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A Concept and Framework of the Extended Ecosystem-Based Fisheries Assessment Approach Incorporating Other Driving Forces

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Abstract: The ecosystem-based fisheries assessment (EBFA) approach to evaluate four management objectives: sustainability, biodiversity, habitat quality, and socio-economic benefits, has been developed in previous studies. The existing EBFA approach is a risk-based assessment framework and was designed to assess the impacts of fisheries on offshore ecosystems. This approach only considers one driving force of wild capture fisheries. However, in coastal ecosystems, there are a number of anthropogenic activities. In this study, we propose an extended EBFA approach that incorporates the effects of capture fisheries and other driving forces, including various human activities and natural processes. This paper focuses on (i) revising the process and equations related to the nested risk indices defined in the existing EBFA approach, and (ii) demonstrating the applicability of the proposed approach by applying it to Uljin coastal waters and comparing the results with the previous case study of the existing EBFA. However, indicators and their relevant reference points have not yet been fully developed—particularly for the tier 1 approach. Hence, further research, especially regarding the reference points, would be required for practical use of the proposed approach.

Keywords: ecosystem; fisheries; sustainability; biodiversity; habitat; socio-economic benefit; driving forces

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1. Introduction

There are major shortcomings in single species management as we can see from the cases of such management, which have led to overfishing in many areas. Single species management is very limited and by focusing only on sustainability and ignoring habitat quality and ecological interactions [1,2].

The world is striving to maintain the sustainability of marine food resources. The FAO stressed the implementation of an ecosystem approach to fisheries (EAF) [3]. In addition, the World Summit on Sustainable Development (WSSD) encouraged the application of an ecosystem-based approach of fisheries by 2010 [4]. The Future We Want, the report released by the United Nations Conference on Sustainable Development (UNCSD), stipulates norms for the conservation of marine ecosystems and the efficient management of fishery resources [5].

In 2016, more than 160 countries around the world adopted the 2030 Sustainable Development Goals (SDGs), and the 14th goal of 'conserve and sustainably use the oceans, seas and marine resources for sustainable development' includes detailed objectives, such as fishery resource management and the conservation of marine ecosystems to preserve food resources in the ocean [6].

In response to these needs for EAF, many countries have studied and developed an ecosystem-based fisheries assessment and management approaches using risk assessment methods that are easy to apply in practice. In Australia, an ecological risk analysis for the effects of fishing (ERAEF) was developed and has been applied to Australian fisheries [7]. In addition, the Marine Stewardship Council (MSC) has been enforcing a certification system through ecosystem-based fisheries assessment [8]. An ecosystem-based fisheries assessment (EBFA) approach has been developed to evaluate the impact of fishing on the Korean marine ecosystem. The EBFA approach assesses risk scores for indicators corresponding to the four management objectives; sustainability, habitat quality, biodiversity, and socio-economic benefits, and estimates the nested indices of the species risk index (SRI), fisheries risk index (FRI), and ecosystem risk index (ERI) [9,10].

In previous studies on EBFA, some problems of the existing EBFA approach were identified and suggested to be resolved [11]. Socio-economic benefits were further added as one of the management objectives, and some overlapping components among indicators were clarified [10]. Socio-economic indicators have been studied and were incorporated with ecological indicators [12,13]. An revised risk scoring method for the EBFA was proposed that substituted the range of risk score zero to two with zero to three, and revised the risk scoring formulae [14]. A study of how to assess fisheries ecosystem in time and space scales by adding spatio-temporal components to the EBFA was developed, and this was applied to Korean waters [15]. Furthermore, a framework for an assessment, prediction, and management approach named IFRAME was developed based on EBFA [16].

The existing EBFA approach has been developed to focusing on offshore fishery and has been limited to assessing the effects of capture fisheries on wildlife fishery resources and their ecosystem. However, in the coastal ecosystems, there are two main ways to harvest fishery resources from the sea, wild capture fishery and aquaculture. Aquaculture has negative impacts on the ecosystem, including potential pollution, disease problems, and loss of habitat [17].

In addition, coastal ecosystems are seriously affected by various human activities, such as recreational fishing activities, land-based pollutant inflow, reclamation, and eroding coast lines [18,19], because they are adjacent to land. Wildlife fishery resources and their ecosystems are affected not only by capture fisheries but also by other driving forces, such as aquaculture, stock enhancement activities, land-based waste and pollution, inshore construction activities, leisure activities, and accidents and disasters (Figure 1). Therefore, in addition to capture fishery, the impacts of aquaculture and other human activities should also be considered especially when assessing coastal ecosystems.

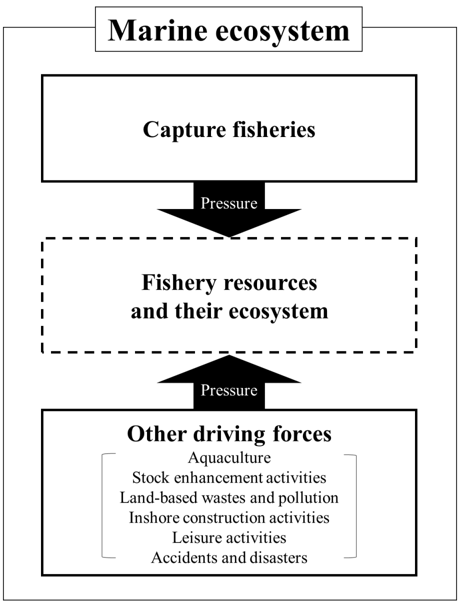

Figure 1. Identification of the driving forces that impact wildlife fishery resources and their ecosystems.

