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Ecological and economic perspectives of two decades of change in a traditional fishing ground in the Philippines

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ABSTRACT

A time-dynamic ecosystem model of the Visayan Sea, a significant traditional fishing area in the Philippines, was employed to calculate a set of ecological indicators from 1997 to 2018. These indicators were used to analyze the biomass, vital rates, community structure, biodiversity, development, and functioning of the Visayan Sea ecosystem. Attributes of system resilience and the ecosystem effects of fishing form the core of the analysis, providing insights into how structural and functional changes have shaped the ecosystem over time. In addition, monetary values of the trends in fisheries landings and catch composition were estimated to document the direct economic consequence of these changes. Results show that the biomass of predator and upper trophic level fishes declined, while small pelagic fishes, herbivores, and benthic invertebrates increased. Most exploited groups exhibited high fishing mortality, and the biodiversity index fell to nearly half its baseline. These trends suggest a development trajectory toward dominance by lower trophic level species, driven by impaired top-down control and increased bottom-up production. Despite structural simplification, the ecosystem remained stable between 1997 and 2018, supported by high detrital cycling and functional redundancy. The detrital pathways were sustained by underutilized low trophic level group biomass following predator decline, while, high species richness within functional groups conferred resilience against external stressors. However, sustained high fishing pressure increasingly threatens these groups. Decreasing catches of high-value large fishes were offset by increasing contributions from smaller fishes and benthic invertebrates, resulting in increased total landings and value over time. However, the average per capita income from fishing declined throughout the period, falling below the national poverty threshold in 2018. Overall, the use of a suite of indicators was useful in evaluating the status of the Visayan Sea between two decades from both ecological and economic perspectives. The combined application of these indicators to re-evaluate existing fisheries policies and their effects with respect to diverse management objectives is further discussed.

1. Introduction

In classical fisheries management, decisions are informed by knowledge derived from single-species model assessments with the objective of maximizing harvests (Cushing, 1968); this later developed towards the aim of sustaining harvests (Hilborn et al., 1995; Sutherland, 2001). For this purpose, stock status indicators and reference points have been developed and well-established in the fisheries management literature (Caddy and Mahon, 1995; Cope and Punt, 2009; Headley, 2020; Hilborn and Walters, 2003). For many fisheries around the world, single-stock management approaches remain as the convention. On the other hand, the ecosystem approach to fisheries management espouses governance that "*strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic, and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries*" (FAO, 2003). This approach calls for the understanding of the interactions of the abiotic and biotic components of ecosystems, and implies that the

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sustainability of fisheries harvests relies on the "health" of the entire ecosystem and its multiple species assemblages, and not just the exploited stocks viewed in isolation. Based on ecological system theory, healthy and sustainable ecosystems are ecosystems that are able to withstand natural and anthropogenic stressors (Rapport et al., 1998; Costanza and Mageau, 1999; Mayer et al., 2004). Central to the debate are the concepts of ecosystem structure or organization, ecological resilience or the rate at which an ecosystem can "absorb" changes caused by disturbances and return to its reference state (Holling, 1973; Pimm, 1984), and ecological stability or the amount of variability in overall structure and functioning over time in the face of disturbance (Noy-Meir, 1974). Thus, holistic ecosystem models that aim to capture the complex linkages between the exploited and non-exploited resources, their responses to pressures, and their relevant external drivers are important in our understanding of the overall structure and functioning of exploited marine ecosystems. This is critical to supporting the sustainability of fisheries harvests given intensifying anthropogenic and natural disturbances in the face of global change.

The Ecopath with Ecosim (EwE) modeling approach (Christensen and Walters, 2004) is a well-established and frequently applied tool to conduct ecosystem-level analysis of both anthropogenic and natural disturbances (Fulton, 2010; Colléter et al., 2015; Villasante et al., 2016; Keramidas et al., 2023) and to inform fisheries management (Mackinson et al., 2018; Piroddi et al., 2022). EwE is a mass-balanced trophic modeling approach that treats the ecosystem components as biomass compartments and their interactions as flows of biomass (or energy). The tracing and quantification of these flows reveals information regarding an ecosystem's structure and functioning, and subsequently, the direct and indirect relationships of the different components across the entire trophic network (Ulanowicz, 1984, 2004). Of practical importance is the calculated suite of standardized ecological indicators as part of the EwE model outputs (Christensen et al., 2005, 2008). These indicators facilitate the comparison between discrete systems (e.g., Tsagarakis et al., 2010) and the status of the same system across different points in time (e.g., Shannon et al., 2003). The network analysis approach likewise comprises a Keystoneness analysis (i.e., the identification of keystone species or groups) (Libralato et al., 2006) as a derivative of the trophic impacts analysis of the different groups that make up the system (Christensen and Walters, 2004). The ECOIND plug-in (Coll and Steenbeek, 2017) expands the ecological indicators to provide further structural information of the biomass, catch, and trophic groups, plus species-specific indicators that are relevant to biodiversity and conservation. The ability to calculate these indicators together makes the EwE modeling approach a convenient "one-stop shop" for exploring and measuring the changes that may have occurred in an ecosystem over time. It has then proven its utility in the conduct of complex marine ecosystem studies, particularly in analyzing the variable impacts of disturbance (both natural and anthropogenic) and different management regimes (Hoover et al., 2013; Wang et al., 2015; Hernvann et al., 2020).

The need to better account for the interaction between biophysical and human components in ecosystem dynamics is increasingly recognized. However, progress in applying interdisciplinary approaches to ecosystem modeling, such as Ecopath with Ecosim (EwE), has been relatively slow (Craig and Link, 2023). Comparative analyses of systems across time, impact assessments, and modeling future scenarios related to climate change, invasive species, and fishing have conventionally relied on ecological indicators alone, or at best, with catch information (Hoover et al., 2013; Szalaj et al., 2022; Ofir et al., 2023; Angelini et al., 2024). While ecological models have advanced in complexity, scale, and spatial resolution (De Mutsert et al., 2023; Boot et al., 2025; Eddy et al., 2025), the integration of economic and social dimensions in the analysis remains underdeveloped, thus limiting the scope of understanding and potential for management application. However, developments in recent years signal a promising shift toward more holistic and policy-relevant assessments (Chakravorty and Armelloni, 2024), with increasing efforts to incorporate economic indicators, human behavioral dynamics, and local ecological knowledge (LEK) into ecosystem models (Wang et al., 2015; Sánchez-Jiménez et al., 2019; Weijerman et al., 2020; Luczkovich et al., 2021; Alms et al., 2022).

Unfortunately, such integrated modeling approaches remain scarce in tropical marine fisheries, despite their importance, given the heavy reliance of many tropical coastal populations on fisheries resources for food and livelihood security. In Southeast Asia, applications of EwE modeling have ranged from characterizing food web structures and quantifying ecosystem network properties (Silvestre et al., 1993; Garces et al., 2003; Van et al., 2010), to analyzing ecosystem changes over time in relation to fishing (Christensen, 1998; Chen et al., 2011), testing hypothetical fisheries management scenarios (Ainsworth et al., 2008; Viet Anh et al., 2014), and conducting spatial simulations of protected area placement (Pitcher et al., 2002). In the Philippines, the EwE modeling approach has been used primarily to characterize the structure and dynamics of aquatic ecosystems (Guarin, 1991; Aliño et al., 1993; Bundy and Pauly, 2001; Campos, 2003). Network analysis using ecological indicators has also been applied to compare four heavily exploited fishing grounds (Lachica-Aliño et al., 2009a). However, the dynamic modeling component, Ecosim, has mainly been used to forecast the potential ecological impacts of alternative harvest and fisheries management scenarios (Bundy, 2004; Bacalso and Wolff, 2014; Bacalso et al., 2016). To date, only three Philippine ecosystem models have utilized EwE's hindcasting capabilities (Geronimo and Aliño, 2009; Lachica-Aliño et al., 2009b; Bacalso et al., 2023b). The limited application of dynamic modeling largely stems from the lack of historical reference data on biomass and catch, as well as the absence of standardized time-series data on fishing effort and environmental variables, even for major fishing grounds.

In contrast, the Visayan Sea offers a unique opportunity for dynamic modeling, having benefited from two decades of consistent monitoring of fisheries landings and the regular conduct of fisheries-independent trawl surveys. These data provide the necessary input parameters and time-series references for both the static and dynamic modeling approaches. Moreover, most of the earlier EwE models in the Philippines have focused primarily on analyzing ecosystem properties, without integrating socio-economic metrics. Addressing this gap, the present study applies a combination of ecological and economic indicators to evaluate temporal changes in the Visayan Sea. By doing so, it aims to provide a more balanced understanding of the historical effects of fishing and fisheries policies, and contribute toward the development of more ecosystem-based fisheries management in tropical fisheries contexts.

Over the past two decades, fisheries policies in the Philippines have influenced fishing trends and management outcomes, particularly in traditional fishing grounds such as the Visayan Sea. Of primary importance is the Republic Act (RA) 8550 or the Philippine Fisheries Code of 1998, which laid the foundation for the development, management, and conservation of fisheries and aquatic resources in the country. Anchored on the goal of poverty alleviation, the Fisheries Code prioritized small-scale municipal fishers (i.e., those operating vessels under 3 gross tons (G.T.)) by granting them exclusive access to marine waters within 15 km from the shoreline. In contrast, commercial fishers using vessels over 3 G.T. were restricted to offshore areas beyond this municipal boundary. The Code also aligned with the Local Government Code of 1991 (RA 7160) by devolving management authority over municipal waters to Local Government Units (LGUs), thereby institutionalizing a decentralized governance approach. The Fisheries Code was amended in 2010 through RA 10654, which sought to curb illegal, unreported, and unregulated fishing (IUUF). This amendment strengthened enforcement mechanisms by significantly increasing the penalties[1] for illegal fishing and limiting the issuance of fisheries licenses based on harvest control

[1] Chapter 6 of Republic Act (RA) 10654 amending Chapter 6 of RA 8550.

rules and stock status.[2] It also explicitly endorsed ecosystem-based fisheries management and integrated coastal area management, and further, underscored the role of science and research in guiding policy decisions.[2] In 2013, a nationwide ban on Danish seines[3] was enacted, followed by the reimplementation of the Visayan Sea closed season to protect small pelagic fish stocks during spawning periods.[4] A year later, a moratorium on new commercial fishing licenses was issued to cap the sector's total capacity.[5] These policies collectively contributed to a steady decline in commercial fishing effort and landings at both national (DA-BFAR, 2022) and regional levels (Mesa, 2019). Meanwhile, the municipal fishing sector expanded significantly in terms of employment and catch contribution, as shown in Fig. 2.

Together, these reforms have led to three key outcomes: (1) a marked shift in fishing effort from commercial to municipal sub-sectors, (2) a stronger role for science and stock assessments in informing management decisions, and (3) the growing adoption of ecosystem-based approaches in fisheries governance. These developments provide essential context for assessing the ecological and economic impacts of fishing in the Visayan Sea and for evaluating the effectiveness of fisheries policies.

