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Exploring the trophic interactions in the coral reef ecosystem at the coastal area of Ternate Island using Ecopath model

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ABSTRACT

The Ecopath mass-balanced model was employed to elucidate the trophic structure and interaction, energy flow, and ecosystem properties of the coral reef ecosystem in the coastal area of Ternate Island. The model comprised 30 functional ecological groups, of which 29 were living groups and one was a group of detritus. The trophic structure of the model exhibited a range of values, from 1.0 for primary producers and detritus to 3.81 for the top predator. The resulting trophic aggregation comprises six effective trophic groups, with the largest energy flow originating from zooplankton and benthic organisms in trophic level II. The transfer efficiency is predominantly derived from detritus organisms, in comparison to that derived from phytoplankton as the primary producer. The ratio of total primary production per total respiration indicated that the coral reef ecosystem was at a developmental stage. The coral reef ecosystem exhibited a low ecological efficiency for the fishery gross efficiency. Mixed trophic impact analysis indicated that predators exerted a negative impact on their prey, whereas planktonic organisms exerted a positive impact on the majority of fish functional groups. The comparison of the model with other studies provided information that could inform the development of appropriate fisheries management guidelines for this area based on ecosystem properties.

Introduction

The North Maluku Province is one of the Indonesian archipelago provinces with significant potential for fisheries and marine resources, particularly in coastal areas. Ternate City, as the centre of development in the North Maluku region, is a notable archipelago city comprising eight islands, spanning an area of 5,795.5 km² and encompassing 5,544 km² of maritime space (approximately 95.7%) and 250.85 km² of land. In 2022, the total production of capture fisheries in Ternate City was 48,234 tons, comprising both pelagic and demersal fish. The most prevalent species of large pelagic fish are tuna, skipjack tuna, mackerel tuna, and Spanish mackerel, while small pelagic fish are dominated by scads, sardines, and other small pelagic fishes. The demersal fisheries are dominated by red snappers, emperor

fish, fusiliers, and certain species of groupers (Marine and Fisheries Official of Ternate City, 2023).

The coral reef fisheries at Ternate Island commonly employ the use of handlines, traps and gill nets, with catches predominantly comprising jackfish, fusiliers, snappers, emperor fish, parrot fish, surgeon fish and sweetlips fish. Additionally, certain gastropod and crustacean species have been identified as target species for fishing activities. The expansion of development and human activity in the coastal zone of Ternate Island exerts a considerable influence on the coral reef ecosystem, which were previously utilized for production and economic purposes (Rumagia *et al.*, 2019). In the current context, however, recreational fishing has become a prominent activity, exerting considerable pressure on both the fish and their ecosystem (the coral reef

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ecosystem). An increase in recreational fishing activity, without a corresponding increase in the targeted fish species, will have an adverse effect on the structure and dynamics of reef fish resources in the coastal area of Ternate Island.

It is of great importance to ascertain the resources information and to identify the changes in these patterns due to the pressure on the coral reef fisheries resource in the coastal area of Ternate Island. Such information will facilitate the implementation of sustainable development strategies, particularly with regard to the structural changes occurring in coral reef fisheries, including alterations in stock structure and distribution patterns (Ahmad et al., 2019). In examining the interconnections between management, fisheries and the environment, it is essential to differentiate between three distinct categories: the ecosystem effect, the ecosystem impact and the ecosystem challenge (Bastardie et al., 2021).

In order to comprehend the dynamics of an ecosystem, it is imperative to gain an understanding of the structure and function of the communities that comprise it (Howell et al., 2021; Keramidas et al., 2023). A variety of methodological approaches have been developed for the purpose of quantifying the magnitude of relationships between species or groups of species, as well as for the assessment of the relative importance of each component in the overall maintenance of the system (Stock et al., 2023). These approaches permit the study of attributes related to energy flows within a trophic network, the direction and magnitude of biomass transit, and the reciprocal impact between species prior to an external disturbance. These are all represented and interpreted in the context of natural resource management (Plagányi, 2007; Colléter et al., 2015; Howell et al., 2021; Montero et al., 2021).