In 2021, the South Korean government Ministry of Oceans and Fisheries (MOF) announced the '3rd Fisheries Resources Management Plan for 2021–2025', including major challenges for the recovery of reduced fisheries resources, ecosystem-based fisheries resource assessment, and improvement of the coastal ecological environment [20]. In particular, South Korea has a long coastline of 14,963 km [21] because it is surrounded by sea on three sides and, therefore, has large coastal regions. In recent years, the proportion of aquaculture production in the total fishery production has annually increased and exceeding the production of wild capture fishery in 2006 [22]. Thus, in order to implement the new fisheries resources management plan properly, a suitable method considering these conditions in Korea should be developed urgently.

This paper aims to revise and extend the existing EBFA approach to apply to coastal ecosystems by incorporating various types of impacts caused by a number of anthropogenic activities other than wild capture fisheries. We conducted a demonstration by applying the extended EBFA approach to Uljin coastal waters and compared the applicabilities of the exsting EBFA and the extended EBFA.

2. Materials and Methods

2.1. Assessment Framework

The process of the extended EBFA approach is illustrated in Figure 2. The first step of the approach is to identify the unit ecosystem, fishery, and species. In this step, we investigate what components and characteristics of driving forces are in the ecosystem, what types of fisheries are operating in the ecosystem, and what kinds of fish species are residing and harvested in the ecosystem.

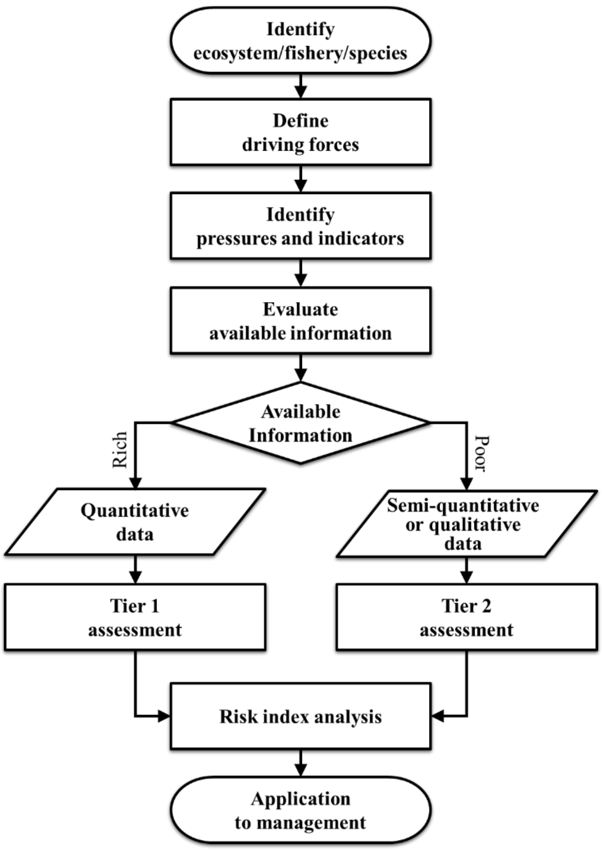

Figure 2. A process flow chart illustrating the extended ecosystem-based fisheries assessment approach.

The second step is to define the impacts of the driving forces on fishery resources and ecosystems. Various driving forces, such as aquaculture, stock enhancement activities, land-based waste and pollution, inshore construction activities, leisure activities, and accidents and disasters can be defined as components of a unit ecosystem.

The third step is to identify the relevant pressures to the driving forces of the ecosystem and to develop proper indicators. These indicators should be prudently selected to represent the state of the fishery resources and marine ecosystems that are affected by each driving force. Since the driving forces and indicators vary by marine ecosystems, the extended EBFA adopted an on/off system for indicators, where each indicator can be active or inactive according to the marine ecosystem's characteristics and components.

The fourth step is to evaluate the available information and scientific data and assess the risk of each indicator. If the available data are rich, Tier 1; quantitative assessment, is employed. On the other hand, if the available data are poor, Tier 2; semi-quantitative or qualitative approach, is used. In this step, the risk score (RS) is calculated for each indicator as

$$RS_i = \frac{I_{target} - I_i}{I_{target} - I_{limit}} + 1, \quad (1)$$

where RS_i is the risk score for indicator i, I_i is a value of indicator i, I_{target} is the target reference point for indicator i, and I_{limit} is the limit reference point for indicator i. A higher RS implies a more risky status than does a lower RS. The minimum limit of a RS is zero, and the maximum limit is three. Thus, RS ranges from 0 to 3.

The fifth step is to carry out risk index analyses. Risk indices, such as the objective risk index (ORI), species risk index (SRI), fishery risk index (FRI), and ecosystem risk index (ERI), are calculated using RS estimated by a Tier 1 or Tier 2 assessment. The nested structure of risk indices used for a risk analysis in the extended EBFA approach is analogous to the previous EBFA approach [9], except for some additional components of the driving forces (Figure 3).