In consideration of the above, this study aimed to evaluate ecosystem-level changes in the Visayan Sea over the past two decades using a suite of standardized and quantifiable ecological indicators. Specifically, it addressed three key questions: (1) How has the Visayan Sea ecosystem responded to anthropogenic (fishing) and natural disturbances? (2) How has policy influenced the fisheries trends and their subsequent ecological and economic outcomes? (3) How useful are ecological indicators in supporting ecosystem-based assessments in the Visayan Sea? Using Ecopath with Ecosim (EwE) modeling, ecosystem states in 1997 and 2018 were compared to assess structural and functional shifts. Key ecological indicators, including biomass and catch structure, network properties, and keystone indices, were analyzed to characterize system resilience and fishing impacts. Additionally, changes in estimated fisheries catches were converted to monetary values to document the direct economic consequences. The findings offer insights into the utility of ecological and economic indicators in highlighting the policy implications of these changes.

2. Materials and methods

2.1. Study area

The Visayan Sea (Fig. 1) is centrally located in the Philippine archipelago between 11° and 12° N latitudes and 123°-124°E longitudes. With an average depth of 40 m, the Visayan Sea is relatively shallow compared to its surrounding waters. This feature facilitates full light penetration to the bottom, resulting in one of the highest primary productivity rates in all marine waters of the country (Campos, 2018). Consequently, the Visayan Sea has long been considered one of the traditional and important fishing grounds in the Philippines. However, it has undergone changes in the past two decades owing to a combination of fisheries and environmental drivers (Bacalso et al., 2023a; Bacalso et al., 2023b). By applying the Ecopath with Ecosim (EwE) modeling approach, Bacalso et al. (2023b) found that the local fishery acts as a major driver of the Visayan Sea ecosystem. However, trophic interactions, including the bottom-up and top-down controls (Arreguín-Sánchez, 2011) are important in modulating the effects of these external drivers.

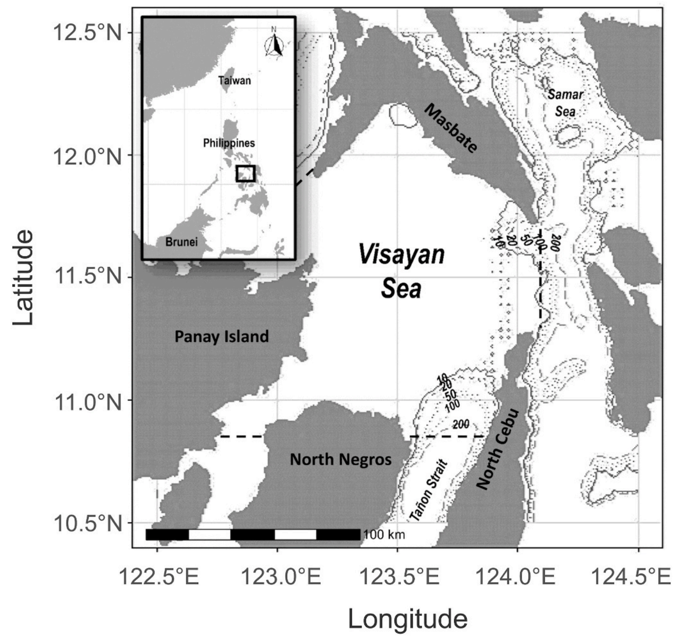

Fig. 1. Location and indicative area of the Visayan Sea (black dashed lines) as applied in this study.

2.2. Visayan Sea ecosystem model

This study made use of the Visayan Sea baseline ecosystem model (Bacalso et al., 2023b), which was constructed using the Ecopath with Ecosim (EwE) v6.6 tool (Christensen et al., 2008). This preceding study aimed to describe the ecosystem's food web structure, properties, and functioning based on fisheries and biological inputs from 1997 to 1998. In summary, the Visayan Sea baseline model consisted of 33 trophically-interacting groups, including 30 consumer groups, 2 primary producer groups (namely, phytoplankton and benthic primary producers) and 1 detritus group (see results Table 1). The fishery was also characterized by 34 distinct fishing fleets that represented the commercial and municipal fishing sub-sectors (Suppl, Table S1). The model's basic equations, construction, key initial input parameters, and calibration were described at length in Bacalso et al. (2023b). For the sake of transparency, a table of data sources and initial input parameters is available as a supplement to this paper (Suppl, Table S2). We utilized the built-in model Pedigree Index function (Christensen and Walters, 2004) to assign confidence scores to the parameter inputs. These ranged from 0 (for parameters either estimated by the model or sourced from other models) to 1 (for parameters sourced from high precision local sampling). Additionally, a sensitivity routine was run to quantify the impact of changes in the input parameters to the estimated (output) parameters (Christensen et al., 2005). Overall, the parameter estimates for a group were found to be most sensitive to the group's own parameter inputs. Larger variations were calculated mainly for the invertebrate groups, which reflect the higher uncertainties (and lower pedigree scores) of their input parameters. From the fish groups, the anchovy biomass showed the highest sensitivity to the group's production/biomass inputs. The Pedigree scores and sensitivity analysis provided objective guidance in balancing the model. Where adjustments in parameter inputs were necessary, adjustments were first made to the low precision and non-local data, followed by the empirically-derived data inputs in $\pm$ 5 % increments.

The baseline model was then calibrated to observed biomass and catch time-series using the Ecosim Stepwise Fitting Procedure (Scott et al., 2016), following the approach of Mackinson et al. (2009). As detailed in Bacalso et al. (2023b), this routine enabled the sequential testing of alternative configurations that incorporated relative fishing

[2] Section 1 of RA 10654 amending Section 2 of RA 8550.
[3] Fisheries Administrative Order No. 246, s.2013.
[4] Fisheries Administrative Order Number 167-3, s.2013.
[5] Bureau of Fisheries and Aquatic Resources Administrative (BFAR) Circular No. 253, s.2014.

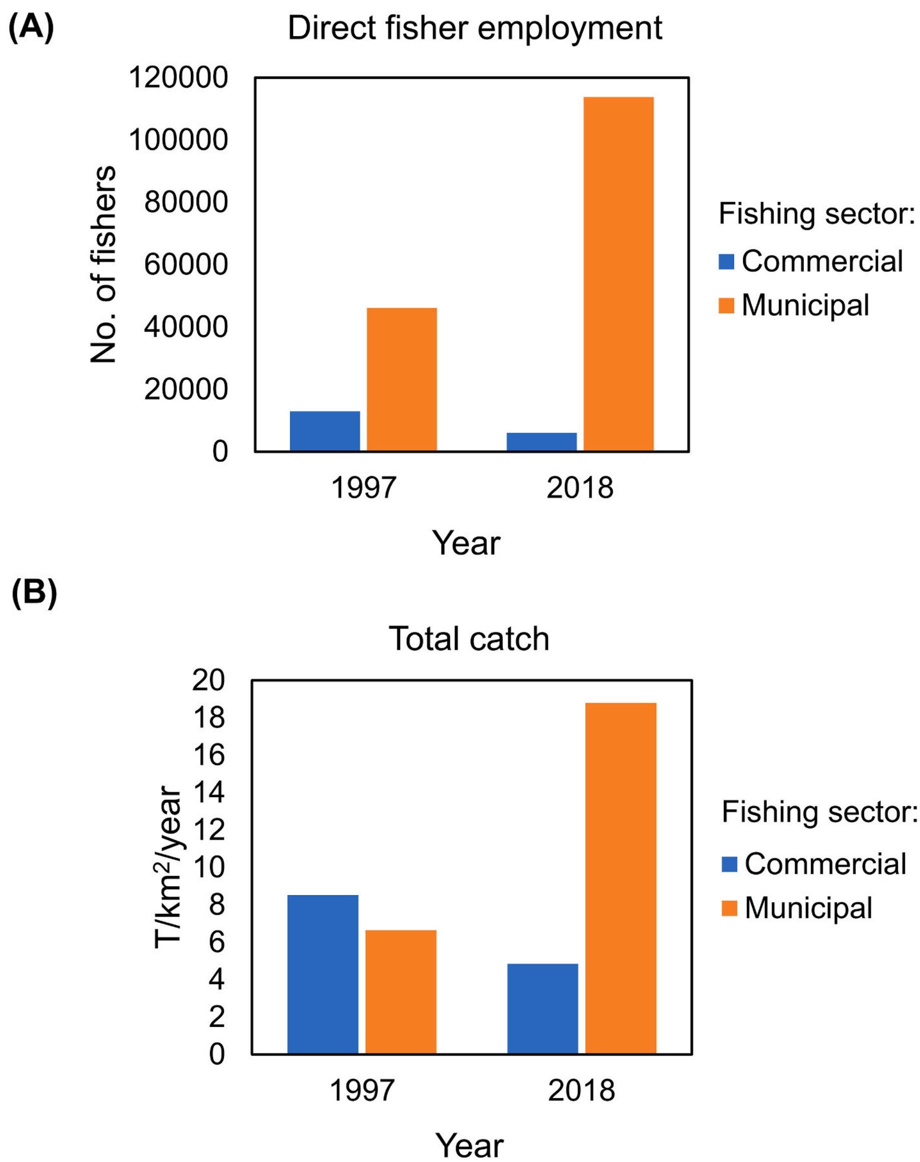

Fig. 2. Comparison of fishing sector contributions to (A) direct fisheries employment and (B) total catch in the Visayan Sea between 1997 and 2018. The fisheries employment was estimated by multiplying the average number of fishers or crew per fishing unit (Source: fisheries inventory 1997 and 2018, see also Suppl. Table S1).

effort time-series drivers, adjustments to vulnerability settings, and environmental forcing functions, including sea surface temperature (SST) and primary productivity anomalies identified as influential to Visayan Sea catch dynamics (Suppl, Figs. S1–S3). Model selection was based on minimizing the model sum of squares (SS) and the small-sample corrected Akaike Information Criterion (AICc) (Burnham and Anderson, 2002). The best-fitting model was the model that achieved the lowest SS and AICc, required the fewest additional parameter estimates, and most closely reproduced observed temporal trends through visual comparison (Bacalso et al., 2023b). From this best-fitting model, the 1997 baseline model outputs and the simulated 2018 end state were extracted and used in the current analysis.

2.3. Comparative analysis between the 1997 and 2018 systems

2.3.1. Ecosystem structure

The basic Ecopath model parameters include biomass (B) (in tons/km^2), production/biomass (P/B) ratio (/year), consumption/biomass (Q/B) ratio (/year), ecotrophic efficiency (EE), and production/consumption (P/Q) ratio (/year). P/B is equivalent to the instantaneous rate of total mortality (Z), which includes both fishing mortality (F) and natural mortality (M). Q/B is equivalent to the rate of a group's food intake relative to its biomass, and thus reflects the level of activity of a group (Christensen et al., 2005). Ecotrophic efficiency (EE) is the fraction of the production that is used in the system (Christensen et al., 2005). Thus, groups with high EEs are either important prey items in the system or are highly exploited by the fishery, or both. P/Q is also known as the gross food conversion efficiency, which falls between 0.1 and 0.3 for most consumer groups (Christensen et al., 2005). It is thus used as one of the diagnostic checks during model construction and parametrization. Altogether, these parameters were used in the current analysis to compare the overall structure of the Visayan Sea between 1997 and 2018 and to detect significant changes in the vital rates of the component groups as measures of performance, especially of those groups that are exploited by the fishery.

