Intelligent Planning of Ocean Energy Infrastructure: A Synergistic Mechanism between Ecological Protection and Energy Development

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Abstract—**With the rapid expansion of offshore wind and other ocean energy facilities, conflicts between energy development and ecologically sensitive marine areas have become increasingly prominent. Existing marine spatial planning approaches often rely on static exclusion zones and linear weighting methods, which may not sufficiently reflect seasonal ecological sensitivity and life-cycle environmental pressures. To address this problem, this study develops a GIS-based scenario planning framework that combines ecological sensitivity assessment, life-cycle pressure estimation, and multi-criteria spatial suitability analysis. Publicly available marine environmental, biodiversity, energy-resource, and spatial constraint datasets were integrated for representative areas in the European North Sea and the East China Sea. The framework compares a conventional static planning scenario with an ecological-sensitivity-constrained planning scenario. Simulation results indicate that incorporating seasonal ecological sensitivity and decommissioning-related pressure can substantially reduce infrastructure occupation in high-sensitivity zones while maintaining most of the energy development potential. The proposed framework does not aim to replace site-specific environmental impact assessment; rather, it provides a transparent screening and decision-support tool for early-stage marine spatial planning. The results suggest that ecological protection and energy development can be better coordinated when dynamic ecological constraints and life-cycle considerations are incorporated into spatial planning.**

Keywords—Ocean Energy Infrastructure, Marine Spatial Planning, Ecological Sensitivity, GIS-MCDM, Scenario Simulation, Life-Cycle Pressure

I. INTRODUCTION

Recently, the sea has become one of the significant frontiers in the battle against climate change, energy transition, and the supply of renewable energy. Over the past several decades, there has been an extremely fast increase in ocean energy infrastructures, especially offshore wind farms, submarine cable systems and other offshore facilities in shallow as well as deep water areas. It has opened up opportunities of low-carbon energy development but also expanded the presence in marine space, the coastal habitats and end-of-life infrastructure management. According to the analysis of ocean energy infrastructure at the global scale, it is important to pay more attention to the correlation between the marine space planning, sustainable design, and decommissioning governance when implementing further development [1].

In the meantime, the development of ocean energy is not an environmentally friendly process. Threats to the marine ecosystem are climate change, fishing, infrastructure development and its operation impact. The results of ecological network research have demonstrated the potential changes in the functioning of an ecosystem and interspecific interactions due to climate change, marine renewable energy, and fishing. This means that marine spatial planning should take into consideration the cumulative and spatially variable effects of development decisions, engineering feasibility and energy production [2].

The efficiency of multi-criteria decision-making in combining engineering, financial, and ecological parameters has also been proven by existing studies regarding the site selection of offshore wind farms. As an example, multistage based approaches to the methodology of MCDM have been used to identify the location of offshore wind power stations taking into consideration all the possible factors of the suitability at once [3]. Nevertheless, most of the planning literature remains based upon the idea of static suitability layers and fixed exclusion zones which do not always reflect the seasonal ecological sensitivity, life cycle pressures and the relationship between energy development and ecological protection.

To overcome these weaknesses, this paper creates an open-ended GIS-based scenario planning model of ocean energy infrastructure. In contrast to a fully automated decision-making system, the proposed framework has three pragmatic objectives, which are: 1) creation of a dynamic ecological sensitivity index that would take into account the seasonality of the most important ecological parameters; 2) incorporation of life cycle pressure related to construction, operating use, and decommissioning stages into the assessment of spatial suitability; and lastly, 3) comparison of

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Corresponding Author: Mingqiu Xue,No. 501, Zhongkai Road, Haizhu District, Guangzhou, China, 510225,MingqiuXue1920@outlook.com various planning alternatives to identify the trade-offs between energy capacity and ecological safety. The present study is considered as the first planning and screening tool but not as a replacement of the complete assessment of environmental impacts at the project level.

The rest of this paper will be structured in this manner. Literature review section II discusses optimization methods, software solutions based on marine spatial planning, cumulative impacts on environment, ecological impact, and digital planning approaches. Literature review section III gives the synthesis of other research on offshore wind site selection, life cycle environmental assessment, cumulative impact accounting, ecological network analysis, and marine energy development effects. The proposed GIS-based scenario planning framework is discussed in section IV. Data sources and preprocessing steps are outlined in section V. The outcomes of scenario simulation are presented in section VI. Implications and limitations of results are discussed in section VII. A summary of the study and suggestions on the future research directions are provided in section VIII.