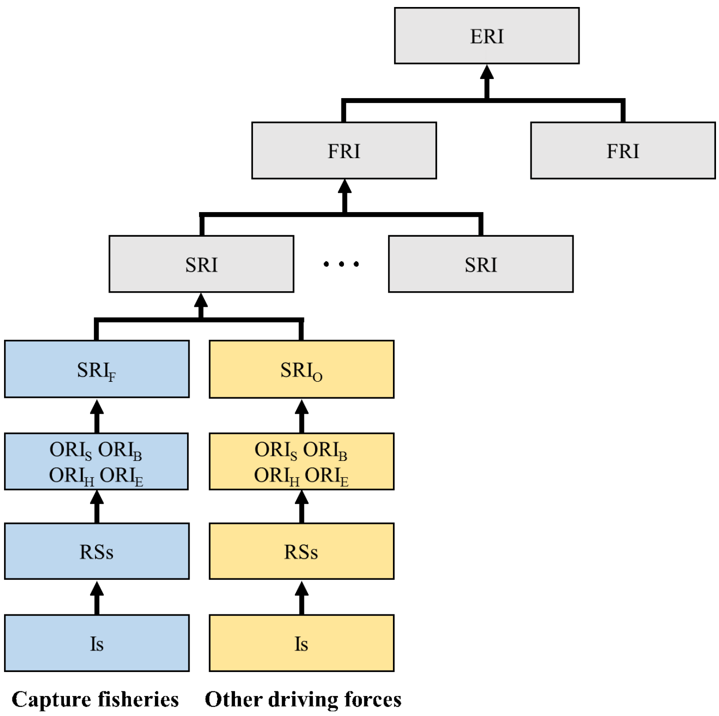

Figure 3. The nested structure of indicators and risk indices used in the extended ecosystem-based fisheries assessment approach. Is denotes indicators; RSs denotes the risk scores for Is; ORI_S, ORI_B, ORI_H, and ORI_E, denote the objective risk indices for sustainability, biodiversity, habitat quality, and socio-economic benefit, respectively; SRI is the species risk index; FRI is the fisheries risk index; and ERI is the ecosystem risk index.

The objective risk index (ORI) can be calculated as

$$ORI_{S,B,H,E} = \frac{\sum W_i RS_i}{\sum W_i}, \tag{2}$$

where ORI is calculated for each objective: ORI_S for sustainability, ORI_B for biodiversity, ORI_H for habitat quality, and ORI_E for socio-economic benefit. W_i is the weighting factor for indicator i.

Since the extended EBFA assesses the effects of capture fisheries and other driving forces on a target species or their marine ecosystems, the species risk index by capture fisheries (SRI_F), and the species risk index by other driving forces (SRI_O) are respectively calculated as the same equation;

$$SRI_{F,O} = \lambda_S ORI_S + \lambda_B ORI_B + \lambda_H ORI_H + \lambda_E ORI_E, \tag{3}$$

where λ_S, λ_B, λ_H, and λ_E are the weighting factors for each management objective, and the sum of them is 1.0.

Then, the calculated species risk indices by capture fisheries (SRI_F) and other driving forces (SRI_O) are integrated as

$$SRI_j = \omega_F SRI_F + \omega_O SRI_O \tag{4}$$

where SRI_j is the SRI for species j. ω_F and ω_O are the weighting factors for capture fisheries and other driving forces, respectively, and the sum of them is 1.0.

The fishery risk index (FRI) is defined as

$$FRI_k = \frac{\sum B_j SRI_j}{\sum B_j}, \tag{5}$$

where FRI_k is the fishery risk index for fishery k, and B_j is the biomass or the biomass index of species j.

The ecosystem risk index (ERI) is defined as

$$ERI = \frac{\sum C_k FRI_k}{\sum C_k}, \tag{6}$$

where ERI is the ecosystem risk index, and C_k is the total catch of capture fishery k.

To assess the risk contribution levels on a target species of capture fisheries and other driving forces, the following equation can be used,

$$FRC_j = \frac{\omega_F SRI_F}{\omega_F SRI_F + \omega_O SRI_O},\ ORC_j = \frac{\omega_O SRI_O}{\omega_F SRI_F + \omega_O SRI_O}, \tag{7}$$

where FRC_j is the capture fisheries' risk contribution on species j, and ORC_j is other driving forces' risk contribution on species j.

In addition, risk indices can be estimated in various ways other than the above indices. For example, SRI, FRI, and ERI consider four management objectives; however, these risk indices can be calculated as SRI_H, FRI_H, and ERI_H, which consider only the habitat quality of the species, fishery, and ecosystem, respectively. For example, as shown in Figure 4, SRI_H is calculated as

$$SRI_H = \omega_F ORI_{HF} + \omega_O ORI_{HO} \tag{8}$$

where SRI_H indicates the species risk index for the habitat quality incorporating effects of capture fishery and other driving forces. ORI_{HF} is the objective risk index for the habitat quality of capture fishery. ORI_{HO} is the objective risk index for the habitat quality of other driving forces.