The ECOIND plug-in was implemented to generate an additional set of ecological indicators that are classified into biomass-based, catch-based, trophic level-based, size-based, and species-based indicators (Coll

Table 1
Model parameters: trophic level (TL), biomass (B, t/km^{61}), production to biomass ratio (P/B,/year), consumption to biomass ratio (Q/B,/year), ecotrophic efficiency (EE) and production to consumption ratio (P/Q,/year) for the Visayan Sea baseline Ecopath model (1997) and the end simulation state (2018).

	Group name	TL		B		P/B		Q/B		EE		P/Q	
		1997	2018	1997	2018	1997	2018	1997	2018	1997	2018	1997	2018
1	Seabirds	3.7	3.6	0.002	0.001	0.40	0.34	64.00	65.58	0.02	0.00	0.01	0.01
2	Sharks (juveniles/young adults)	4.2	4.0	0.028	0.001	0.92	1.76	6.87	6.82	0.46	0.60	0.13	0.26
3	Rays	3.3	3.4	0.053	0.035	1.61	1.51	7.62	7.61	0.54	0.76	0.21	0.20
4	Pel-pred fish (i)	3.4	3.3	0.076	0.009	1.66	1.71	19.88	20.21	0.55	0.48	0.08	0.08
5	Pel-pred fish (a)	3.9	3.7	0.029	0.002	1.96	3.30	11.56	12.13	0.64	0.72	0.17	0.27
6	Anchovies	3.0	3.0	1.747	2.117	3.26	2.74	22.40	21.32	0.90	0.85	0.15	0.13
7	Sardines (i)	2.2	2.2	0.978	1.200	3.15	2.37	33.83	30.95	0.96	0.98	0.09	0.08
8	Sardines (a)	2.7	2.8	0.730	0.840	4.72	5.70	19.07	19.07	0.63	0.60	0.25	0.30
9	Mackerels (i)	2.7	2.7	0.755	0.744	3.10	2.95	34.32	30.98	0.90	0.61	0.09	0.10
10	Mackerels (a)	2.8	2.8	0.411	0.180	4.20	7.35	19.03	19.63	0.70	0.63	0.22	0.37
11	Scads (i)	3.0	3.0	0.805	1.389	2.75	3.17	31.31	30.09	0.67	0.28	0.09	0.11
12	Scads (a)	3.3	3.3	0.630	0.428	3.25	5.80	17.60	18.01	0.64	0.68	0.18	0.32
13	Demersal fish (>30 cm)	3.7	3.7	0.296	0.057	2.14	3.69	10.44	10.58	0.67	0.69	0.20	0.35
14	Demersal fish (<30 cm)	3.1	3.1	1.665	0.780	3.92	4.86	16.04	15.97	0.86	0.74	0.24	0.30
15	Jacks, barracudas	3.7	3.6	0.286	0.000[a]	2.24	3.02	13.60	13.66	0.46	0.43	0.16	0.22
16	Reef-associated carnivorous, piscivorous fish (>30 cm)	3.8	3.8	0.331	0.030	2.08	2.54	9.82	10.01	0.61	0.68	0.21	0.25
17	Reef-associated zoobenthos-feeding fish (<30 cm)	3.1	3.2	1.326	1.540	2.64	2.75	16.92	16.53	0.79	0.74	0.16	0.17
18	Reef-associated herbivorous fish	2.0	2.0	0.258	0.258	1.83	1.73	34.00	33.36	0.59	0.50	0.05	0.05
19	Rabbitfish	2.0	2.0	0.066	0.020	2.90	3.00	37.06	37.04	0.79	0.53	0.08	0.08
20	Reef-associated planktivorous fish	3.2	3.2	0.377	0.450	2.14	1.97	18.04	17.88	0.67	0.68	0.12	0.11
21	Jellyfish	3.2	3.2	0.013	0.049	6.50	3.49	26.00	14.58	0.90	0.56	0.25	0.24
22	Octopus	3.4	3.5	0.121	0.199	2.32	2.19	13.20	12.89	0.85	0.85	0.18	0.17
23	Squids	3.2	3.2	0.471	0.266	2.72	2.44	14.79	15.27	0.90	0.67	0.18	0.16
24	Marine crabs	2.8	2.8	2.089	3.329	3.50	3.40	16.20	15.91	0.90	0.87	0.22	0.21
25	Shrimps	2.2	2.3	6.690	9.760	3.26	3.18	19.00	18.97	0.90	0.89	0.17	0.17
26	Mollusks	2.3	2.3	5.279	6.299	3.92	3.91	15.75	15.88	0.90	0.91	0.25	0.25
27	Other epibenthos	2.2	2.2	4.896	5.172	2.28	2.27	12.25	12.26	0.90	0.90	0.19	0.19
28	Worms, infauna	2.1	2.1	15.995	18.414	6.50	6.41	25.00	24.98	0.90	0.93	0.26	0.26
29	Sessile benthos	2.1	2.1	11.224	11.980	1.75	1.73	15.00	15.09	0.50	0.50	0.12	0.11
30	Zooplankton	2.2	2.2	14.566	17.413	33.00	32.39	145.00	145.33	0.95	1.00	0.23	0.22
31	Phytoplankton	1.0	1.0	16.070	18.359	135.00	141.63			0.86	0.86		
32	Benthic primary producers	1.0	1.0	26.751	25.535	15.00	15.35			0.50	0.51		
33	Detritus	1.0	1.0	86.280	96.874					0.44	0.46		

[a] < 0.001; adult stanza (a), immature/juvenile stanza (i).

and Steenbeek, 2017) (refer to results Table 3 for the descriptions of indices). These built-in standardized indicators are based on earlier works that tracked changes in aquatic ecosystems due particularly to external pressures, such as fishing (Fulton, 2010; Shin and Shannon, 2010; Coll et al., 2016). ECOIND calculates these indicators for the baseline Ecopath model and when Ecosim dynamic simulations are run. Thus, it facilitates a comparison of the overall ecosystem structure and status based on the relative abundance and species assemblage in the community, trophic groups, and catches. For this purpose, additional inputs were supplied to the baseline model to define the traits of the different taxa that comprise each functional group (Suppl, Table S3). Based on available data, these include the taxonomic composition of each functional group, type and general ecology of the organisms comprising each group, their relative contribution to the catch of the group, and their known mean and maximum sizes. This information was sourced primarily from local fisheries monitoring surveys and assessment reports (Armada, 2004; Guanco et al., 2009; Mesa, 2014). In addition, known information relating to the conservation status of the component taxa were also provided. These include their IUCN conservation status (IUCN, 2022) and Vulnerability Index (0–100), which refers to the intrinsic vulnerability of the species to extinction (Cheung et al., 2005). These inputs were sourced primarily from FishBase (Froese and Pauly, 2023) for the fish groups and SeaLifeBase (Palomares and Pauly, 2022) for non-fish groups. Further, the built-in Monte Carlo analysis plug-in was applied to assess the sensitivity of the simulation outputs to the Ecopath model input parameters. A total of 100 trials were run using the coefficient of variation (CV) of the biomass, P/B ratio, Q/B ratio, diets, and catches from the model pedigree evaluation. The Monte Carlo simulation results were used to determine the 5th and 95th percentile confidence intervals of the ECOIND outputs and to conduct significance testing of the similarities (Mann–Whitney *U* test; MacFarland and Yates, 2016) of calculated indicators from different years. For the current analysis, the indicators from the 1997 baseline model and the 2018 end simulation state were used.

Furthermore, the keystone groups in EwE were identified based on the group's trophic impact on all the other groups in the food web (excluding themselves; Libralato et al., 2006) and the group's contribution to the total system biomass (Power et al., 1996). In this analysis, we utilized the operational keystone index ranking developed by Valls et al. (2015) to identify the groups with a calculated high ecosystem impact in relation to their biomass, and to determine if this ranking had changed in a span of two decades.

2.3.2. Ecosystem properties and functioning (network analysis)

Ecopath provides a summary of ecosystem attributes (or system summary statistics) that represent aspects of ecosystem development and maturity (Christensen, 1995; Odum, 1969). Following Vasconcellos et al. (1997), these attributes provide insights into the following three points regarding general system information, and their associated indicators.

1) Community energetics:
   a) *Total system throughput*, which represents the sum of all flows in the ecosystem (consumption, exports, respiratory flows, and flows into detritus), and quantifies the "size of the entire system in terms of flows" (Ulanowicz, 1986);
   b) *Total net primary production*, which is the summed primary production from all producers (Christensen et al., 2005);

Table 2
Model-calculated fishing mortality rates (F) (/year), ratio of fishing mortality to total mortality (F/Z) and ratio of natural mortality to total mortality (M/Z) for the Visayan Sea baseline Ecopath model (1997) and the end simulation state (2018).

	Group name	F		F/Z		M/Z	
		1997	2018	1997	2018	1997	2018
1	Seabirds	0.00	0.00	0.00	0.00	1.00	1.00
2	Sharks (juveniles/young adults)	0.39	1.05	0.43	0.60	0.57	0.40
3	Rays	0.68	1.14	0.42	0.75	0.58	0.25
4	Pel-pred fish (i)	0.64	0.83	0.38	0.48	0.62	0.52
5	Pel-pred fish (a)	1.20	2.36	0.61	0.72	0.39	0.28
6	Anchovies	0.33	1.37	0.10	0.50	0.90	0.50
7	Sardines (i)	0.95	1.50	0.30	0.63	0.70	0.37
8	Sardines (a)	2.81	3.42	0.59	0.60	0.41	0.40
9	Mackerels (i)	1.14	1.73	0.37	0.59	0.63	0.41
10	Mackerels (a)	2.84	4.66	0.68	0.63	0.32	0.37
11	Scads (i)	1.03	0.85	0.37	0.27	0.63	0.73
12	Scads (a)	1.97	3.96	0.61	0.68	0.39	0.32
13	Demersal fish (>30 cm)	0.99	2.46	0.46	0.67	0.54	0.33
14	Demersal fish (<30 cm)	2.01	3.25	0.51	0.67	0.49	0.33
15	Jacks, barracudas	0.94	1.30	0.42	0.43	0.58	0.57
16	Reef-associated carnivorous, piscivorous fish (>30 cm)	0.98	1.67	0.47	0.66	0.53	0.34
17	Reef-associated zoobenthos-feeding fish (<30 cm)	0.90	1.80	0.34	0.65	0.66	0.35
18	Reef-associated herbivorous fish	0.26	0.76	0.14	0.44	0.86	0.56
19	Rabbitfish	1.12	1.54	0.39	0.51	0.61	0.49
20	Reef-associated planktivorous fish	0.47	1.18	0.22	0.60	0.78	0.40
21	Jellyfish	0.00	0.00	0.00	0.00	1.00	1.00
22	Octopus	0.20	0.52	0.09	0.24	0.91	0.76
23	Squids	1.18	1.53	0.43	0.63	0.57	0.37
24	Marine crabs	0.16	0.67	0.05	0.20	0.95	0.80
25	Shrimps	0.05	0.14	0.02	0.04	0.98	0.96
26	Mollusks	0.05	0.08	0.01	0.02	0.99	0.98
27	Other epibenthos	0.01	0.02	0.01	0.01	0.99	0.99
28	Worms, infauna	0.00	0.00	0.00	0.00	1.00	1.00
29	Sessile benthos	0.00	0.00	0.00	0.00	1.00	1.00
30	Zooplankton	0.00	0.00	0.00	0.00	1.00	1.00
31	Phytoplankton	0.00	0.00	0.00	0.00	1.00	1.00
32	Benthic primary producers	0.00	0.00	0.00	0.00	1.00	1.00