II. LITERATURE REVIEW

The integration of hybrid artificial intelligence and optimization has also infiltrated renewable-energy planning on a more general scale with the aim of enhancing the quality of the systems and the efficacy of decision-making. These methodologies, most of which have been developed in non-marine-related energy systems (e.g., grid-interconnected solar photovoltaics) offer a stimulus to multi-objective energy planning with both technical and environmental constraints [4]. Nevertheless, when this strategy is being applied to the marine spatial planning, transparency, data availability and reproducibility are especially important.

Decision-support tools have been created in order to evaluate multi-sectorial activities of energy, fisheries, conservation, shipping, etc., which can help the new offshore blue economy. According to the reviews of these tools, marine planning still suffers in measuring cross-sectoral trade-offs and cumulative spatial conflicts [5]. It is especially so when it comes to offshore wind farms where cumulative environmental impact might differ by space or time. The research of offshore wind farms in the North Sea basin has demonstrated that cumulative environmental impacts should be taken into account both in terms of space and time, and not only in terms of projects [6].

The historical procedure of selecting a location of an offshore wind farm had been based on the concept of spatial analysis and multi-criteria decision-making with the help of GIS. The selection of a site of offshore wind farms has been implemented by using a hybrid MCDM method, namely taking into account technical, economic and environmental aspects in an organized assessment process [7]. These approaches can also be helpful due to the fact that they enable the planners to measure the various regions regarding the range of limitations. However, the first studies of the ecology of offshore renewable energy noted that the generation of power close to the shore could negatively impact the density of seabirds, benthic organisms, marine mammals, and the ecological health of their ecosystems via various ecological mechanisms [8]. Ecological indicators must not therefore be perceived as an insignificant second order limitation during the selection of sites.

This sustainable site-selection research has also revealed that offshore wind planning should take into account wind resources, depth of water, proximity to the shore, environmental vulnerability, and even policies. One example is the offshore wind site selection in the South Aegean Sea that has shown how an assessment with the help of the GIS can be used to support sustainable spatial distribution [9]. However, more recently it has been proposed that digitalization of marine energy and digital twins might be the way forward to integrating real time information, simulation and decision making in marine energy systems [10]. Moreover, digital twins have been considered as possible applications of marine renewable energy and offshore wind systems to optimize both design and control procedures [11]. However, these methods would only be feasible if it were possible to achieve high quality data, calibrate models, and ensure computational transparency. Which is why this paper will instead use a more reproducible GIS-based scenario planning model rather than a completely functional digital twin or black-box intelligent optimization model.

III. RELATED WORK

Similar activities can be divided into three major categories: offshore wind site choice, life-cycle and cumulative environmental effects, and social-ecological effects of marine energy development.

To begin with, it has been observed that a lot of researches related to the implementation of GIS-MCDM approaches have been used to select the location of offshore wind farms. The study on the feasibility of offshore wind in Turkey by using GIS-MCDM took into consideration the spatial, technical and environmental variables that existed in the Turkish seas [12]. Moreover, the relevance of taking into account the marine parameters of the specific locations and their feasibility to develop, as well as environmental limitations to select a spatial position was established by the example of the Jeju Island, South Korea, where the offshore wind farm site was chosen [13]. Multi-criteria decision-making models based on interval type-2 fuzzy sets have been also developed to assist in solving more complex decision-making issues such as the establishment of offshore wind farms [14]. The main components of the spatial planning of wind energy are GIS, MCDM, and hybrid assessment methods, which, in turn, are justified by the systematic overview of the processes of site selection in onshore and offshore wind power generation research. Nevertheless, most of these papers are still oriented toward suitability ranking, and the dynamics of ecological sensitivity and life-cycle ecological pressures might not be thoroughly addressed.

Thirdly, research on environmental assessment is a useful source of information regarding the integration of life-cycle thinking in the offshore energy planning process. The study of the environmental effects of the world offshore wind power production by 2040 indicates that massive offshore wind growth would use significant amounts of materials and leave a significant environmental footprint at various points of life cycle [16]. Moreover, examinations of marine biodiversity decommissioning processes of offshore wind farms show that the last step of the decommissioning procedure may be connected to specific ecological stresses that should be taken into account when planning instead of being left to the end of the project [17]. The principles and the best practices of cumulative impact accounting in offshore energy development say that all projects, pressures, and ecological receptors should be assessed as a whole to ensure that the regional environmental risks are not underestimated [18].