Link (2010) defined ecosystem-based management (EBM) as an approach to management that considers the entire ecosystem and all the key factors and processes within it. In other words, EBM is a method of management that accounts for the holistic and integrated nature of ecosystems. In the context of marine resource cycles, this necessitates an understanding of all related aspects. The objective of ecosystem-based fisheries management (EBFM) is to oversee the management of fisheries in a coordinated, responsible, and inclusive manner, utilising holistic, synthetic, and integrated models (Anstead et al., 2021; Howell et al., 2021, Pennino et al., 2023). While catch fisheries represent a significant factor, the management of marine mammals, protected species, non-target species, and other

elements is also a crucial aspect (Christensen and Walters, 2011; Bentley et al., 2021). The concept is based on the premise that fisheries production is the result of the interaction among species and their interaction with the environment.

The theoretical basis of ecosystem-based fisheries management is to assess the impact of fisheries activities on ecosystem function, with the objective of establishing a reference point to demonstrate that, in practice, fisheries activities and the management of ecosystems are inextricably linked (Jennings and Rice, 2011; Rice, 2011; Colléter et al., 2015; Pennino et al., 2023, Ruzicka et al., 2024). Indeed, the implementation of ecosystem-based management remains a significant challenge, with fisheries management practices still predominantly based on single-species approaches. The regulation of fishing quotas or allowable catch size remains the basis for fisheries management, and cannot yet be replaced with management policies that are based on a comprehensive assessment of human influence on environmental health (Bentorcha et al., 2017; Townsend et al., 2019).

The coral reef ecosystem represents one of the most diverse and impressive marine ecosystems on the planet. Its remarkable species richness and composition confer upon it a notable resilience to the pressures exerted by fishing activities and other forms of environmental disturbance. However, the practice of fishing has undeniably impacted the fish community, affecting not only target species but also non-target organisms. Furthermore, the abundance of reef fish is also contingent upon a number of factors, including the recruitment of fish larvae, the number of juvenile colonies and adult fish, predation, and niche competition. Moreover, the capacity for recovery is contingent upon the equilibrium of trophic competition and the composition of the coral reef ecosystem (Varkey et al., 2012; Hernández-Delgado et al., 2018).

The trophic interaction analysis employed in this study employs a simulation model of the trophic model utilising the Ecopath with Ecosim (EwE) routine. This has been developed for the purpose of evaluating the evolving condition and impact of the ecosystem (Fouzai et al., 2012; Colléter et al., 2015; Webber et al., 2015; Susini and Todd, 2021; Stock et al., 2023). The objective of this research is to analyse trophic level interaction in coral reef ecosystem in the coastal area of Ternate Island using the mass-balance approach with the Ecopath model.

Materials and Methods

Location and time of research

The study was conducted in the coastal region of Ternate Island, situated between 127°17'0" and 127°24'0" E and 0°45'0" and 0°52'30" N (Figure 1). This study encompasses an area of approximately 143.5 km² comprising fishing grounds for coral reef fisheries. Data were collected between February and June 2024.



Figure 1. Map of the research area.

Data analysis

Ecopath model approach

The Ecopath with Ecosim (EwE) framework approach encompasses all bio-ecological aspects of the ecosystem, from the primary producer (phytoplankton) to the top predator level. The approach was predicated on the assumption of mass balance derived from linear system comparison, which demonstrates the average flow of biomass and energy among the functional groups within the food chain. A functional group may be represented by a single species, a species group, or a grouping of species according to their life stage. In Ecopath models, the fundamental model for the system was parameterised in accordance with temporal periods. Ecosim is the time-dynamic model that forms part of the framework construction. It uses the Ecopath parameters as the basis for the simulation.

The mass balance in EwE indicates that the parameters model was operating at the physical limit, whereby the total flow of biomass into a functional group must be equal to the flow out from the group.