   c) *Net system production*, which is the difference between total primary production and total respiration, where the value approaches zero in mature systems (Christensen et al., 2005);
   d) *Ratio of total primary production to total respiration*, where total respiration is described as an activity measure of the upper trophic level functional groups in the system (González et al., 2016) and thus the value approaches 1 toward more mature systems (Odum, 1969);
   e) *Ratio of total primary production to biomass*, which declines as biomass is expected to accumulate over time or as a system matures (Christensen et al., 2005); and
   f) *Ratio of total biomass to total throughput*, which is expected to increase as a system matures (Christensen, 1995).
2) Complexity, for which the following indicators are computed:
   a) *Connectance index*, which refers to the ratio of the number of actual trophic links to the number of possible links in the system (Gardner and Ashby, 1970). It is correlated with system maturity as food chains are expected to shift from linear to more web-like as a system matures (Odum, 1969); and
   b) *System omnivory index*, which is the average omnivory index of all consumers weighted by the logarithm of each consumer's food intake. It is an alternative measure to characterize web-like feeding interactions in systems (Christensen et al., 2005).
3) Overall homeostasis (or stability), for which the following indicators are computed:
   a) *Finn's cycling index*, which represents the fraction of an ecosystem's throughput that is recycled (Finn, 1976) and is considered as an indicator of a system's ability to maintain structure and integrity (Ulanowicz, 1986);
   b) *Finn's mean path length*, which is the average number of groups that an inflow or outflow passes through and is expected to increase as a system matures (Christensen, 1995);
   c) *Ascendancy*, which is a measure of ecosystem growth and development reflective of the increase in energy throughput and information content of these flows (Ulanowicz, 1986) and is associated with attributes of ecosystem maturity (Odum, 1969);
   d) *Overhead*, which is calculated as 1-Ascendancy and reflects the system's strength in reserve against perturbations (Ulanowicz, 1986).

Furthermore, the summary statistics also provide fisheries indices at the ecosystem level, namely, the *mean trophic level of the fishery*, which is calculated as the weighted average TL of harvested groups and the *gross efficiency of the catch*, which is the sum of all realized fisheries catches relative to the total primary production (Christensen et al., 2005). The gross efficiency tends to be higher in systems targeting low trophic level resources. Finally, the *total transfer efficiency* refers to the mean of the transfer efficiencies of the discrete trophic levels and indicates the efficiency of flows from one trophic level to the next (Christensen et al., 2005). It is calculated as the sum of the exports from a given trophic level plus the flow that is transferred from one trophic level to the next relative to throughput (Christensen et al., 2005). It is further split into transfer efficiencies from the primary producer (from phytoplankton and benthic producers) and detritus.

2.3.3. *Estimating fisheries values*

In an aquatic ecosystem where fishing is an important economic activity, the value of fisheries landings is considered a direct economic expression of the use benefits that can be derived from the ecosystem. In the current analysis, the values of the landings over time were estimated using the annual average wholesale prices of the representative fisheries commodities (PSA, 2022a). To facilitate the comparison of values across time, the wholesale prices were standardized relative to the 1997 values using the trends in the Philippine consumer price index (CPI) (PSA,

Table 3
Comparison of ECOIND outputs between the Visayan Sea baseline model 1997 and the 2018 end state.

Indicator	Description	Units	1997	2018	2018/1997
Biomass-based					
Total B	Total biomass	t/km^2	210.72	229.66	1.09
Commercial B	Biomass of commercial species	t/km^2	41.51	46.70	1.12
Fish B	Biomass of fish species	t/km^2	10.65	9.25	0.87
Invertebrates B	Biomass of invertebrate species	t/km^2	46.98	57.07	1.21
Invertebrates B/Fish B	Biomass of invertebrates over fish		4.41	6.17	1.40
Demersal B	Biomass of demersal species	t/km^2	48.70	57.86	1.19
Pelagic B	Biomass of pelagic species	t/km^2	5.63	5.25	0.93
Demersal B/Pelagic B	Biomass of demersal over pelagic species		8.65	11.02	1.27
Predatory B	Biomass of predatory organisms (TL > 4)		0.03	0.00[a]	0.02
Kempton's Q	Kempton's biodiversity index (Q)		3.61	1.78	0.49
Catch-based					
Total C	Total catch	$t/km^2/yr$	15.20	24.47	1.61
Fish C	Catch of all fish species	$t/km^2/yr$	13.53	19.70	1.46
Invertebrate C	Catch of all invertebrate species	$t/km^2/yr$	1.68	4.77	2.84
Invertebrates/Fish C	Catch of invertebrates over fish	$t/km^2/yr$	0.12	0.24	1.95
Demersal C	Catch of demersal species	$t/km^2/yr$	5.19	7.54	1.45
Pelagic C	Catch of pelagic species	$t/km^2/yr$	7.92	12.98	1.64
Demersal/pelagic C	Catch of demersal over pelagic	$t/km^2/yr$	0.65	0.58	0.89
Predatory C	Catch of all predatory species (TL > 4)	$t/km^2/yr$	0.01	0.00[a]	0.05
Trophic-based					
TL catch	Trophic level of the catch		2.95	2.88	0.98
MTI	Marine trophic index, TL of the catch incl. org with TL ≥ 3.25		3.46	3.34	0.97
TL community	Trophic level of the community (including all organisms)		1.47	1.47	1.00
TL community 2	Trophic level of the community (including all organisms with TL ≥ 2)		2.32	2.29	0.99
TL community 3.25	Trophic level of the community (including all organisms with TL ≥ 3.25)		3.52	3.40	0.96
TL community 4	Trophic level of the community (including all organisms with TL ≥ 4)		4.17	4.0	0.96
Species-based					
Intrinsic Vul. Index	Intrinsic vulnerability index of the catch		20.90	19.11	0.91
IUCN species B	Biomass of IUCN-endangered species in the community	t/km^2	0.18	0.10	0.55
IUCN species C	Catch of IUCN-endangered species	$t/km^2/yr$	0.08	0.04	0.50
Size-based					
ML of fish community	Mean length of fish in the community	cm	18.39	14.63	0.80
ML of fish C	Mean length of fish in the catch	cm	17.09	15.29	0.89

[a] < 0.01.

2022b) (Suppl, Fig. S4). The adjusted values of the commercially-exploited groups were used as multipliers to the estimated annual landings of the same groups over time, as defined by the equation:

$$V_{ij} = Y_{ij} \times P_{ij}$$

where V is the estimated value of the commercially-exploited group i in year j, Y is the estimated yield or landings, and P is the adjusted wholesale price. Finally, the per capita share of landed values was calculated by dividing the total estimated value for each year by the estimated direct fisher employment for that same year. Direct fisher employment was defined as the number of individuals engaged in municipal capture fishing or crew members in commercial fishing operations. Employment was estimated by multiplying the average crew size per fleet type (Suppl, Table S1) by the corresponding number of gear units, using gear inventory records (Armada, 2004; Bacalso, 2019) and fishing effort estimates provided by the National Stock Assessment Program (NSAP) (Mesa, 2019) across the years.

3. Results

3.1. Changes in ecosystem structure

The basic parameters of the Visayan Sea baseline model (1997) and the end simulation state (2018) are shown in Table 1. The calculated trophic level (TL) of the sharks, the main predator group (TL > 4.0) in the Visayan Sea, decreased by 5 % from 1997 to 2018. The calculated TLs of several other upper-TL consumers, namely, the pelagic predator fish and the jacks and barracudas were also lower by 6 % and 4 %, respectively. However, the calculated TLs of most small fish groups and invertebrates were similar between 1997 and 2018.

The biomass of all fish groups with TL ≥ 3.25 were lower in 2018 compared to 1997. The biomass of the rabbitfish and the small demersal fish (<30 cm) also decreased to just under 1 t/km.[2] On the other hand, the biomass of the anchovies, sardines, juvenile scads, reef-associated zoobenthos-feeding fishes and reef-associated planktivorous fishes were higher in 2018 than in 1997. The biomass of all invertebrate groups except squids were also higher. This contrasting increase in biomass of lower-TL groups alongside a decline in upper-TL group biomasses is reflected as a decreasing trend in biomass ratios between 1997 and 2018, from the lower to the upper trophic level groups (Fig. 3-A).

The calculated Production/Biomass (P/B) ratios of most fish groups were higher in 2018 owing to higher fishing mortality rates (F) and subsequently, higher exploitation ratios (F/Z = Fishing mortality/Total mortality) (Table 2). These high exploitation ratios are consistent with the exploitation ratios calculated by stock assessment studies in the Visayan Sea (Mesa, 2019). Despite also showing higher F and F/Z ratios in 2018, the rays, anchovies, the juvenile life stages of the sardines and mackerels, the reef-associated herbivorous and planktivorous fishes, and the exploited invertebrates (octopus, squids, marine crabs, shrimps, and shelled mollusks) had lower P/B ratios in 2018. These values appear to coincide with the lower Natural mortality/Total mortality ratios, thus indicating the significance of natural mortality, particularly predation, in regulating these group's biomasses, and hence their production rates. Overall, there was an increasing trend in P/B ratio changes from the lower to the upper trophic level groups between 1997 and 2018 (Fig. 3-B). On the other hand, there were no obvious trends in the Consumption/Biomass (Q/B) ratio and Ecotrophic Efficiency (EE) changes with respect to the groups' trophic levels (Fig. 3-C & -D). However, with the changes in Production/Consumption (P/Q) ratios being positively correlated with the changes in P/B ratios ($p < .001$), there was also a similarly increasing trend in P/Q ratio changes with increasing trophic levels (Fig. 3-E).