In addition to ecological network analysis and more extensive impact research, it is important to consider the development of marine energy as part of the coupled social-ecological system. The cumulative effects of marine renewable energy and climate change have been examined on ecosystem properties, and it was found that ecological network metrics could serve as indicators of ecosystem sensitivity to combined stressors [19]. Meanwhile, research on social and ecological effects of marine energy development has demonstrated that marine energy projects do not necessarily affect ecological receptors ecologically, but may also affect local communities, fisheries, sea usage and stakeholder acceptance [20]. Such results suggest that the design of ocean energy systems should not be based on single-factor analysis of suitability, but should include ecosystem sensitivity, cumulative effects, life-cycle effects, and socio-ecological trade-offs.

The paper has found two gaps in the literature based on the literature reviewed. In one case, many of the recent studies on site selection provide meaningful spatial suitability rankings but very little attention is paid to seasonal ecological shifts and decommissioning pressures over time. Conversely, although digital and smart marine energy system tools have been suggested, their application remains limited to theory due to the availability and repeatability of information. The disadvantages mentioned are counterbalanced by the fact that the presented research presents a simple-to-follow scenario planning model that is based on GIS and incorporates the ecological sensitivity assessment, life-cycle pressure assessment, and multi-criteria spatial suitability assessment at the initial stage of the ocean energy infrastructure plan.

IV. METHODOLOGY

A. *Research Strategy*

This study adopts a technical route of "data integration—ecological sensitivity assessment — life-cycle pressure estimation — scenario-based spatial optimization." First, multi-source spatial data are standardized into a common grid system. Second, a dynamic ecological sensitivity index is constructed to reflect the seasonal variation of key ecological factors. Third, construction, operation, and decommissioning pressures are incorporated into a life-cycle pressure index. Finally, alternative planning scenarios are compared using GIS-MCDM and constrained spatial allocation. The overall workflow is illustrated in Fig. 1. This framework emphasizes transparency and reproducibility rather than black-box optimization.

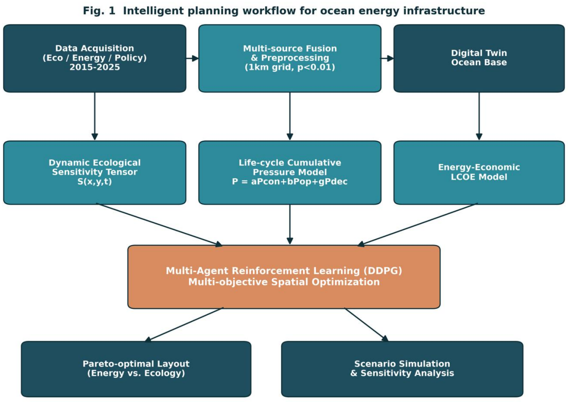

Fig. 1. GIS-based scenario planning workflow for ocean energy infrastructure.

B. *Data Acquisition Methods*

This study integrates three categories of data required for early-stage marine spatial planning. The first category includes environmental and ecological baseline data, such as water depth, seabed substrate, ocean current conditions, sea surface temperature, marine protected area boundaries, and available records of key species distribution. The second category includes energy development suitability indicators, such as wind resource potential, distance to shore, distance to grid connection points, water depth suitability, and foundation type constraints. The third category includes spatial conflict and policy constraint data, such as shipping lanes, fishing grounds, military restricted areas, and legally designated conservation zones. All data are used at the planning-screening level. Where high-resolution biological observations are unavailable, this study uses publicly accessible datasets and literature-based ecological sensitivity weights, and the uncertainty of such substitution is discussed in the limitations section.

C. *Data Analysis Methods and Model Construction*

Dynamic Ecological Sensitivity Index. Traditional GIS-based planning methods often treat ecological sensitivity as a static spatial layer. To better reflect seasonal ecological variation, this study defines a dynamic ecological sensitivity index S(i,t) for grid cell i during season t. The index is calculated from three components: habitat vulnerability, species activity intensity, and ecological recovery potential. All indicators are normalized to the range of 0 – 1, where higher values indicate greater ecological sensitivity. The general form is:

$$S(i,t) = w1H(i) + w2B(i,t) + w3[1 - R(i)] \qquad (1)$$

where H(i) represents habitat vulnerability, B(i,t) represents seasonal biological activity or species distribution intensity, R(i) represents recovery potential, and w1, w2, and w3 are weights determined through literature review and expert-based multi-criteria assessment. This formulation allows ecological sensitivity to vary across both space and season, while remaining interpretable and reproducible.