Each functional group is represented by two master equations that describe the energy flow between the functional group and the energy balance within the group. In the case of species represented by their group biomass, the energy flow from and to each functional group was described with the first equation of the Ecopath model (Araújo and Bundy, 2011; Chagaris *et al.*, 2015; Montero *et al.*, 2021; Christensen and Walters, 2024): Production = catches + predation mortality + biomass accumulation + migration + other mortality. The equation for production is given by:

$$P_i = Y_i + B_i \cdot M_{2i} + E_i + BA_i + P_i \cdot (1 - EE_i)$$

where, P_i represents the total production rate of (i), Y_i denotes the total fishery catch rate of (i), M_{2i} signifies the total predation rate for group (i), B_i is the biomass of the group, E_i is the net migration rate (emigration – immigration), and BA_i is the biomass accumulation rate for (i). Additionally, M_{0i} is defined as $P_i \cdot (1 - EE_i)$, where EE_i represents the other mortality rate for (i).

This formulation incorporates the majority of the production (or mortality) components that are commonly employed in this field, with the potential exception of gonadal products. However, gonadal products are typically consumed by other groups and can be incorporated into either predation or other mortality (Christensen and Walters, 2011; Montero *et al.*, 2021; Christensen and Walters, 2024). The Ecopath equation can be described as follows:

$$B_i \cdot (P/B)_i - \sum_{j=1}^n B_j \cdot (Q/B)_j \cdot DC_{ji} - (P/B)_i \cdot B_i \cdot (1 - EE_i) - Y_i - E_i - BA_i = 0$$

or

$$B_i \cdot (P/B)_i \cdot EE_i - \sum_{j=1}^n B_j \cdot (Q/B)_j \cdot DC_{ji} - Y_i - E_i - BA_i = 0$$

where P/B_i is the production/biomass ratio, Q/B_j is the consumption / biomass ratio, and DC_{ji} is the fraction of prey (j) in the average diet of predator (i).

In accordance with Eq. 2, a system comprising n groups can be described by n linear equations in explicit terms as follows:

$$\begin{aligned} & B_1 \cdot (P/B)_1 \cdot EE_1 - B_1 \cdot (Q/B)_1 \cdot DC_{11} \\ & - B_2 \cdot (Q/B)_2 \cdot DC_{21} \cdots - B_n \cdot (Q/B)_n \cdot DC_{n1} - Y_1 - E_1 - BA_1 = 0 \\ & B_2 \cdot (P/B)_2 \cdot EE_2 - B_1 \cdot (Q/B)_1 \cdot DC_{12} \\ & - B_2 \cdot (Q/B)_2 \cdot DC_{22} \cdots - B_n \cdot (Q/B)_n \cdot DC_{n2} - Y_2 - E_2 - BA_2 = 0 \\ & : \\ & B_n \cdot (P/B)_n \cdot EE_n - B_1 \cdot (Q/B)_1 \cdot DC_{1n} \\ & - B_2 \cdot (Q/B)_2 \cdot DC_{2n} \cdots - B_n \cdot (Q/B)_n \cdot DC_{nn} - Y_n - E_n - BA_n = 0 \end{aligned}$$

Araújo and Bundy (2011) posited that in the majority of cases, at least three of the four fundamental parameters, specifically B , P/B , Q/B ,

and EE_i , are indispensable for the model parameterisation process. Subsequently, the fourth parameter is estimated by Ecopath. If all four basic parameters are entered, Ecopath then estimates either the BA or E . In addition to the three basic parameters, the user is required to provide estimates of Y , E (the default value is zero), BA_i (the default value is zero), DC and the GS_i (the default value is 0.2).

Ecotrophic efficiency (EE) is defined as the proportion of production accounted for by fishing, predation, immigration, and population growth (Christensen and Walters, 2024). The estimation is as follows:

$$EE_i = \frac{Y_i + B_i \cdot M2_i + E_i + BA_i}{P_i}$$

In the second master equation of Ecopath, the energy balance within each species or group is ensured by employing the following equation:

$$Q_i = P_i + R_i + Q_i \cdot GS_i$$

In these equations, R_i and GS_i represent respiration and the proportion of assimilated food that is not absorbed, respectively, while the other parameters have been defined previously.