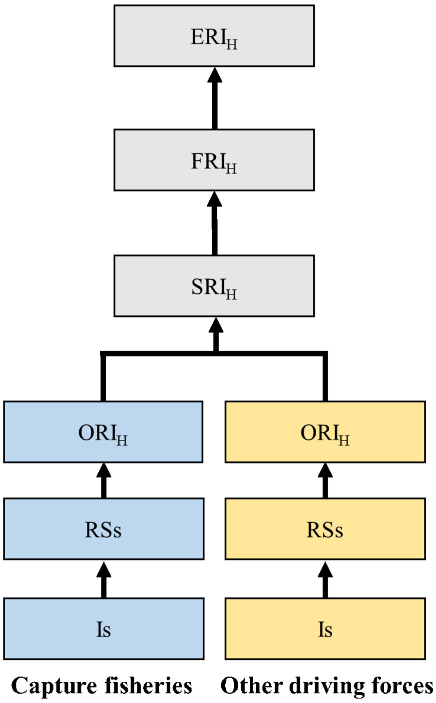

Figure 4. An example nested structure of the risk indices considering only habitat quality. ORI_H, SRI_H, FRI_H, and ERI_H indicate an objective risk index for habitat quality, species risk index for habitat quality, fishery risk index for habitat quality, and ecosystem risk index for habitat quality, respectively.

Finally, the results from the risk index analysis can be utilized as measures to implement fisheries management at various management unit levels of species, fisheries, and ecosystems.

2.2. Application: Uljin Coastal Waters

To demonstrate the applicability of the extended EBFA, we selected a target ecosystem and estimated risk indices according to the procedure of Figure 2. In addition, they were compared with the results from the previous study using the existing EBFA.

2.2.1. Target Ecosystem, Fisheries, and Species

Uljin was selected as the target ecosystem, where the existing EBFA study was conducted [23]. Uljin is located in the east coast of South Korea, and has a 111.8-km long coastline [21]. The population is concentrated along the Uljin coast, and various activities, such as commercial capture fishery, recreational fishing, and aquaculture, are carried out in the adjacent waters. Although, in the previous study, a total of three fisheries and five species were selected to assess the Uljin coastal waters, only two target fisheries of gillnet and set net fisheries, and one target species of common squid (*Todarodes pacificus*) were selected to simplify the demonstration of the extended EBFA. The average annual catch amount of common squid by gillnet and set net fisheries were reported as 414 mt and 930 mt, respectively [23].

2.2.2. Driving Forces and Indicators

Excluding the impacts of wild capture fishery, which has already been studied, other driving forces and their indicators were defined for the application in consideration of Appendix A. First, a total of four factors, including leisure activities, aquaculture, land-based pollution, and accident and disaster, were identified as driving forces that have a significant impact on the fisheries resources and their ecosystems in the Uljin coastal waters. Next, we identified which pressures of each driving forces affect the ecosystem, and a total of nine indicators were selected in consideration of importance and the available information for assessment. The indicators were classified into the four management objectives of EBFA: sustainability, habitat quality, biodiversity, socio-economic benefit (Table 1).

Table 1. Selected other driving forces and their indicators for the extended EBFA in the Uljin coastal waters.

Management Objective	Driving Force	Indicator
Sustainability	Leisure activities	Catch by leisure activities (S1)
	Accident and disaster	Deaths by disaster (S2)
Habitat quality	Aquaculture	Fish waste (H1)
	Land-based pollution	Domestic sewage (H2)
		Industrial sewage (H3)
		Industrial heated effluent (H4)
	Leisure activities	Waste by leisure activities (H5)
Biodiversity	Accident and disaster	Jellyfish bloom (B1)
Socio-economic benefit	Accident and disaster	Economic loss by Jellyfish (E1)

Two indicators, catch by leisure activities (S1) and waste by leisure activities (H5), especially regarding recreational fishing, were selected because this directly affects the sustainability of target species by generating pressure on fishing resources, and indirectly affects the habitat quality of coastal waters by generating environmental problems from abandoned fishing gear and bait [24,25].

Although various aquaculture effects have been reported [26–28], only one indicator of fish waste (H1) for aquaculture was selected considering reports on the damage cases and available information.

Based on the concentration of residential and industrial facilities along the Uljin coast, in particular, and nuclear power plant locations, three indicators for land-based pollution were selected: domestic sewage (H2), industrial sewage (H3), and industrial heated effluent (H4) [29,30]. As the indicators for the driving forces of accident and disaster, deaths by disaster (S2), jellyfish bloom (B1), and economic loss by jellyfish (E1) were chosen to consider a reduction in sustainability and biodiversity and also economic loss due to jellyfish bloom [31–33].

2.2.3. Risk Scoring and Derived Indices

Considering the method of previous case study of Uljin coastal waters [23] and available information; relevant reference points for the tier 1 approach have not been fully studied yet, so we adopted the tier 2 approach using semi-quantitative and qualitative assessment. RSs for eight indicators were estimated using relevant reports and quantitative statistical data [21,22,34–37] and by referring to the criteria table of risk states of the tier 2 approach adopted from the existing EBFA (Table 2, Table S4 in the Supplementary File).

The results of SRI_F for common squid harvested by gillnet and set net were obtained from the previous case study [23]. The ORIs for four management objectives (ORI_S, ORI_H, ORI_B, and ORI_E), the SRIs for other driving forces (SRI_O), the SRIs incorporating capture fishery and other driving forces for common squid harvested by gillnet (SRI_G) and set net (SRI_S), the FRIs for gillnet (FRI_G) and set net (FRI_G), and finally the ERI for Uljin coastal waters were calculated procedurally according to Equation (2)–(6), and compared with the results from the previous case study [23]. We assumed that the weights for all indicators and risk indices were the same.