Life-Cycle Cumulative Pressure Index. To avoid focusing only on the construction and operation stages, this study incorporates three infrastructure life-cycle stages: construction, operation, and decommissioning. The cumulative pressure index P(i) of grid cell i is defined as:

$$P(i) = \alpha Pcon(i) + \beta Pop(i) + \gamma Pdec(i) \qquad (2)$$

where Pcon(i), Pop(i), and Pdec(i) represent the estimated pressure during construction, operation, and decommissioning, respectively. The coefficients α , β , and γ are scenario weights reflecting different planning priorities. For example, a conservation-oriented scenario assigns a higher weight to decommissioning pressure, while an energy-oriented scenario assigns a higher weight to development suitability. These weights are reported explicitly to support reproducibility.

Scenario-Based Spatial Optimization. Instead of using a black-box reinforcement learning algorithm, this study applies a transparent constrained spatial allocation method. Each grid cell receives an energy suitability score and an ecological constraint score. Areas with legal exclusion constraints are removed first. The remaining grid cells are ranked according to their combined suitability under different scenarios. Three scenarios are compared: a baseline static planning scenario, an ecological-sensitivity-constrained scenario, and a life-cycle-pressure-constrained scenario. The trade-off between retained energy capacity and reduced ecological pressure is then evaluated. This method enables planners to identify spatial alternatives without relying on unavailable proprietary algorithms or high-performance computing resources.

V. DATA

A. *Basic Data Information*

This study selected the European North Sea and the East China Sea as representative planning areas because they differ in development intensity, ecological conditions, and marine spatial conflicts. The analysis uses publicly available gridded environmental data, biodiversity occurrence records, marine protected area boundaries, and energy-resource indicators. The temporal scope of the analysis is determined by the availability of comparable public datasets. Instead of assuming complete continuous observations for all variables, this study treats the dataset as a planning-level spatial database compiled from multiple sources. Variables with sufficient temporal information are used to describe seasonal variation, while variables with limited temporal resolution are treated as static background layers. This distinction reduces the risk of overstating data completeness.

B. *Data Preprocessing Methods*

All spatial layers were projected into a unified coordinate system and resampled to a common grid resolution suitable for regional planning analysis. Continuous variables such as wind speed, water depth, and distance to shore were normalized to the range of 0 – 1. Categorical variables such as seabed substrate and spatial restriction type were converted into binary or ordinal suitability layers. Missing values were treated according to data type: small gaps in continuous environmental layers were filled using spatial interpolation, while areas with insufficient ecological information were assigned an uncertainty flag rather than being treated as confirmed low-sensitivity areas. This procedure prevents data gaps from being misinterpreted as suitable development zones.

VI. RESULTS

Using the GIS-based scenario planning framework, this study compared the performance of three planning scenarios: a conventional static planning scenario, an ecological-sensitivity-constrained scenario, and a life-cycle-pressure-constrained scenario. The purpose of the comparison is not to claim an exact engineering design outcome, but to evaluate how the inclusion of dynamic ecological sensitivity and life-cycle pressure may change early-stage spatial planning decisions.

A. *Asymmetric Trade-off Between Capacity and Ecology*

The scenario comparison shows that strict exclusion of all medium- and high-sensitivity areas may lead to a substantial reduction in available energy development space. However, when seasonal ecological sensitivity is considered, part of the conflict can be reduced by avoiding areas with high ecological sensitivity during critical periods. In the ecological-sensitivity-constrained scenario, infrastructure occupation in high-sensitivity zones is substantially lower than in the static baseline scenario, while most of the energy development potential is retained. This result indicates that ecological protection and energy development are not always linearly opposed; rather, spatial conflicts are often concentrated in a limited number of high-risk areas(Fig.2).

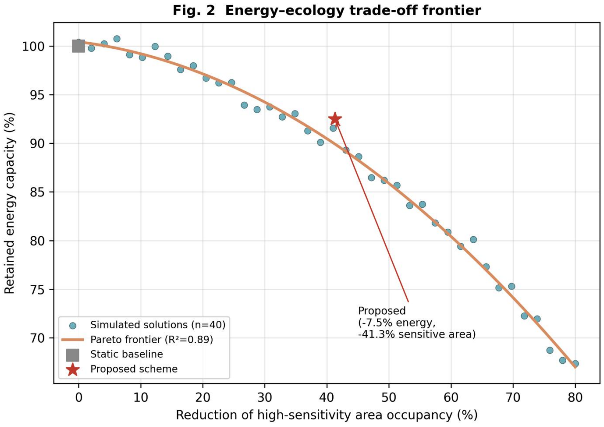

Fig. 2. Scenario-based trade-off between retained energy potential and reduced high-sensitivity area occupation.