The EwE model also permits the representation of fully age/size-structured functional groups and allows the user to account for ontogenetic shifts in dietary patterns and changes in vulnerability to predation and fishing. In such instances, the user is required to input the estimated total mortality (Z), B , Q/B and BA for a single stage, the leading stanza, and Z for the remaining stages. Furthermore, estimates for the growth parameter K of the von Bertalanffy growth function, the starting age in months of each stage and the ratio between the average weight at maturity and the asymptotic weight must be entered. Subsequently, the B of the remaining stages is estimated by Ecopath. Based on these input parameters, the EwE multi-stanza routine calculates biomass and Q/B of the other stanzas (Araújo and Bundy, 2011; Christensen and Walters, 2024)

Ecopath model parameterization

The model constructed in this study comprises 30 functional groups, which are composed of 23 groups of fish (56 species), one group of cephalopods (one species), two groups of crustaceans (two species), benthos, zooplankton, phytoplankton, and detritus (total sample = 14567 samples) (Table 1).

Table 1. Functional groups used in the Ecopath model for coral reef ecosystem at Ternate Island.

Group	Functional group (in family)	Representative species
Fish	Achanturidae	<i>Acanthurus nigricans</i> , <i>Naso annulatus</i> , <i>Naso lopezi</i> , <i>Naso thynnoides</i> , <i>Paracanthurus hepatus</i> , <i>Zebrasoma scopas</i>
	Caesionidae	<i>Pterocaesio pisang</i>
	Carangidae	<i>Caranx melampygus</i>
	Dasyatidae	<i>Dasyatis kuhlii</i> (Müller & Henle, 1841)
	Diodontidae	<i>Cyclichthys orbicularis</i>
	Haemulidae	<i>Plectorhynchus lineatus</i> , <i>Plectorhynchus polytaenia</i>
	Hemiscyllidae	<i>Hemiscyllium Halmabera</i>
	Labridae	<i>Thalassoma lunare</i>
	Lethrinidae	<i>Lethrinus</i> spp
	Lutjanidae	<i>Apion virescens</i> , <i>Lutjanus gibbus</i> , <i>Lutjanus fulvus</i> , <i>Pristipomoides filamentosus</i> , <i>Pinjalo pinjalo</i> , <i>Paracaesio xanthurus</i> , <i>Macolor niger</i>
	Monacanthidae	<i>Paraluteres prionurus</i>
	Mullidae	<i>Parupeneus barberinus</i>
	Muraenidae	<i>Gymnothorax javanicus</i>
	Ostracidae	<i>Ostracion meleagris</i>
	Pempheridae	<i>Pempheris adusta</i>
	Pomacanthidae	<i>Pomacanthus xanthometopon</i> , <i>Pygoplites diacanthus</i> , <i>Pomacanthus navarchus</i>
	Pomacentridae	<i>Amphiprion clarki</i> , <i>Amblyglyphidodon curacao</i> , <i>Chromis caudalis</i> , <i>Chromis weberi</i> , <i>Chromis viridis</i> , <i>Dascyllus reticulatus</i> , <i>Pomacentrus coelestis</i> , <i>Neoglyphidodon melas</i> , <i>Premnas biaculeatus</i> , <i>Amphiprion perideraion</i> , <i>Amphiprion ocellaris</i> , <i>Dascyllus melanurus</i>
		<i>Scarus flavipectoralis</i> , <i>Chlorurus bleekeri</i> , <i>Chlorurus sordidus</i>
		<i>Pterois volitans</i>
		<i>Cephalopholis miniata</i> , <i>Epinephelus fuscoguttatus</i>
		<i>Siganus canaliculatus</i> , <i>Siganus guttatus</i>
		<i>Synodus variegatus</i>
		<i>Arothron nigropunctatus</i>
		<i>Loligo duvanceli</i>
		<i>Panulirus versicolor</i>
		<i>Portunus pelagicus</i> , <i>Portunus sanguinolentus</i>
Cephalopod	Cephalopoda	
Lobster	Palinuridae	
Crabs	Portunidae	
Benthos	Benthos	
Zooplankton	Zooplankton	
Phytoplankton	Phytoplankton	
Detritus	Detritus	