Table 2. Criteria of the risk states of the tier 2 ecosystem-based fisheries assessment (employed from the existing EBFA [10]).

Magnitude	Abundance	Condition	Likelihood	Frequency	Range	Risk Score
Extremely small	Never or None	Optimal, Best	High degree of uncertainty	Never	<5%	0.0
Small	Part or a few	Negligible	Highly unlikely	Rarely	5–20%	0.5
Moderately small	Some	Minor	Unlikely	Sometimes	20–40%	1.0
Average	Considerable or average	Moderate	Ambiguous	Average	40–60%	1.5
Moderately large	Many or Major	Major, significant	Likely	Often	60–80%	2.0
Large	Most	Severe, highly significant	Highly likely	Frequently	80–95%	2.5
Extremely large	All	Catastrophic, Worst	High degree of certainty	Always	>95%	3.0

3. Results

All RSs of selected indicators regarding the Uljin coastal waters were estimated as shown in Table 3. Since recreational catch statistics were not available in Korea, the annual number of marine recreational fishing visitors by region was considered. As a result, 1.5 was given for the RS of catch by leisure activities (S1) because the number of marine recreational fishing visitors in Uljin was recorded at around the 40–45th percentile in Korea. Waste by leisure activities (H5) was scored at an RS of 1.5.

Table 3. The estimated risk scores and derived risk indices for Uljin coastal waters from the extended EBFA approach (RS: risk score for each indicator, ORI: objective risk index for each management objective, SRI_O: species risk index by other driving forces, SRI_F: species risk index by capture fishery, SRI:species risk index incorporating other driving forces and capture fishery, FRI: fishery risk index, ERI: ecosystem risk index, G: gillnet fishery, and S: set net fishery).

Management Objective	Indicator	RS		ORI		SRI_O		SRI_F		SRI(FRI)		ERI
		G	S	G	S	G	S	G	S	G	S	
Sustainability	S1	1.5	1.5	1.5	2.0	1.8	2.2	2.4	1.7	2.1	2.0	2.0
	S2	1.5	2.5									
Habitat quality	H1	1.5	2.5	1.7	2.3							
	H2	1.5	1.5									
	H3	2.0	3.0									
	H4	2.0	3.0									
	H5	1.5	1.5									
Biodiversity	B1	2.0	2.0	2.0	2.0							
Socio-economic benefit	E1	2.0	2.5	2.0	2.5							

Recently on the Uljin coastal waters, due to the occurrence of red tide, the mass mortality of fish–especially in fish farms and set nets—has been frequently reported. Since set nets are fixed in the water and located in the vicinity of the fish farms, they are more affected than other fisheries by not only the direct effect of the death of the target species but also by the indirect effect of environmental damage from waste-farmed fish. Thus, 2.5 was assigned to the RS of death by disaster (S2) and fish waste (H1) for set net fisheries, whereas 1.5 was given to them for gillnet fisheries due to the fishing grounds being relatively less affected.

According to the statistics of sewage discharge, the total amount of domestic sewage increased by approximately twice as much; however, the amount of sewage that had not undertaken sewage treatment did not change significantly, and thus the RS of domestic sewage (H2) for gillnet and set was evaluated as 1.5.

On the other hand, the amount of industrial sewage, also having heated water problems, has nearly doubled in recent years, and cases of damage to fisheries due to the effects of eutrophication and heated effluent by industrial waste water have been frequently reported. Therefore, the RS of industrial sewage (H3) and industrial heated effluent (H4) for set net fishery was given as 3.0, and the RS for gillnet fishery was given as 2.0.

Lastly, based on the monitoring results of jellyfish bloom from the National Institute of Fisheries Science (NIFS) in South Korea, a number of jellyfish blooms have been reported due to the ecological effects of various human activities such as climate change and heated waste water. This phenomenon is known to have a great influence on the decrease in fishery production of target species and biodiversity. In particular, research reported that the economic loss by jellyfish bloom is more serious with regard to set net fishery. On the basis of these rationales, the RS of jellyfish bloom (B1) affecting the biodiversity for two fisheries was assigned as 2.0 equally. The Rs of economic loss by jellyfish was evaluated as 2.5 for set net fishery and 2.0 for gillnet fishery,

Using estimates of RSs, the nested indices: ORI, SRI_O, SRI, FRI, and ERI, were calculated as shown in Table 3. The results of a previous case study were used as the SRI_Fs for gillnet and set net fisheries. As only one target species of common squid was selected for each fishery, the SRI and FRI were estimated to be the same value. From the previous case study of existing EBFA, the SRI_F of common squid for gillnet and set net fisheries were obtained as 2.4 and 1.7; however, the results of SRI(FRI) from the extended EBFA were estimated to be 2.1 and 2.0, respectively. Finally, ERI from the previous study, which was re-calculated with the selected target fisheries and species, and the extended EBFA values were estimated to be 1.9 and 2.0, respectively.

4. Discussion

We proposed an extended EBFA approach that incorporates the effects of capture fishery and other driving forces, including various human activities and natural processes. This paper focuses on (i) revising the process and equations related to nested risk indices defined in the existing EBFA approach and (ii) demonstrating the applicability of the proposed approach by applying it to Uljin coastal waters and comparing the results with the previous case study of the existing EBFA. The final goal of this paper is to emphasize that the intensive development of indicators and their relevant reference points for various driving forces are needed for practical use of the EBFA.