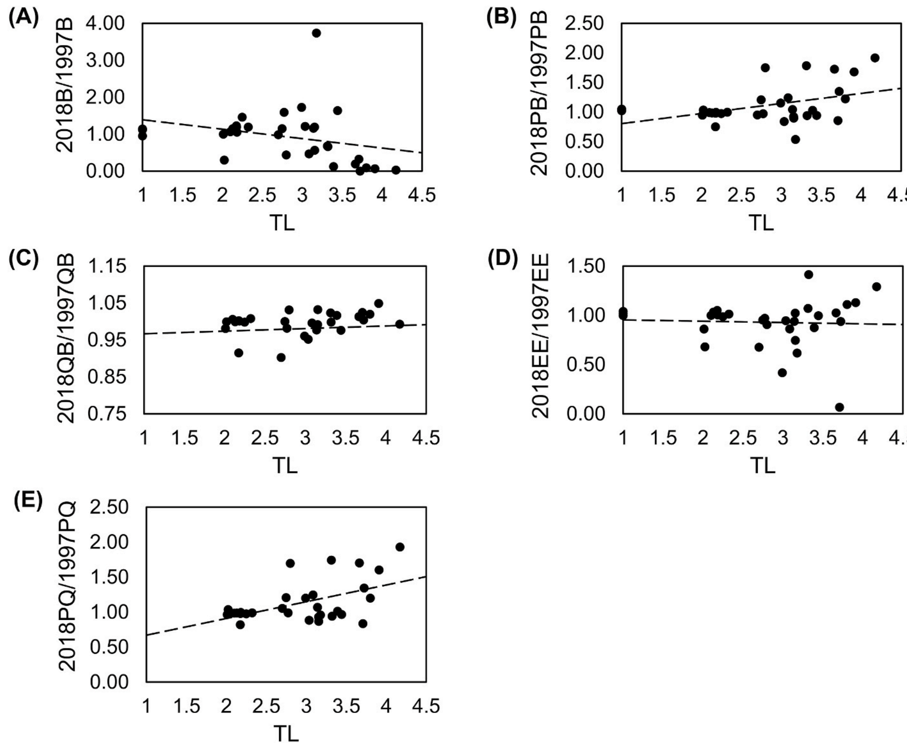

Fig. 3. Relative changes in (A) Biomass, (B) production/biomass (P/B) ratios, (C) consumption/biomass (Q/B) ratios, (D) ecotrophic efficiencies, (EE) and (E) production/consumption (P/Q) ratios of the different groups that make up the Visayan Sea ecosystem between 1997 and 2018 arranged from lower to higher trophic levels (TL).

The ECOIND outputs (Table 3) provide further insights into the implications and consequences of these structural changes in the Visayan Sea ecosystem. Overall, the calculated total biomass of the system was significantly higher in 2018 compared to 1997 ($p < .001$). However, the calculated Kempton's biodiversity index (Q) was significantly lower in 2018 ($p < .001$). It is also important to note, that in 2018 the collective biomass of all fish groups was lower, while the biomass of the invertebrates was significantly higher ($p < .001$) compared to 1997. Consequently, the ratio of the invertebrate biomass to fish biomass increased by almost 40 % within a span of two decades. The higher demersal biomass in 2018 is attributed to the increase in benthic invertebrate biomass, which initially demonstrated a declining trend prior to 2010 followed by a steady increase thereafter (Fig. 4-A). Excluding the benthic invertebrate biomass, however, a declining trend in demersal fish biomass emerged (Fig. 4-B). As for the pelagic fishes, an overall declining trend in predator fish biomass was compensated by an increase in the biomass of several small pelagic fish groups (e.g., anchovies). In general, the biomass of the pelagic fishes was higher than the biomass of the demersal fishes by 57 % and 69 % in 1997 and 2018, respectively. As for the primary producers, phytoplankton and detritus biomass values were higher in 2018 by 14 % and 12 %, respectively, while the biomass of the benthic primary producers was 5 % lower.

Despite the overall decrease in biomass across fish groups, the collective biomass of commercially-exploited groups was higher in 2018 due to the increase in biomass of exploitable invertebrates in the system. Subsequently, the invertebrate/fish catch ratio was significantly higher ($p < .001$) in 2018. All the catch indicators, except the predatory catch, were also significantly higher ($p < .001$) in 2018. The lower demersal/pelagic catch ratio in 2018 reflected the increasing contribution of small pelagic fishes in the catch.

The changes in biomass structure and catch composition were likewise reflected in the trophic-based catch and community indicators. The average trophic level of the catch in 1997 slightly decreased by 2 % in 2018 ($p < .01$), which implies a further shift in catch composition towards even lower trophic level groups. Trophic-based indicators representing the upper trophic level consumers (i.e., Marine trophic index, TL community 3.25 and 4) were also lower in 2018, while the indicator TL community 2 showed a minor, but nevertheless, significant ($p < .001$) difference. The unchanged TL of the entire community (including all organisms) implies that, while the absolute biomasses may have changed, the biomass proportions aggregated by trophic level remained the same.

The intrinsic vulnerability index in 2018 was lower compared to 1997. This is expected, as more species groups of low vulnerability are increasingly targeted by the fishery (i.e., the fast growing, early-maturing and highly productive groups of small-sized fishes and invertebrates). This is likewise reflected in the overall lower calculated mean lengths of the fish in the community and in the catch in 2018. Seven species out of the 231 unique taxa described in the Visayan Sea model are listed by the IUCN (2022) as "endangered", "vulnerable", and "near-threatened" (Suppl, Table S2). Except for the *Sardinella* species, their biomasses and catches decreased, thus resulting in the overall lower IUCN indicators of biomass and catch in 2018.

The keystone index ranking of the different groups that make up the Visayan Sea ecosystem are visualized in Fig. 5. The keystone rank of several of the system's high-TL consumers, namely the pelagic predatory fishes, demersal piscivores, the jacks and barracudas, and the reef-associated piscivores remarkably decreased in 2018, suggesting their weakened top-down function (i.e., as regulators of prey biomass) due to the significant decrease in their own biomasses. The keystone rank of the squids, which are not only important prey to the consumers in the system, but are also commercially-exploited by the fishery, was likewise lower in 2018 along with a decrease in biomass. On the other hand, the keystone index rank of the anchovies, juvenile sardines, mackerels, herbivorous reef fish, and phytoplankton all increased in 2018, suggesting the increasing functional effects of these prey groups and the pelagic primary producers to the rest of the consumer groups in the system.

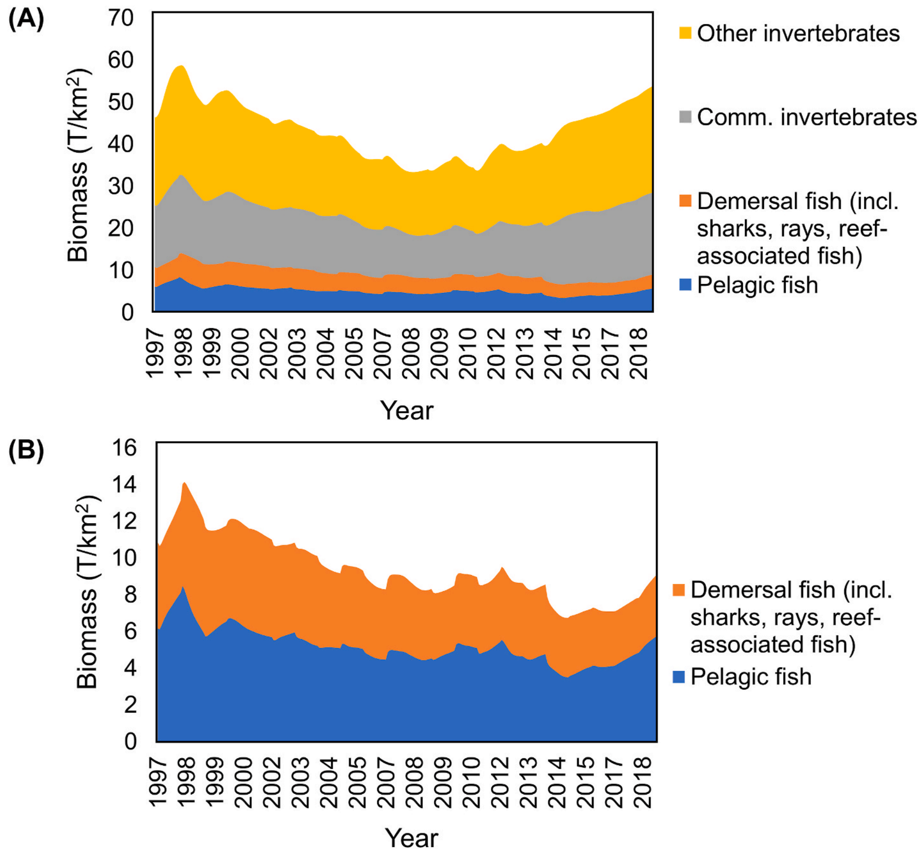

Fig. 4. Model-generated trends in (A) cumulative fish and invertebrate biomass (excluding sessile benthos and zooplankton) and (B) only the demersal fish and pelagic fish biomass. Commercially exploited invertebrates refer primarily to the benthic crabs, shrimps, squids, gastropods, and bivalves.

3.2. Changes in ecosystem functioning

A summary of the calculated ecosystem properties of the Visayan Sea in 1997 and 2018 are presented in Table 4. The total system throughput (TST) was considerably higher in 2018. Similarly, all contributory flows were also higher. However, the overall profiles of these flows were similar between the 2 years, with the sum of all consumption contributing to between 46 % and 47 % of the flows, the sum of exports between 9 % and 10 %, the sum of respiratory flows with 27 % contribution in both years, as well as a similar sum of flows into detritus at 17 %. The sum of all production and net primary production were both higher in 2018 indicating higher activity in the ecosystem associated with the primary producers (González et al., 2016). The total catch was substantially higher in 2018 with increasing contribution from groups from the lower trophic levels as indicated by the lower mean trophic level of the catch (TL_C). The higher Gross efficiency (GE) of the catch also reflected this, and further suggests that a higher fraction of the primary production ended up in the fishery. While the total primary production/total respiration (NPP/R) and total biomass/total throughput (B/TST) ratios barely changed between the 2 years, the total primary production/total biomass (NPP/B) ratio was slightly higher in 2018, which is an indicator of a system approaching an immature state (Christensen, 1995). The connectance index (CI) and the system omnivory index (SOI) also appeared to be stable between the two years, thus giving no indication that the system was either gaining or losing structural complexity. Similarly, the Finn's mean path length (FML) was the same between the two years. However, the FCI and total throughput cycled were higher in 2018, suggesting the system's increasing ability to maintain structural integrity. The apparent stability of the Visayan Sea system within the two decades is further evidenced by the ascendancy (A), overhead (O), and transfer efficiency (TE) values that show little to no difference between 1997 and 2018.

3.3. Changes in fisheries landings and values

The simulated trends in total landings and catch value contribution of the commercially-important fishery groups in the Visayan Sea are shown in Fig. 6. Four groups, namely the small demersal fishes (<30 cm), sardines, mackerels, and scads consistently contributed to an average of 70 % of the total landings from 1997 to 2009 (Fig. 6-A). From 2010 onwards, their contribution to the total landings went down to an average of 60 %, while the contribution of the anchovies, shrimps and crabs steadily increased from around 18 %–40 %. On the other hand, the contribution of the large demersal, pelagic, and reef-associated fishes averaged at only 8 % during the first half of the time series, and further declined to less than 4 % in the second half.

Using the adjusted fish prices, the commercially-exploited groups' contribution to the total value of the landings over time were compared. Overall, the total value of the landings also increased over time, but the contributions of the different groups to the total value changed (Fig. 6-B). The small demersal fish group consistently contributed to an average of 30 % of the total value from 1997 to 2014. Thereafter, this decreased from 25 % to 18 % by the end of the time series. On the other hand, as the catch contribution of the crabs and shrimps increased over time, so did their contribution to the total value. In the last 3 years of the simulation, these 2 groups contributed to approximately 50 % of the estimated total value of the landings.