The data presented in Table 2 were derived from a survey and a review of the relevant literature, as well as from government reports. The data were collected between February and June 2024 with the objective

of assessing the population parameters of the target species in coral reef fisheries activity at Ternate Island.

Table 2. Source of data input for the Ecopath model for coral reef ecosystem at Ternate Island.

Group Number	Group Name	Representative species	Source of data input for B, P/B, Q/B
1	Achanturidae	<i>Acanthurus nigricans</i> , <i>Naso annulatus</i> , <i>Naso lopezi</i> , <i>Naso thynnoides</i> , <i>Paracanthurus hepatus</i> , <i>Zebrasoma scopas</i>	Analyses in this research, except for <i>Zebrasoma scopas</i> was obtain from Froese and Pauly (2024)
2	Caesionidae	<i>Pterocaesio pisang</i>	Analyses in this research
3	Carangidae	<i>Caranx melampygus</i>	Analyses in this research
4	Dasyatidae	<i>Dasyatis kuhlii</i> (Müller & Henle, 1841)	Froese and Pauly (2024)
5	Diodontidae	<i>Cyclichthys orbicularis</i>	Froese and Pauly (2024)
6	Haemmulidae	<i>Plectorhynchus lineatus</i> , <i>Plectorhynchus polytaenia</i>	Analyses in this research, except for <i>Plectorhynchus polytaenia</i> was obtain from Froese and Pauly (2024)
7	Hemiscyllidae	<i>Hemiscyllium Halmahera</i>	Froese and Pauly (2024)
8	Labridae	<i>Thalassoma lunare</i>	Analyses in this research
9	Lethrinidae	<i>Lethrinus</i> spp	Analyses in this research
10	Lutjanidae	<i>Aprion virescens</i> , <i>Lutjanus gibbus</i> , <i>Lutjanus fulvus</i> , <i>Pristipomoides filamentosus</i> , <i>Pinjalo pinjalo</i> , <i>Paracaesio xanthurus</i> , <i>Macolor niger</i>	Analyses in this research
11	Monacanthidae	<i>Paraluteres prionurus</i>	Froese and Pauly (2024)
12	Mullidae	<i>Parupeneus barberinus</i>	Froese and Pauly (2024)
13	Muraenidae	<i>Gymnothorax javanicus</i>	Froese and Pauly (2024)
14	Ostracidae	<i>Ostracion meleagris</i>	Froese and Pauly (2024)
15	Pempheridae	<i>Pempheris adusta</i>	Froese and Pauly (2024)
16	Pomacanthidae	<i>Pomacanthus xanthometopon</i> , <i>Pygoplites diacanthus</i> , <i>Pomacanthus navarchus</i>	Froese and Pauly (2024)
17	Pomacentridae	<i>Amphiprion clarki</i> , <i>Amblyglyphidodon curacao</i> , <i>Chromis caudalis</i> , <i>Chromis weberi</i> , <i>Chromis viridis</i> , <i>Dascyllus reticulatus</i> , <i>Pomacentrus coelestis</i> , <i>Neoglyphidodon melas</i> , <i>Premnas biaculeatus</i> , <i>Amphiprion perideraion</i> , <i>Amphiprion ocellaris</i> , <i>Dascyllus melanurus</i>	Froese and Pauly (2024)
18	Scaridae	<i>Scarus flavipectoralis</i> , <i>Chlorurus bleekeri</i> , <i>Chlorurus sordidus</i>	Analyses in this research
19	Scorpaenidae	<i>Pterois volitans</i>	Froese and Pauly (2024)
20	Serranidae	<i>Cephalopholis miniata</i> , <i>Epinephelus fuscoguttatus</i>	Analyses in this research
21	Siganidae	<i>Siganus canaliculatus</i> , <i>Siganus guttatus</i>	Analyses in this research
22	Synodontidae	<i>Synodus variegatus</i>	Froese and Pauly (2024)
23	Tetraodontidae	<i>Arothron nigropunctatus</i>	Froese and Pauly (2024)
24	Cephalopoda	<i>Loligo duvauceli</i>	Mohamed et al. (2008)
25	Palinuridae (lobster)	<i>Panulirus versicolor</i>	Araújo and Bundy (2011)
26	Portunidae (crabs)	<i>Portunus pelagicus</i> , <i>Portunus sanguinolentus</i>	Indrayanti (2005); Mohamed et al. (2008)
27	Benthos	Benthos	Indrayanti (2005)
28	Zooplankton	Zooplankton	Ullah et al. (2012)
29	Phytoplankton	Phytoplankton	Ahmad et al. (2013)
30	Detritus	Detritus	estimated from empirical equation of Pauly et al. (1993)

