, excluding mariculture and deep-sea fishing, were utilized. The areas of total coastal wetlands, salt marshes, mangroves, and tidal flats were obtained from Wang et al.¹¹. The areas of coral reefs and seagrasses were unavailable, precluding their analysis.

Guidance matching index calculation

To quantify the extent to which the eco-restoration projects were guided by technical standards, restoration techniques for each type of coastal wetland were summarized, and the degree to which technical standards covered restoration techniques was calculated (Table S3)⁵⁰. Furthermore, each restoration technique was divided into four stages (i.e., designing, implementation, monitoring, and management). Restoration standards were counted at each stage (Table S4)⁵⁰, and

coverage values were calculated as follows:

$$C_i = \frac{\sum_j t_{ij}}{\sum_j N_{T_{ij}}} \quad (1)$$

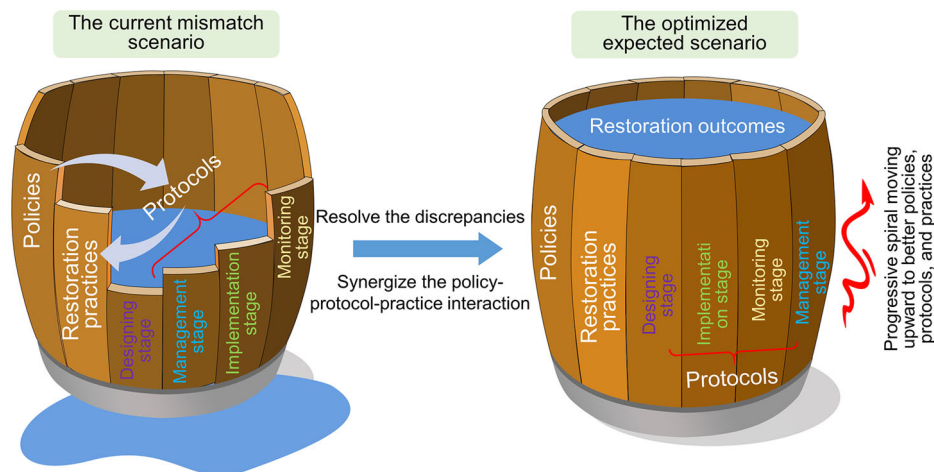
$$t_{ij} = \begin{cases} 1, & t_{ij} = s_{ij} \\ 0, & t_{ij} \neq s_{ij} \end{cases}, \{t_{ij}\} \subseteq \{T_{ij}\}, s_{ij} \in \{s_{ij}\} \quad (2)$$

Where C_i is the coverage value of the technical guiding standard to restoration techniques in a certain ecosystem. $N_{T_{ij}}$ is the total number of restoration techniques in a certain ecosystem and $\{T_{ij}\}$ represents the total restoration techniques. s_{ij} represents a specific restoration standard and $\{s_{ij}\}$ is the aggregation of restoration standard category. $t_{ij} = s_{ij}$ represents a specific restoration technique that is guided by a standard. While $t_{ij} \neq s_{ij}$ represents a specific restoration technique without a guiding standard.

Multiple semantic retrieval classification and text mining analysis for policy documents

To quantify the focus of policy on the different types of coastal wetlands and their time-series evolution, the method of multiple semantic retrieval classification was used to analyze the distribution frequency of each ecosystem type (i.e., salt marshes, mangroves, coastal waters, beaches, seagrasses, and coral reefs) in all policy documents. The coastal wetland types were identified by a collection of system-specific Chinese words with the same semantics as all considered policies (Table S5)⁵⁰.

Fig. 6 | Conceptual framework showing how to mitigate the cask effect of policy-protocol-practice interactions concerning coastal restorations. The left illustration represents the mismatch scenario in which the protocols' designing, implementation, and management stages are "short board". The right side shows the optimized expected scenario toward better restoration outcomes. The cask effect can be alleviated by enhancing policy-protocol-practice feedback and effectiveness evaluation (e.g., TRLs) across all restoration stages.



The LDA model, an unsupervised machine learning technique, was used to identify the subject information hidden in the corpus of policies and then automatically categorize these policies⁵¹. In this model, each policy document is viewed as a mixture of a few topics, and each word's presence is attributable to one of the document's topics. The LDA posits that each policy document follows a probability distribution composed of specific topics, and each topic follows a probability distribution comprising many words⁵¹. Thus, the text information of each policy document was converted into quantifiable digital information that the model easily identified. According to the topics extracted from the LDA model, policies were classified into five focuses: fisheries development, coastal resource protection, coastal environmental protection, coastal ecological protection, and coastal ecological restoration (Table S6)⁵⁰. The code for the above-mentioned analyses was written and performed using GEMSIN package⁵² in Python 3.7 (Supplementary Text).

Text similarity analysis for restoration standards

To measure the text similarity among restoration standards, the unstructured documents of standards were transformed into a structured numerical vector using classified LSI models⁵². The LSI is a mathematical optimization for representing word meanings in an orthogonal vector space created through an unsupervised learning method applied to a large text corpus, which has been suggested to successfully model human linguistic and cognitive knowledge through extensive psychological experiments⁵³. The LSI was calculated using the bag-of-words tokenization, term frequency-inverse document frequency (TF-IDF) value, and Doc2Vec methods (Supplementary Text). Vector cosine methods were used to measure the similarity of standard documents. The cosine similarity of two standard documents x and y is estimated as:

$$Sim_{cos}(x, y) = \frac{\sum_{i=1}^M w_i(x) \times w_i(y)}{\sqrt{\sum_{i=1}^M w_i(x)^2} \times \sqrt{\sum_{i=1}^M w_i(y)^2}} \quad (3)$$

Where, w_i is the term weighted vector transformed Doc2Vec with the LSI weights, and M is the number of documents. The resulting similarity of any two documents ranges from 0, meaning independence, to 1, meaning the same, with in-between values indicating intermediate similarity. This text analysis was implemented using the GEMSIN package in Python 3.7.

Spectral clustering and network analysis for restoration standards

Based on the similarity matrix between two standard documents for a specific coastal ecosystem, standards were grouped using the spectral clustering method (Supplementary Text). By adjusting the grouping number of spectral clustering, the documents with more than 30% similarity

were clustered into a group. The theme of each standard group was summarized by manual full-text interpretation. To reveal the overall structure of China's coastal restoration standards, networks for multiple coastal wetland types were constructed using standard documents as nodes and the similarity value between two standards as the distance between the node pairs. In addition, China's standards have a fixed format, and an important feature of these standards is that they list other standards they have cited, similar to the reference section of an academic article (Fig. S2). The citing path as arcs was added to the standard networks. Gephi software was used to visualize the networks of coastal restoration standards.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data supporting the analyses and results of this study have been deposited to the online repository, Open Science Framework (OSF)⁵⁰.

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Author contributions

T. X., Z.N., B.C., and T.J.B. conceived the manuscript, analyzed the data, and led the writing. Q.H., C.C., Z.Z., C.B.C., Y.Z., Q.W., G.C., S.L., J.B., and Z.Y. contributed substantially to reviewing and editing the manuscript.

Competing interests

The author declares no competing interests.

Additional information

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