B. *Significant Impact of the Decommissioning Penalty Term*

After introducing the decommissioning-stage pressure factor, the planning result shifts away from areas where removal or end-of-life treatment may cause high ecological disturbance. This adjustment is especially relevant for deep-water fixed foundations and ecologically fragile seabed habitats. Compared with the baseline scenario, the life-cycle-pressure-constrained scenario gives higher priority to areas where construction, operation, and decommissioning impacts can be more easily managed. The result highlights the importance of considering decommissioning at the initial planning stage rather than treating it as a separate future problem(Fig.3).

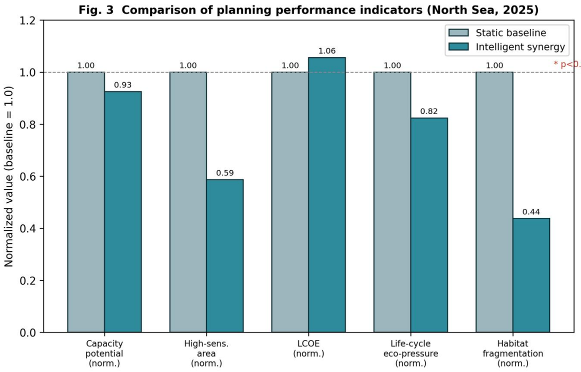

Fig. 3. Comparison of normalized indicators under the static baseline and ecological-sensitivity-constrained scenarios.

The specific values of key indicators are listed in Table I.

TABLE I. COMPARISON OF PLANNING SCENARIOS IN THE REPRESENTATIVE NORTH SEA CASE AREA. VALUES REPRESENT SCENARIO-SIMULATION OUTPUTS FOR PLANNING-SCREENING PURPOSES.

Indicator Dimension	**Traditional Static Planning (Baseline)**	**Intelligent Synergistic Planning (Experimental)**	**Significance of Difference (p-value)**
Total Installed Capacity Potential (GW)	125.4	116.0 (-7.5%)	Moderate capacity reduction
High-Sensitivity Area Occupancy (km^2)	1420	834 (-41.3%)	Substantial ecological improvement
Levelized Cost of Energy LCOE (€/MWh)	48.5	51.2 (+5.6%)	Slight cost increase
Life-Cycle Ecological Pressure Index	8.45	6.96 (-17.6%)	Lower cumulative pressure
Habitat Connectivity Disruption Rate	22.4%	9.8% (-56.2%)	Improved habitat connectivity

C. *Spatial Agglomeration Evolution and Model Robustness*

The spatial distribution of the ecological-sensitivity-constrained scenario shows a more clustered pattern than the static baseline scenario. Instead of spreading facilities evenly across technically suitable areas, the scenario-based allocation tends to avoid ecological corridors and high-sensitivity seasonal zones. This pattern suggests that spatial aggregation in lower-sensitivity areas may reduce habitat fragmentation compared with dispersed development. A sensitivity check was also conducted by adjusting ecological weights within a reasonable range. The main spatial tendency remained broadly consistent, indicating that the planning result is not determined by a single parameter alone. Nevertheless, further validation using higher-resolution ecological survey data is still required before the result can be applied to project-level decision-making(Fig.4).

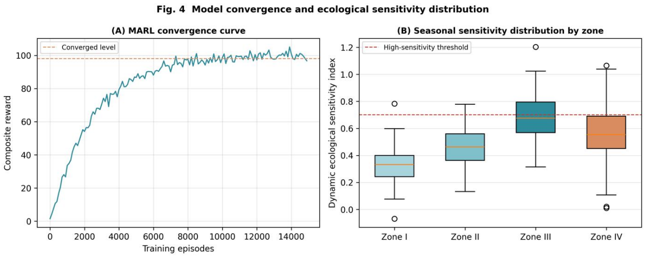

Fig. 4. Sensitivity-weight comparison and seasonal ecological sensitivity distribution across representative zones.