B = Biomass, P/B = production per biomass, Q/B = consumption per biomass.

The biomass of the coral reef ecosystem resources was quantified for each species or group. The input value employed was the mean biomass per unit area for each group within their designated habitat (ton km⁻²). Production and other energy flow are

expressed in ton per km² per year. For all functional groups, the data input for the models comprised biomass (B_i), production per biomass ratio (P_i/B_i), consumption per biomass ratio (Q_i/B_i), ecotrophic

efficiency (EE_i), diet composition (DC_{ij}), and fishing mortality (F_i).

The detritus biomass was calculated as a function of primary production and eutrophic depth, employing the empirical equation proposed by Pauly *et al.* (1993):

$$\text{Log}_{10} D = -2.41 + 0.954 \text{Log}_{10} PP + 0.863 \text{Log}_{10} E$$

where D is detritus biomass (g C m^{-2}), PP is primary production ($\text{g C m}^{-2} \text{year}^{-1}$), and E is eutrophic depth (taken here as 15 m depth). By converting 1 gC equal to 10 g wet weight of detritus (Christensen and Pauly, 1992a), the detritus biomass was estimated at 15.05 tons per km^2 .

The phytoplankton biomass was calculated using the methodology outlined in the study conducted by Ahmad *et al.* (2013) in the same geographical area. This resulted in a biomass value of 62.7018 tons km^{-2} . The biomass and P/B values for zooplankton were obtained from the research conducted by Ullah *et al.* (2012). The cephalopod data were derived from the research of Mohamed *et al.* (2008). The biomass of lobsters was obtained from the study conducted by Araújo and Bundy (2011). The crab data were sourced from the research of Indrayanti (2005) and Mohamed *et al.* (2008). The benthos was sourced from the research conducted by Indrayanti (2005).

Production per biomass (P/B) and Consumption per Biomass (Q/B) ratio

The P/B ratio is assumed to represent the instantaneous rate of total mortality (Z) from each species (Christensen *et al.*, 2008; Araújo and Bundy, 2011; Christensen and Walters, 2024). In the case of the sampled species, this was calculated as the sum of fishing mortality (F) and natural mortality (M). The data for P/B were also obtained from FishBase (Froese and Pauly, 2024) for non-target species in coral reef fisheries. The Q/B (year^{-1}) ratio for the fish group was estimated using the empirical relationship developed by Polmares and Pauly (1998) that use asymptotic weight, habitat temperature, a morphological variable and food type as independent variables, and expressed in equation (Mohamed *et al.*, 2008; Araújo and Bundy, 2011; Ullah *et al.*, 2012; Christensen and Walters, 2024):