The results of application show that the ERI, ecosystem risk index for Uljin coastal waters, was higher than the ERI from the previous study. This indicates that the sum of FRIs or SRIs were estimated to be higher than the previous results due to additional considerations regarding other driving forces. Particularly, in the case of set net fisheries, the SRI was higher than the previous result (SRI_F) but for gillnet fisheries. This is because set net fisheries operate in a location that is more vulnerable to the impacts from other driving forces, such as land-based pollution and aquaculture. This shows that the impacts of driving forces vary by the type of fishery. This implication can be used as an example of supporting the necessity of the extended EBFA.

A number of integrated ecosystem modeling approaches considering many factors of marine ecosystems have been developed [38–40]. They have the advantage of simulating the complicated mechanism of marine ecosystems and, providing useful quantitative information for fisheries management. However, they require a great deal of input data and comprehensive knowledge to use them fully, and thus require much time and effort for practical use.

On the other hand, the proposed approach would be beneficial to save the time for applying if the tier 2 approach for semi-quantitative or qualitative analysis is employed. Furthermore, the approach with its on/off indicator system would allow the implementation of a fully integrated ecosystem-based fisheries assessment and the application to any marine ecosystem, not only offshore fisheries but also inshore, offshore, and distant fisheries. Given that the proper indicators for target ecosystem are developed, various marine ecosystems, such as a mangrove ecosystems, coral reef ecosystems, and marine protected areas (MPAs), can be examined by the approach.

Although many case studies applying the existing EBFA have been made to prove the practical applicability of EBFA [15,23,41–45], they have considered only the impacts of capture fisheries on ecosystems while ignoring the impacts of other driving forces. Recently, EFBA's extensibility beyond fisheries to other human activities has been reported [46,47]. Taken together, this paper is a proactive study for developing a risk assessment tool incorporating various human activities with respect to the EBFA.

Using the nested risk indices of the extended EBFA, it would be straightforward to establish proper strategies and tactics by identifying which fishery/species/indicators are at high risk and deciding what means will be needed to reduce the risk of them. In addition, the proposed approach could be used as a integrated tool for achieving the goals of the '3rd Fisheries Resources Management Plan for 2021–2025' implementing EBFM for sustainable fisheries announced by the Korean government [20].

However, indicators and their relevant reference points regarding other driving forces have not been fully developed yet in particular for the tier 1 approach due to the lack of scientific studies on relevant reference points. We preliminarily propose that potential reference points could be used for the two tier approaches (Tables S1–S4 in the Supplementary File) according to the guidelines described in the previous EBFA and other relevant research [9,10,48].

Although equal weighting factors were used for the simple applications in this study, the influence of the assigned weightings on the results would be significant in practical use. Therefore, as described in a previous study of EBFA, weightings should be carefully assigned by conducting a series of expert workshops or consultations, considering the importance of achieving the objectives, a scientific basis for estimating the indicators and reference points, the availability of data and information, and the characteristics of the target ecosystem [9].

This appears to be far from the practical applications of tier 1 thus far. Hence, further studies on the (i) development of indicators and their relevant target and limit references through practical application to various ecosystems, and (ii) integration of the extented EBFA and IFRAME [16] to allow the implementation of fundamental EBFM processes of assessment, forecasting, and management regarding various human activities are required to conduct practical application of the extended EBFA approach.

5. Conclusions

In this study, an ecosystem-based risk assessment approach incorporating the effects of capture fishery and other driving forces, including various human activities and natural processes, was proposed by revising the previous approach. The semi-quantitative and qualitative tier 2 approach of the extended EBFA was applied to Uljin coastal waters in South Korea. The results from application suggest a necessity of the extended EBFA to evaluate various types of ecosystems, including coastal waters, and applicability of the approach in the future.

In addition, we demonstrated that the benefits of the approach include less data and effort being required compared with other ecosystem models and the applicability to various ecosystems with the on/off indicator system. The approach would be straightforward to establish proper strategies and tactics to address risky pressures and driving forces. However, more research remains to be done on the indicators and reasonable reference points, in particular, to the tier 1 approach before the extended EBFA can be used in practical application.

Supplementary Materials: The following are available at https://www.mdpi.com/article/10.3390/jmse9050545/s1, Table S1: Tier 1 indicators and reference points for capture fisheries activities in the extended EBFA, Table S2: Tier 1 indicators and reference points for other driving forces in the extended EBFA, Table S3: Tier 2 indicators and reference points for capture fisheries activities in the extended EBFA, Table S4: Tier 2 indicators and reference points for other driving forces in the extended EBFA.

Author Contributions: Conceptualization, C.-I.Z.; methodology, H.K. and C.-I.Z.; investigation, H.K.; writing—original draft preparation, H.K.; writing—review and editing, H.K. and C.-I.Z.; visualization, H.K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EAF	Ecosystem approach to fisheries
EBFM	Ecosystem-based fisheries management
EBFA	Ecosystem-based fisheries assessment
ERI	Ecosystem risk index
FRI	Fisheries risk index
RS	Risk score
ORI	Objective risk index
SRI	Species risk index
SRI_F	Species risk index by capture fishery
SRI_O	Species risk index by other driving forces

Appendix A. Potential Indicators and Reference Points

Some potential indicators and their reference points that can be employed to apply the extended EBFA are described in this section and Supplementary File.