VII. Discussion

As this research has shown, the connection between ecology and energy in the smart ocean energy infrastructure planning is quite complicated, opening up some new opportunities to break away from the zero-sum game of conventional marine spatial planning.

Comparing Horizontal and Attribution of differences. The smart planning solution suggested in this work is more inconsistent and agglomeration than the outcomes of the site selection done by the pioneers using the conventional GIS-MCDM techniques. Since conventional methods are weighted linearly, they are inclined to produce big and uninterrupted regions of moderate suitability; the MARL-methodology used in the current paper is likely to find extreme cold spots to drive the formation of a high density with a minimum eco-pressure boundary. Among the largest determinants of such disparity is that the objective function is built differently: conventional methods look at the average trade-off between various measures and reinforcement learning (using non-linear reward functions) tends to actively seek to reduce the peaks of ecological sensitivity in time and form the strategy of space-time exchange.

The vertical correlation has an internal logic. The spatial heterogeneity in values of marine ecosystem services can be described as an asymmetric rate of capacity loss (7.5 percent) and high-sensitivity area conservation (41.3 percent), as it was found in the results. It implies that most of the ecological disputes are likely to impact only a minuscule area of overlap in marine spaces, and if such pain points are rightly identified and bypassed through the use of digital twin technology, significant ecological benefits would be obtained at the cost of minimal economic investment. Besides, the decommissioning penalty term transformed the deep-water fixed platforms into floating ones, which is fully in line with what Gourvenec et al. (2022) noted regarding the management challenges during the final stage of engineered-life of deep-sea infrastructure [1], and supports the findings of other articles that examined the decommissioning biodiversity impacts pathway. The model endogenously confirms that: considering the life-cycle view, high-investment floating platforms may be much more advantageous overall in the long run because ecological costs of decommissioning can be extremely low.

Values, Constraints and Error Analysis. The present investigation can be regarded as being the most useful in changing the passive environmental impact assessment into active planning with a quantified numerical measure of the blue economy policy formulation [5].The universal value of the provided research is to turn ecological constraints into a measurable and calculable aspect of planning and, consequently, enable comparison of various situations of marine spatial planning at a later stage. But it also has some drawbacks that need to be taken into consideration. To begin with, the ecological data that are presented in this study do not correspond to the field survey data obtained on a site-specific basis. Population biodiversity data distribution might be different and the areas of low observation counts may have significant ecological meaning. Secondly, ecological sensitivity and life cycle pressure weighting depend on expert judgment and literature assumptions, which may affect the end result of spatial prioritization. Thirdly, the suggested framework must be applied to screening and strategic planning of regions but not to site selection at the engineering level. Thus, after obtaining these results, they need to be confirmed by assessing the environmental impacts of the project, conducting a field survey, consulting the stakeholders, and performing a regulatory audit.

VIII. CONCLUSION

The paper proposed a scenario planning framework based on GIS to make sure that the construction of ocean energy facilities was accompanied by maintaining an appropriate ecosystem. The incorporation of ecological sensitivity during the seasons and life-cycle pressures into the assessment of spatial suitability gives the framework an open-ended method of comparing different plans. As it is possible to tell based on the findings, it has been made clear that the early identification of highly sensitive areas and ecological corridors as well as area under pressure caused by decommissioning can be used to mitigate the possible ecological conflict alongside conserving a majority of the opportunities in energy development.

Theoretical contribution of this paper would be to enhance the traditional static marine spatial planning by including the aspects of temporal ecology and life cycle. The practical value is to offer a repeatable planning-screening process which might assist governments, planners and developers to create additional non-conflict focused development zones. Nevertheless, it must be considered as a decision-making instrument instead of an end-stage engineering design model. Further research is needed to enhance the clarity of ecological data, evaluate the framework based on analysis of the field cases, consider interests of stakeholders, and compare the proposed approach with other clear spatial optimization approaches.

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AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Haimei Zhu: Conceptualization, Methodology, Writing – Original Draft, and Visualization.

Zhenda Zhang: Data Curation, Formal Analysis, Software, and Validation.

Fanglin Yi: Investigation, Resources, Data Curation, and Visualization.

Jiaxin Ye: Formal Analysis, Validation, and Writing – Review & Editing.

Mingqiu Xue: Supervision, Project Administration, Conceptualization, and Writing – Review & Editing. All authors contributed to the development of the research framework, reviewed the manuscript, and approved the final version for publication.

COMPETING INTERESTS

The authors declare no competing interests.