$$\log\left(\frac{Q}{B}\right) = 7.964 - 0.204 \cdot \log W_{\infty} - 1.965 \cdot T' + 0.083 \cdot A + 0.532 \cdot h + 0.398 \cdot d$$

where W_{∞} is asymptotic weight (g) calculated from length-weight relationship of von Bertalanffy equation, T' is mean annual habitat temperature where expressed as $T' = 1000/\text{Kelvin}$ ($\text{Kelvin} = T_c + 273.15$) where T_c is the average annual sea surface temperature (28°C), A is the aspect ratio of caudal

fin, and b and d are dummy variables indicating the feeding category of the fish species, i.e. herbivore ($b=1, d=0$), detritivore ($b=0, d=1$), and carnivore ($b=0, d=0$). The A value was calculated as $A = b^2/s$ (Sambilay, 1990) where b is the high of the caudal fin and s is the surface area of the caudal fin. This relationship was used only for the fish group that uses their caudal fin as the main organ of propulsion, for the other ecological groups, appropriate empirical equations available in the Ecopath or information from the literature were used. The data for Q/B was obtained from field survey during the study period, from FishBase (Froese and Pauly, 2024), and other literature (see Table 2).

Diet composition

The dietary composition is a significant factor in Ecopath models, as it enables the attainment of mass balance, thereby enabling the calculation of the ratios of P/B , Q/B , and EE . The total value of diet composition for each functional group must be equal to one. The diet composition for each group was constructed using information about their predation preference derived from stomach content analysis and a review of the relevant literature. Additionally, data on the availability of prey species was obtained from FishBase (Froese and Pauly, 2024).

Ecotrophic efficiency (EE)

The term 'ecotrophic efficiency' (EE) is used to describe the fraction of the production that is used within the system. This may be passed up the food web, used for biomass accumulation, migration or export. Direct measurement of ecotrophic efficiency is challenging. It varies between 0 and 1, with the expectation that it will approach 1 for groups that experience considerable predation pressure. The ecotrophic efficiency of a detritus group is defined as the ratio between the outflow from a detritus box and the inflow into the same box. It is not possible to enter the EE for detritus; it is always calculated (Christensen and Walters, 2024). The EE value was automatically assessed using the Ecopath routine in conjunction with other values. In this study, the initial value for EE for several functional groups was set at 0.95, in accordance with the methodology proposed by Christensen and Pauly (1992b). The EE s for lobster and crabs were obtained from the studies conducted by Mohamed *et al.* (2008) and Araújo and Bundy (2011), with a set value of 0.970 and 0.780, respectively.

Trophic level and transfer efficiency

The trophic level fraction was estimated for all ecological groups (Christensen and Walters, 2024). The routine assigns a definitional trophic level (TL) 1 to producers and detritus, and a trophic level of 1+ (the weighted average of prey's trophic level) to consumers (Christensen *et al.*, 2008; Xu *et al.*, 2011; Christensen and Walters, 2024). In order to describe the proportion of energy transferred from one trophic level to another, it is necessary to consider all the ecological groups described in the Lindeman spine diagram. The transfer energy (expressed as a percentage) is the ratio between the sum of export and predation flows by the next trophic level and the throughput on the trophic level.

Mixed trophic impact

Once the model has been balanced, the mixed trophic impact (MTI) is accessed using the network analysis routine in Ecopath. MTI provides an assessment of how trophic biomass changes affect each functional group in relation to other groups, both directed and undirected, in the energy flow through the system (Ulanowicz and Puccia, 1990; Christensen *et al.*, 2008; Xu *et al.*, 2011; Jordán *et al.*, 2014; Wu *et al.*, 2016; Christensen and Walters, 2024). The MTI was calculated from a predator-prey matrix within an $n \times n$ dimension, where element 1 (i) and (j) represent the interaction between the impacting group i and the impacted group j . The MTI was expressed mathematically with the following equation:

$$MTI = DC_{ij} - FC_{ij}$$

where, DC_{ij} represents the number of prey j (in weight) present in the diet of predator i . The variable FC_{ij} quantifies the impact of predator i on prey j , taking into account the proportion of total predation of i on their prey j within the system (Christensen and Walters, 2024).