Appendix A.1. Capture Fishery

Figure A1 shows a typical mechanism of how ecological impacts can occur through capture fishery activities. High fishing pressure will heavily reduce fishery resources, eventually causing a depletion of the exploitable or spawning stocks. Fishing operations will also reduce the biodiversity of the fish community due to the selected fishing of target species, bycatches, and discards. Physical damage and the loss of fishing gear during fishing operations will deteriorate the quality of the habitats on which the fish stocks depend.

The decrease in the sustainability of the stocks and the biodiversity, together with the deterioration of their habitat quality, will eventually lead to negative effects on the socio-economic benefits, such as a loss of profit due to a reduced catch amount. Finally, a total of seventeen indicators were employed from the existing EBFA [9,10] as the effects of capture fishery (Table A1), and their reference points are described in Tables S1 and S3.

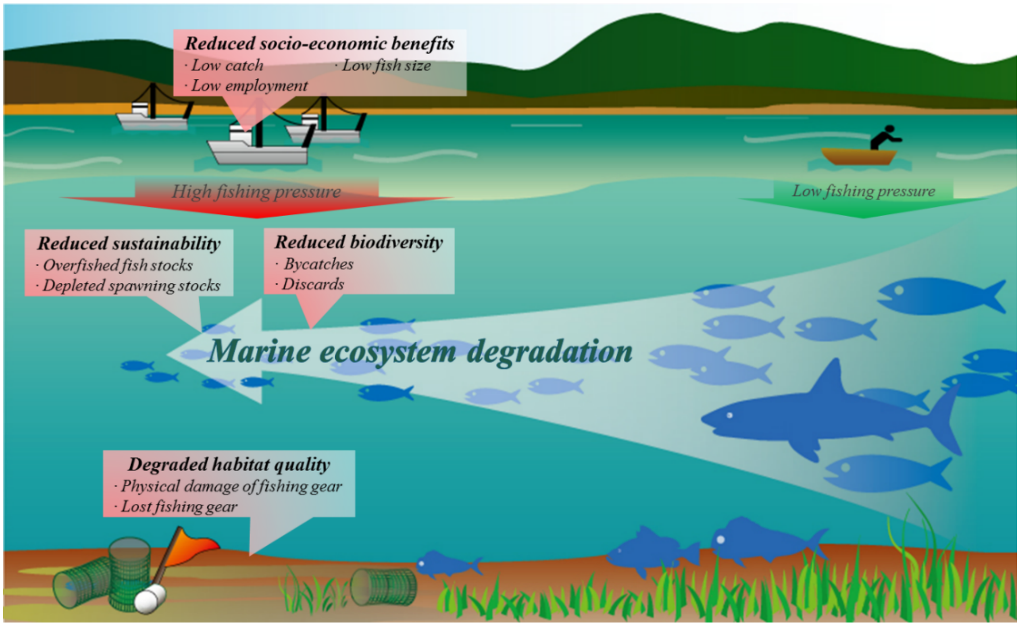

Figure A1. The ecological impacts of the driving force of capture fisheries on the fishery resources and their ecosystem.

Table A1. Indicators for capture fisheries activities in the extended EBFA (employed from the previous EBFA [9,10]).

Management Objective	Indicator
Sustainability	- Biomass (B) or CPUE - Catch or fishing Mortality (F) - Age (or length) at first capture (t or L) - Rate of mature fish (MR) - Ratio of (released stock abundance)/(wild stock abundance) in catch (r/w)
Habitat quality	- Critical habitat damage rate (DH/H) - Lost fishing gear (frequency, FR) - Discard wastes rate (DW) - Pollution rate of spawning and nursery ground (PG/G)
Biodiversity	- Bycatch rate (BC/C) - Discard rate (D/C) - Diversity index (DI)
Socio-economic benefits	- Income per person employed (IPPE) - Ratio of profit to sales (RPS) - Employment rate (ER)

Appendix A.2. Other Driving Forces

Figure A2 shows some of the impacts on fishery resources and their marine ecosystems that can occur from driving forces other than capture fisheries. These include the effects of aquaculture, stock enhancement activities, leisure activities, inshore construction activities, land-based waste and pollution, and accidents and disasters.

The impacts of aquaculture include the emission of organic matter from dead fish, uneaten food, and excreta; introduction of escapees; spread of pests and disease; ecological carrying capacity; attraction of wild fish; alteration of existing fish habitats; and altering or reducing current speeds [26,27,49].

The potential impacts of enhancements on marine ecosystems may vary by the type of enhancement system. The impacts on non-target species are of the most concern in ranching systems where organisms that do not recruit naturally in the receiving ecosystem may be released in high numbers and harvested intensively. Species introduced outside their native range pose particular risks. In stock enhancement activities, ecological and genetic impacts on the wild stock component tend to be of the most concern [50,51].