Despite the increase in total landings and total value over time, the estimated average annual share per fisher or crew member to the value of the landings decreased from around 129 thousand Philippine Pesos (Php) in 1997 to 97 thousand Php in 2018 as the direct fisheries employment doubled within this time. Further, the estimated per capita

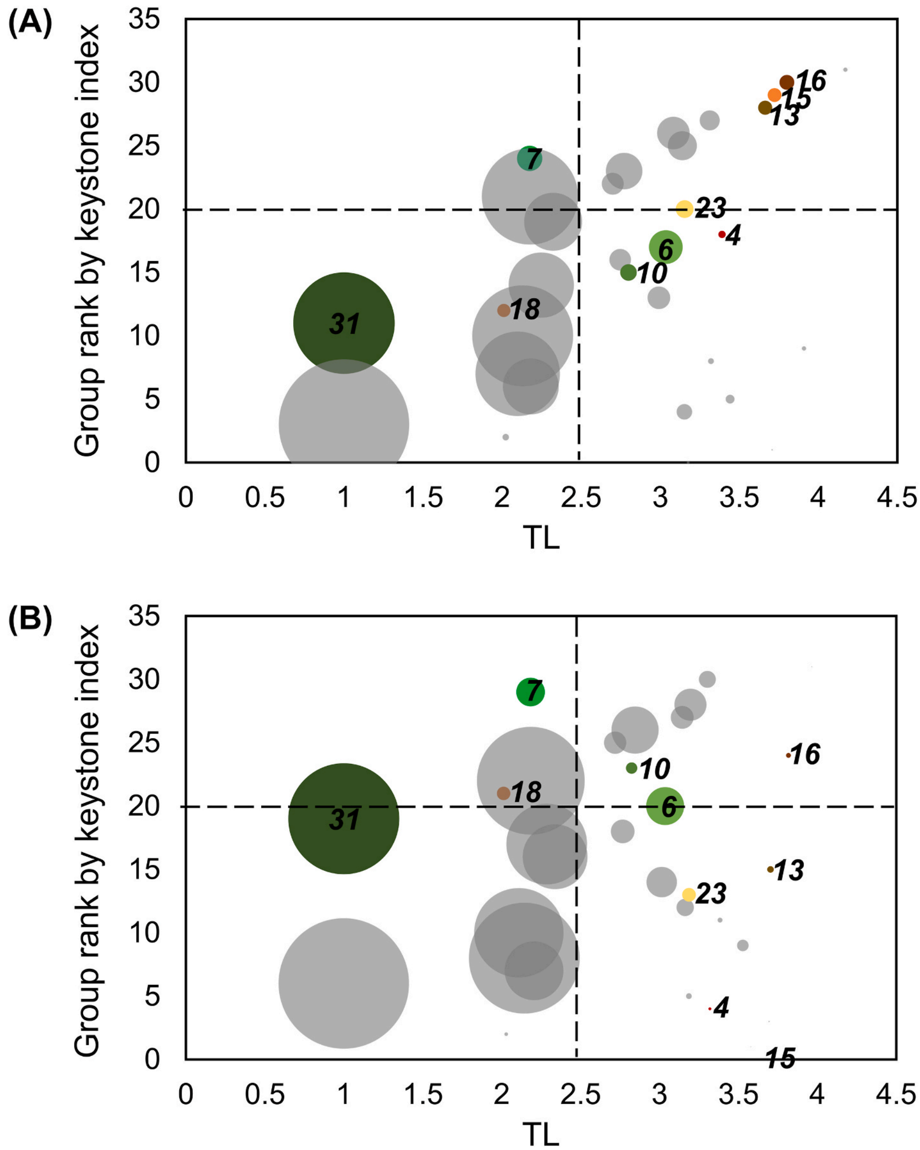

Fig. 5. Keystone index graphs (after Valls et al., 2015) generated from (A) the Visayan Sea baseline model 1997 and (B) the end simulation state 2018.The groups are depicted as circles scaled by their calculated biomasses. The dashed lines dissecting the graphs into 4 compartments were added arbitrarily. Groups whose keystoneness rank changed remarkably between the baseline model and the end state are color-coded and marked for emphasis: **4:** Pelagic intermediate predatory fish (j); **6:** Anchovies; **7:** Sardines (j); **10:** Mackerels (a); **13:** Demersal piscivorous fish; **15:** Jacks, barracudas, **16:** Reef-associated piscivorous fish (Groupers, snappers, emperors); **18:** Herbivorous reef fish; **23**: Squids; **31**: Phytoplankton.

monthly income in 2018 was 8083 Php, which was below the 2018 Philippine poverty threshold pegged at Php 10,727 per month (PSA, 2020). Following the same computation, the total value share between the commercial and the municipal fishers in 1997 was estimated at 22 % and 78 %, respectively. In 2018, this changed to 5 % and 95 % between the commercial and municipal fishers, respectively.

4. Discussion

In this study, we compared the status of the Visayan Sea ecosystem between two decades using a suite of ecological indicators. These indicators provided insights into the Visayan Sea's response to a major source of disturbance (i.e., fishing pressure), and the influence of policies that reflect diverse management objectives (sustainability of the stocks, conservation of resources, and poverty alleviation). Coupled with a straightforward analysis of the direct economic consequences of the changes in the catches over time, the study managed to answer the three main questions that were raised.

(1) How has the Visayan Sea ecosystem responded to anthropogenic (fishing) and natural disturbances in the past 2 decades?

Continuous stress over the past 2 decades characterized by a progressive intensification of fishing activities and environmental variability (Bacalso et al., 2023a; Bacalso et al., 2023b) promoted a structural change in the Visayan Sea towards increasing lower TL groups and primary producers. It likewise reinforced a development trajectory toward a more immature ecosystem state where opportunistic and fast-growing species dominate. The current analysis provided further evidence of the influence of fisheries extraction by showing the increase of fishing mortalities and exploitation ratios of most exploited groups in the Visayan over the time series. These model-generated indices likewise fall within the upper range of fishing mortality and exploitation ratios that were computed for the highly exploited stocks in the Visayan Sea (Guanco et al., 2009; Mesa, 2014, 2019) and in other traditional fishing grounds in the Philippines (Belga et al., 2018; Candelario et al., 2018; Gaerlan et al., 2018; Olaño et al., 2018; Ramos et al., 2018). It is

Table 4
System summary statistics and ecological network analysis indices of the Visayan Sea baseline model 1997 and the 2018 end simulation state.

Parameter	Units	1997	2018	2018/1997
Total system throughput (TST)	$t/km^2/yr$	6998.74	8155.79	1.17
Sum of all consumption (C)	$t/km^2/yr$	3229.39	3811.54	1.18
Sum of all exports (E)	$t/km^2/yr$	688.42	759.21	1.10
Sum of all respiratory flows (R)	$t/km^2/yr$	1882.31	2232.83	1.19
Sum of all flows into detritus (D)	$t/km^2/yr$	1198.63	1352.21	1.13
Sum of all production	$t/km^2/yr$	3271.92	3808.45	1.16
Total catch (Ca)	$t/km^2/yr$	15.16	23.62	1.56
Mean trophic level of the catch (TL_C)		2.95	2.89	0.98
Gross efficiency (catch/net p.p.) (GE)		0.0059	0.0079	1.34
Calculated total net primary production (NPP)	$t/km^2/yr$	2570.72	2992.04	1.16
Total primary production/total respiration (NPP/R)		1.37	1.34	0.98
Net system production	$t/km^2/yr$	688.42	759.21	1.10
Total primary production/total biomass (NPP/B)		22.35	23.59	1.06
Total biomass/total throughput (B/TST)		0.02	0.02	1.00
Connectance Index (CI)		0.29	0.29	1.00
System Omnivory Index (SOI)		0.20	0.19	0.95
Finn's Cycling Index (FCI, of total throughput)	%	8.35	8.75	1.05
Finn's mean path length (FML)		2.72	2.73	1.00
Throughput cycled (incl. detritus)	$t/km^2/yr$	584.2	713.9	1.22
Ascendancy (A)	%	24.82	24.44	0.98
Overhead (O)	%	75.18	75.56	1.01
System transfer efficiency (TE, overall)	%	11.65	11.54	0.99
Transfer efficiencies from primary producer	%	11.04	11.00	1.00
Transfer efficiencies from detritus	%	13.66	13.33	0.98

important to note, however, that the baseline model indices reflect an ecosystem that is already in a highly disturbed (or stressed) state (Bacalso et al., 2023b). The current analysis showed that since the baseline year, the pelagic fish biomass was already larger than the demersal fish biomass (Fig. 4-B) in what was traditionally considered as a demersal fishery. A trawl survey conducted in 1948 estimated the demersal standing stock in the Visayan Sea at approximately 6.03 tons/km^2 (Warfel and Manacop, 1950), which is roughly 2–4 times higher than more recent estimates that ranged between 1.55 and 3.09 tons/km^2 (2003–2017) (Ampoyos-Arinque, 2018). The 1948 survey also reported higher overall demersal fish densities compared to contemporary assessments. This suggests that structural changes must have already occurred prior to our baseline year (1997), and that the Visayan Sea may have continued to develop along this path in the following 20 years. However, due to the limited availability of historical time series fisheries data prior to the established baseline year, a detailed examination of earlier drivers of change was not feasible. As such, the analysis and interpretations presented in this study are primarily grounded in observed trends and ecosystem dynamics from 1997 onward, which represents the earliest reliable reference point for assessment.

As suggested by Pauly et al. (1998), intensive fishing not only brings about changes in ecosystem structure, but also, ecosystem functioning. Over the two decades examined, the Visayan Sea ecosystem has exhibited a marked decline in top-down control as high-TL species have experienced substantial reductions in biomass. This pattern is indicative of a trophic cascade (Frank et al., 2005; Baum and Worm, 2009), wherein decreased predation pressure on lower TL species leads to their population expansion, with cascading effects throughout the food web. The resulting increase in low TL prey biomass has benefited opportunistic zoobenthic feeders and planktivorous species. However, diet composition analyses in the Visayan Sea (Mequila and Campos, 2007) revealed that low TL organisms (i.e., shrimps, calanoids, nematodes, and amphipods) also constitute the primary food sources for dominant reef-associated, soft-bottom demersal, and pelagic fish groups. Notably, the study also found no significant shift in prey preference across fish size classes, indicating broad diet overlap among consumer groups. This overlap suggests generalist feeding strategies that capitalize on the abundant low TL prey as an accessible energy source in the Visayan Sea. This helps explain the observed decline in average consumer TLs, which is further reflected in the reduction of several trophic-based community indicators (Table 3) between the two decades. This also supports our analysis of keystone index ranking that showed how these groups' bottom-up role became more important over time (Fig. 5). The changes in the catch composition likewise reflected the changes in the biomass composition of the community (i.e., shifting toward lower TL groups). This trajectory mirrors patterns observed in other highly exploited fishing grounds in the Philippines (Muñoz, 1991; Pauly and Mines, 1982; Silvestre et al., 1991).

Uncertainties in the invertebrate parameter estimates due to input data limitations (i.e., low Pedigree scores) may propagate through the trophic network and affect fine-scale interactions. Nevertheless, the aggregate dynamics of invertebrate groups are more critical for overall ecosystem functioning than fluctuations in individual taxa; as discussed previously, most consumer groups in the Visayan Sea are generalist feeders with broad diets. This dietary flexibility helps buffer the system against uncertainty in specific invertebrate groups. Thus, while these uncertainties highlight the need for caution when interpreting fine-scale dynamics, they do not preclude broader insights into system-level behavior.

Taken together, considerations from the changes in ecosystem-structure provide important context for interpreting the network-based attributes described below. The increase in Total System Throughput (TST) is attributed to the increase in biomass and activity of groups from the primary producers and lower trophic levels. This leads to a more simplified overall system structure (i.e., information flows). These two system attributes apparently counterbalanced each other to maintain the system's Ascendancy (which is the product of TST and average mutual information). Despite these changes and the overall increase in fishing pressure, no collapse of species (resources) has yet been observed, suggesting a highly resilient system. This resilience of the present configuration of the Visayan Sea system is also indicated by the Finn's Cycling Index (FCI), Connectance Index (CI), System Omnivory Index (SOI), mean path length (FML), and transfer efficiencies that changed minimally during the study period. In contrast, the cycling of throughput increased substantially by 22 %. This provides a clue to the apparent stability of the Visayan Sea ecosystem between the two decades. Ulanowicz's theory on ecosystem resilience and stability (Ulanowicz, 1986) states that high cycling, particularly of detritus,

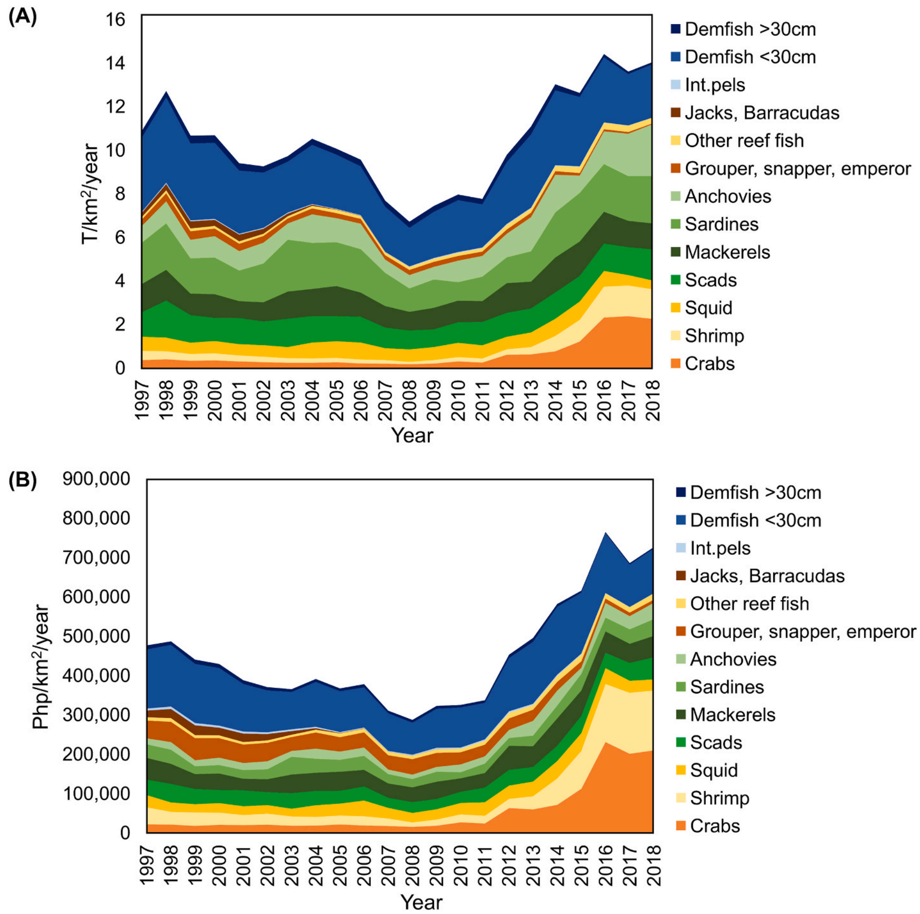

Fig. 6. Cumulative (A) annual catch contribution of commercially important fish and invertebrate groups and (B) their corresponding estimated values (Php 52.67 = USD 1 at 2018 average exchange rates).

confers ecosystem resistance to change (stability) as the availability of the stored and recycled resources buffers the system to external shocks. This is a characteristic commonly demonstrated by aquatic systems that are naturally exposed to disturbance on a regular basis, such as lagoons and fjords (Vasconcellos et al., 1997). Thus, this index is also regarded as a measure of a system's coping mechanism to stress or disturbance (Ulanowicz, 1986). Specifically, detritus provides an additional and alternative energy source within an ecosystem. This allows for a diversification of consumer types within trophic levels (e.g., herbivory and detritivory in TL II). This then provides a buffer against biomass or energy fluxes, hence, stability (Moore et al., 2004). In the Visayan Sea models, nearly one-fourth of the cumulative flows that end up as predator consumption (TL II to IV) originated from the detritus.

We propose two potential mechanisms underlying the enrichment and recycling of the detrital pool in the Visayan Sea. The first is the sustained decline in the biomass of upper-TL consumers, which resulted in the underutilization of lower TL-biomass, particularly, the benthic invertebrates and plankton. As reflected in the model's network analysis, this shift promoted shorter trophic links or pathways and increased the flow of unconsumed biomass back into the detrital pool, where it became available once again to abundant low TL consumers. The second mechanism involves wind as an external physical driver. Given the relatively shallow depth of the Visayan Sea, seasonal and daily wind-induced mixing facilitates vertical nutrient transport across the water column (Campos, 2018). This dynamic allowed both demersal and pelagic consumers frequent and regular access to energy from both the primary production and detrital pathways.

Resilience may also be attributed to the mechanism of functional redundancy (Rice et al., 2013), wherein different species with similar ecological functions provide a buffering effect to stress. More specifically, when the biomass of one species declines due to a stressor, say fishing, another species of similar ecological function tends to compensate. In the Visayan Sea, local fisheries assessments have documented a shift in sardine species composition over time. Historically, *Sardinella gibbosa* and *S. fimbriata* were the dominant sardine species in the catch; however, *S. lemuru* has become more prominent in recent years. Whether or not this is truly indicative of population-specific responses to the effects of fishing is still inconclusive and merits further analysis. However, changing environmental conditions may offer an alternative explanation. According to species distribution data (Kaschner et al., 2019), *S. gibbosa* prefers lower levels of primary productivity and higher dissolved oxygen concentrations relative to the other two species. Notably, the Visayan Sea has experienced rising net primary productivity over the past decade (Bacalso et al., 2023a) alongside declining bottom dissolved oxygen levels (Ampoyos-Arinque, 2018). These environmental changes may have facilitated a form of sequential species succession (Chapin et al., 1997; Norberg et al., 2001), whereby shifts in relative abundance reflect species-specific tolerances or adaptations to environmental stressors to maintain the overall group abundance and ecosystem function under varied environmental conditions. This further implies that high species diversity within a functional group is an advantage to maintain stability (Lindegren et al., 2016). In the Visayan Sea, most of the functional fish groups featured a high documented number of species (as shown in Suppl, Table S3), which may be considered as a contributing factor to their resilience. However, progressive increase in fishing mortality on species-specific targets could negatively alter these species' abundance, eventually reducing the species diversity within a group and potentially compromising its overall function. This has already been demonstrated by the impaired top-down function of the pelagic predators due to a significant decrease in their diversity and biomass (Fig. 5-B). Further, the dramatic decrease of the Kempton's Q index should serve as a serious warning as it corroborates the findings of an independent study, which estimated that around 20 % of the commercial and 30 % of the ornamental species found in other biogeographic regions in the Philippines are no longer found in the Visayan Sea region (Nañola et al., 2011).

Therefore, the identification and quantification of thresholds for functional groups and the ecosystem as a whole (Sasaki et al., 2015; Del Solar et al., 2022) would be the ideal next step in order to inform the design of fisheries policies aimed to address high fishing mortalities of target species and to mitigate the observed biodiversity decline in the Visayan Sea. While fishing appears to be the most substantive driver of the Visayan Sea ecosystem from 1997 to 2018, local environmental factors variably affected the different groups. SST and primary productivity rates linked to monsoon rainfall patterns appeared to have had the most wide-ranging impacts. Specifically, the increase in average SST and periods with above average rainfall saw concurrent declines of representative small pelagic and demersal fish species (Bacalso et al., 2023a). Hence, we reiterate here the need to include these environmental variables in the analysis and interpretation of intra- and inter-year catch variations.

(2) How has policy influenced the fisheries trends and their subsequent ecological and economic outcomes?

Fisheries policies are intended to direct fisheries-related activities with respect to specific management objectives. In the last 2 decades, the national and local policies that had important bearing on the management of the Visayan Sea fisheries resources aimed to protect fish stocks from overexploitation, and at the same time, to alleviate poverty. Effort controls were the principal measures applied to address overexploitation. They were focused on the reduction of the total fishing effort of the commercial fishing operations and in eliminating IUU fishing. The effort trends (Suppl, Fig. S2) showed apparent success in limiting the effort and consequently, the catches by the commercial fishing sub-sector (Fig. 2-B). Specifically, the commercial purse seines in the Visayan Sea (averaging over 50 G.T.) exhibited steady declines since the enactment of the Philippine Fisheries Code in 1998, which restricted commercial fishing to marine areas beyond 15 km from the shoreline. In 2013, a nationwide ban on Danish seine operations also led to a further decline in the effort of commercial Danish seines (averaging 18 G.T.) in the area. Conversely, smaller commercial fishing operations (3–15 G.T.) have either maintained stable effort levels or shown marked increases over the same period. Notably, the rise in ring net operations from 2008 onward coincided with the sharp decline in purse seine effort, suggesting that fishing operators may have transitioned to smaller vessels to sustain fishing activities and livelihoods. Interviews conducted during the latest fishing inventory also revealed how some of these operators circumvented the moratorium on commercial fishing licenses by registering as small-scale municipal fishers. This added to the effort increase of the municipal fishing sub-sector and the subsequent increase in total fisheries extraction that exceeded the baseline levels. Since the municipal (mainly artisanal and subsistence-level) fishing capacities are restricted by vessel size (<3 G.T. per fishing unit), their individual catch rates are considerably lower compared to the commercial fishing operations; thus, they are often viewed as less of a threat to stock sustainability. However, many case studies have demonstrated how this sub-sector can collectively cause substantive ecological impacts if left unregulated (Bacalso and Wolff, 2014; Bundy, 2004; Bundy and Pauly, 2001). Yet, the prioritization of the labor-intensive municipal fishing sub-sector can be viewed as a strategy to address poverty alleviation. Indeed, this sector has benefitted from the fishing policies through an increase in overall employment. But this begs the question, was the objective of poverty alleviation actually achieved?