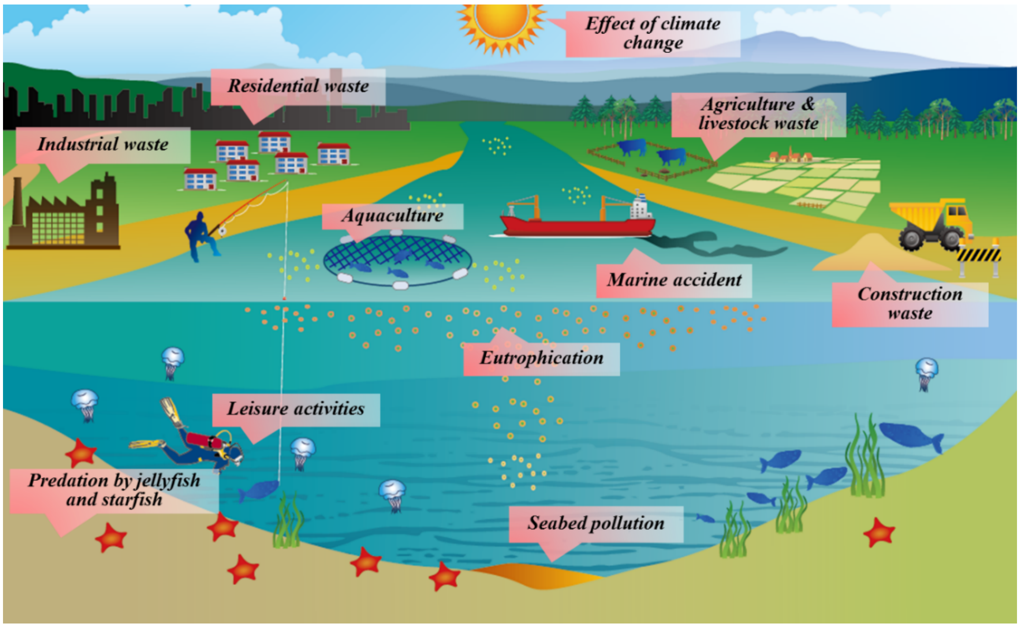

Figure A2. The ecological impacts of other driving forces on fishery resources and their ecosystem.

The impacts of leisure activities include waste and metals from leisure activities, catch by illegal, unreported, and unregulated leisure activities, physical damage of existing fish habitats, and extra income and employment from supporting leisure activities [52]. Impacts of inshore construction activities include waste from construction activities, seabed-sand collection, and shoreline change and sediment inflow by reclamation [53,54].

The impacts of land-based waste and pollution include the discharge of organic and inorganic matters from residential runoff, industrial runoff, and farm runoff; discharge of heated effluent; and discharge of ballast water from ports [55,56].

The impacts of accidents and disasters include oil spills from ship accidents; the ecological impacts of climate changes and fluctuations; critical events, such as red tide, whitening, oxygen depletion, typhoons, jellyfish blooms, and rapid increases of starfish and sea urchins; and fishing equipment damage by accident or disaster [54,57–59].

Thus, a total of six driving forces: aquaculture, stock enhancement activities, land-based waste and pollution, construction activities, leisure activities, and accidents and disasters, were defined as the other driving forces, and the potentially relevant indicators (Table A2) and reference points were proposed (Tables S2 and S4).

Table A2. Indicators for other driving forces in the extended EBFA.

Management Objective	Driving Force	Indicator
Sustainability	Aquaculture	- Cultured/wild biomass ratio ($R_{c/w}$)
	Leisure activities	- Catch by leisure (C_L)
		- Catch by tideland education (C_T)
	Accident and disaster	- Predation by jellyfish (P_J)
		- Predation by starfish (P_S)
		- Deaths by eutrophication (DA)
		- Deaths by oil pollution (DO)
	Stock enhancement	- Biomass enhancement by fries or juveniles release (BE)

Table A2. *Cont.*

Management Objective	Driving force	Indicator
Habitat quality	Aquaculture	- Fish waste (W_F)
		- Aquaculture debris (AD)
		- Fish food waste (FW)
		- Water circulation (WC)
	Land-based pollution	- Domestic sewage (DS)
		- Domestic excreta (DE)
		- Industrial sewage (IS)
		- Industrial organic matter (IO)
		- Industrial heated effluent (IH)
	Construction activities	- Waste by construction (W_C)
		- Seabed-sand collection (SC)
		- Shoreline change by reclamation (SC_r)
		- Sediment inflow by reclamation (SI)
	Leisure activities	- Waste by leisure activities (W_L)
		- Heavy metal waste by leisure activities (HM)
		- Habitat physical damage by leisure activities (HD_L)
		- Tideland habitat physical damage by tideland education (HD_T)
	Accidents and disasters	- Global warming by climate change (GW)
		- Ocean acidification by climate change (OA)
		- Eutrophication(red tide occurrence) (RT)
		- Whitening event (WE)
		- Water runoff by storm (WR)
		- Oil pollution by ship accident (OP)
		- Oxygen deficient event (OD)
		- Typhoon event (TE)
	Stock enhancement	- Artificial reefs deployment (AR)
Biodiversity	Aquaculture	- Attracted wild fish by uneaten food (AF)
		- Escaped cultured species (Ec)
		- Disease spread to wild fish (DS)
	Land-based pollution	- Ballast water discharge (BD)
	Accident and disaster	- Jellyfish bloom (JB)
		- Starfish bloom (SB)
Socio-economic benefits	Leisure activities	- Extra income from supporting leisure activities (EI_L)
		- Extra employment by leisure activities (EE_L)
	Accidents and disasters	- Fishing gear or ship damage by accident or disaster (FD)

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