Conventionally, in a fishery where subsistence fishing is dominant, management priorities cater to a more basic need, i.e., food security. Following this, policies are set to maximize the catches at maximum sustainable yield (MSY) and not profits at maximum economic yield (MEY), which is thought of as the more conservative reference point to avoid overexploitation of stocks (Caddy and Mahon, 1995). Our study illustrates this tension as the tradeoff between the economic share per fisher (decreasing) and fisher employment (increasing) over time. While the total landings and their overall values were higher in 2018 compared to the landings and values in 1997, our calculations showed that the per capita income from fishing has decreased substantially. Viewed together with the surplus production models for the Visayan Sea stocks (Mesa, 2019), these results can be considered as the direct economic consequences of fishing effort levels that have already exceeded both the MEY and the MSY. They also reflect the economic consequences of fishing down the food web (Pauly et al., 1998), which follows a typical pattern of fishing from the less productive, high-TL, and high-value species to the more productive, low-TL, and low-value species.

Interestingly in this case, the greatly enhanced catches of the low-TL but high-value crabs and shrimps more than compensate for the concomitant decrease in catches of the high-TL fish groups in the Visayan Sea (Fig. 6-B). Fishing these naturally highly-productive resources thus presents an opportunity to increase not only the overall fisheries production, but also the total value and average incomes of fishers in the area. However, this must be balanced with considerations for the long-term sustainability of the stocks. In fact, the blue swimming crab (*P. pelagicus*) fishery in the Visayan Sea has already experienced historical boom-and-bust periods that were attributed to overexploitation (Ingles, 1996; Mesa et al., 2018). Consequently, management measures were implemented, specifically in the main blue swimming crab producing and processing regions. However, it has only been recently that a comprehensive management plan for these stocks was established.[7] On the other hand, no similar management plan exists for the local wild shrimp stocks, which are usually caught by rudimentary barrier nets and push nets, or as by-catch of trawling and seining operations. While the model-calculated exploitation ratio for this group is still low, this needs to be validated by stock assessments in order to reduce the current high uncertainty concerning their stock status, with respect to fishing and environmental variabilities (Thiaw et al., 2009). In anticipation of an increased interest in exploiting this alternative high-value resource, precautionary management measures, at the very least, are needed to prevent biomass and catch collapses that were reported in heavily-exploited invertebrate stocks elsewhere (Arreguin-Sanchez et al., 2008; Eddy et al., 2015).

This study has shown that the municipal fishing sub-sector grew to be a significant influence on the Visayan Sea ecosystem over the course of two decades. This highlights the important role of the local government units (LGUs) that have the direct mandate to manage the municipal fishing sub-sector. This implies a need to invest in the LGUs' capacity to manage their resources and in promoting the resilience of fishing communities to variabilities in resource abundance due to natural and anthropogenic factors. A fundamental capacity requirement is the LGUs' ability to develop and maintain a comprehensive local database of fishers, boats, and fishing gears, as mandated by the Philippine Fisheries Code of 1998. However, national-scale inventories led by the Bureau of Fisheries and Aquatic Resources (DA-BFAR) remain irregular. While past initiatives like the Coastal Resource Management Project (CRMP) (CRMP, 2004) helped to build LGU capacities in developing local fisheries databases as part of an improved local implementation of coastal resources management, the sustainability of these efforts has been inconsistent. The sustainability often hinges on key factors such as the

[7] The Blue Swimming Crab National Management Plan 2020 (https://www.bfar.da.gov.ph/wp-content/uploads/2022/07/Blue-Swimming-Crabs-National-Management-Plan.pdf).

financial resources of the LGU to fund public services and projects,[8] ongoing collaborations with research institutions or NGOs, and whether there is a priority fishery or species that is monitored by the National Stock Assessment Program (NSAP). Encouragingly, sustainability appears more likely when LGUs are motivated by incentives such as awards, recognitions, or certifications; examples include the Department of the Interior and Local Government's (DILG) Seal of Good Local Governance (SGLG)[9] and the Bureau of Fisheries and Aquatic Resources' (DA-BFAR) *Malinis at Masaganang Karagatan* (MMK) program[10]. These programs incentivize LGUs to continuously enhance the delivery of public services while promoting sound environmental governance and the responsible management of natural resources, including fisheries.

This likewise calls for stronger partnerships between the LGUs and national agencies to prevent the often recognized disjoint between nationally-set policies and local management realities (Green et al., 2003). Nationwide consultations in the development of fisheries management plans (such as those for the Blue Swimming Crab and sardines) represent a positive step forward. These processes involved extensive engagement with multi-sector stakeholders at various levels (national, regional, provincial), with fisheries experts and the DA-BFAR facilitating meaningful dialogue and input. The integral role of the Fisheries and Aquatic Resources Management Councils (FARMCs) further underscored the importance of participatory governance. FARMCs are composed of representatives from diverse sectors, including fisherfolk, local government units (LGUs), non-government organizations (NGOs), the private sector, youth, and women to ensure that diverse local perspectives, needs, and concerns are raised during consultations. This aims to promote more inclusive and responsive fisheries management decisions. Additionally, supporting LGU alliances or networks with common goals, as demonstrated in the Balayan Bay experience (Bacalso et al., 2023c), shows promise in fostering collaborative and ecosystem-based management approaches across municipal boundaries. The M-EAFM reference guides and materials (DA-BFAR, 2017) offer useful tools for LGUs and networks of LGUs to monitor the implementation and effectiveness of these initiatives in a more integrated manner.

Overall, fisheries policies in the Visayan Sea have played a central role in shaping the ecological and economic outcomes over the past two decades. These outcomes highlight the limitations of fragmented management and the need for more integrated approaches. The adoption of the Visayan Sea Ecosystem Approach to Fisheries Management (EAFM) Framework Plan in 2022 (FMA 11, 2022) marks a key policy milestone by shifting focus toward holistic, science-based management that considers both ecological sustainability and human well-being. This plan evaluates proposed management actions not only on their biological impacts but also on their implications for livelihoods, food security, and economic sustainability. Currently, the plan is being expanded to cover all of Fisheries Management Area 11 (FMA 11) to which the Visayan Sea belongs. The FMA 11 Technical Working Group (TWG), through inclusive sectoral consultations, takes proactive steps to identify safety nets such as fisheries and non-fisheries livelihood alternatives to mitigate potential displacement and income loss, thereby helping prevent unregulated effort shifts between sectors. At the local level, strengthening inter-LGU cooperation and investing in local management capacity will further align national policy goals with local realities. Ultimately, achieving the desired ecological and economic outcomes in the Visayan Sea fisheries will require sustained investments in LGU capacity, robust national-local partnerships, and the creation of consistent opportunities for participatory and science-informed decision-making.

(3) How useful are ecological indicators in supporting the ecosystem-based assessments in the Visayan Sea?

This study has shown the usefulness of the employed operational indicators for comparing the status of the Visayan Sea ecosystem between two decades. The indicators were successful in integrating the results of species-based assessments to describe important changes that have occurred in the community structure, biodiversity, and overall system functioning. The network analysis likewise facilitated our understanding of the properties that have contributed to the resilience of the Visayan Sea ecosystem, which was shown to be because of, and in spite of, the structural changes that have occurred. Moreover, the constant fishing pressure appears to be an important mediating factor. Therefore, this and other possible mediating factors associated with environmental processes (e.g., nutrient influx brought about by increased rainfall) must be considered by rehabilitation projects in the Visayan Sea, as the system's enhanced resistance to disturbance may also apply to management efforts that are intended to drive changes in the community structure and abundance.

This then calls for a need to put into context the term "healthy ecosystem" as a goal for management. By definition, a healthy ecosystem exhibits stable and resilient properties (Costanza and Mageau, 1999). Based on this definition, the current state of the Visayan Sea ecosystem may be considered as "healthy". However, this is not reflected in aspects related to biodiversity conservation and the quality and delivery of ecosystem services (Truchy et al., 2015). In this regard, specific attributes to describe a desired ecosystem state serve as more practical management goals rather than simply, "a healthy ecosystem". This likewise implies that fisheries policies must express specific management objectives and recognize that tradeoffs may exist based on the properties of the ecosystem, as well as social and economic goals. As revealed in the analysis, the reduced overall biomass of predator groups in the Visayan Sea released the prey groups from predation mortality. This included the biomass of marine crabs and shrimps that are economically viable resources at present and may contribute to the poverty alleviation objective of management. On the other hand, stricter effort regulations must be applied especially to the prevailing IUU fishing activities and the dominant municipal fishing sub-sector if restoring biodiversity, sustaining the stocks of highly-exploited fish groups, and conserving threatened and vulnerable stocks are desired. Therefore, the combined use of the ecological and economic indicators can help in the reevaluation of current fisheries policies and their effectiveness in relation to specific priority objectives.

The value of using multiple indicators was recognized by the DA-BFAR in FMA 11. In collaboration with data analysts from the NSAP and the FMA 11 TWG, the Visayan Sea ecosystem model was later updated to reflect the most recent fishing effort estimates and was used as a platform to reevaluate scenario options for an existing Visayan Sea closed season policy. It was further used to evaluate the potential impacts of a proposed harvest strategy focused on addressing IUU fishing and significantly reducing the proportion of undersized or juvenile fish caught by the different gear groups, particularly those using fine mesh nets. Using a combination of stock-based performance indicators, ecological indicators, and livelihood impacts analysis, the proposed harvest strategy was successfully presented to the FMA 11 Management Board, which approved it for subsequent stakeholder consultation. In preparation, the TWG proceeded with the profiling of fish workers that will be affected by the regulation and have conducted consultations to identify the appropriate safety nets. Further, information materials and policy briefs were developed to help communicate the proposed harvest strategy to the relevant stakeholder groups, including the potentially affected fishers, managers, and decision-makers. Overall, the

[8] RA 11964 An Act Institutionalizing the Automatic Income Classification of Provinces, Cities, and Municipalities, and for Other Purposes.

[9] DILG 2023 Memorandum Circular on the Seal of Good Local Governance (https://www.dilg.gov.ph/PDF_File/issuances/memo_circulars/dilg-memocircular-202339_c61a75dc8d.pdf).

[10] National Search for Outstanding Coastal Community - MMK (https://sdg.depdev.gov.ph/national-search-for-outstanding-coastal-community-malinis-at-masaganang-karagatan/).

application of an ecosystem model to complement the single-species assessment models and the integration of biological, ecological, and economic indicators to evaluate potential impacts of existing and proposed fisheries management policies were instrumental in further advancing the ecosystem approach to fisheries management in the Visayan Sea and FMA 11.

CRediT authorship contribution statement

Regina Therese M. Bacalso: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Matthias Wolff:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Giovanni Romagnoni:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Marie Fujitani:** Writing – review & editing, Supervision, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.108027.

Data availability

Annual fish prices and consumer price index data are free to access and download from the Philippine Statistics Authority (PSA) (http://www.census.gov.ph). Fisheries data used in this study may be accessed through the NSAP Interactive Atlas (https://nsap.nfrdi.da.gov.ph). For more detailed data needs, queries may be directed to the National Fisheries Research and Development Institute (NFRDI).

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