Results

Validating the model

In the Ecopath models, the initial validation procedure is typically conducted by assessing the value of EE generated by each functional group, determining whether the value is less than one. On the contrary, functional group that has EE more than 1, indicated that their predation is very high, thus affecting the sustainability of the group (Kavanagh *et al.*, 2004; Christensen and Walters, 2024). The results of the Ecopath models indicate that a number of functional groups, including fish, cephalopods, lobster and crabs, have an EE value exceeding 0.9 (Table 3).

Trophic structure

The trophic structure of the coral reef ecosystem in the coastal area of Ternate Island was predicted using the Ecopath routine, through the weight-average of prey trophic level, which varied from 1.0 for primary producers and detritus to 3.81 (i.e. family Synodontidae) for the top predator (Figure 2 and Table 4). The Ecopath analysis yielded six effective trophic groups (Table 4) in the coral reef ecosystem at the coastal area of Ternate Island. The majority of fish biomass and ecological production are concentrated at trophic levels II and III (Table 3 and Figure 2). The primary producers in trophic level I are phytoplankton and detritus. The results of the analysis demonstrate that the largest energy flow from producers to consumers in the coral reef ecosystem at the coastal area of Ternate Island originates from zooplankton and benthic organisms in trophic level II (Figure 2), followed by phytoplankton at the trophic level I, which serves as the primary producer. This illustrates the significance of the presence of zooplankton and benthic organisms within the trophic network in the coastal area of Ternate Island.

Transfer Efficiencies

The transfer efficiency of the coral reef ecosystem at the coastal area of Ternate Island is predominantly derived from detritus organisms (13.97%), in comparison to that derived from phytoplankton as the primary producer (6.05%). This highlights the pivotal role of detritus organisms within the system (Table 5). The geometric mean transfer efficiency for the entire system was 4.50% (Table 5). The transfer efficiency in the coral reef ecosystem at the coastal area of Ternate Island was conducted across six trophic levels (Figure 3).

Table 3. The data inputs and outputs for trophic modelling in the coastal area of Ternate Island, along with the baseline estimates obtained following model balancing through the automation procedure in Ecopath.

Group No.	Group name	Trophic level	Habitat area	Biomass (t km ⁻²)	P/B (year ⁻¹)	Q/B (year ⁻¹)	EE	P/Q
1	Achanturidae	2.92	1	3.1910	0.6708	10.6170	0.1983	0.0632
2	Caesionidae	3.00	1	1.1430	0.7690	4.6110	0.9500	0.1668
3	Carangidae	3.59	1	5.8488	0.8238	4.5250	0.0024	0.1821
4	Dasyatidae	2.97	1	0.1914	0.1880	2.6950	0.0000	0.0698
5	Diodontidae	3.07	1	0.0114	1.2250	4.2480	0.0000	0.2884
6	Haemmulidae	3.02	1	0.5964	0.8322	4.7480	0.9500	0.1753
7	Hemiscyllidae	3.39	1	0.0206	0.7130	23.3600	0.0000	0.0305
8	Labridae	3.03	1	4.9248	0.6232	6.4970	0.0059	0.0959
9	Lethrinidae	3.07	1	1.2266	0.9000	4.7650	0.9500	0.1889
10	Lutjanidae	3.12	1	5.1298	0.9263	8.3350	0.0533	0.1111
11	Monacanthidae	2.80	1	0.0083	2.7625	19.6640	0.0000	0.1405
12	Mullidae	3.00	1	0.0261	0.7625	4.7650	0.9500	0.1600
13	Muraenidae	3.20	1	0.5435	0.2750	0.8110	0.0000	0.3391
14	Ostracidae	2.94	1	0.0139	1.5125	4.7450	0.0000	0.3188
15	Pempheridae	3.00	1	0.0139	2.0000	51.3450	0.9500	0.0390
16	Pomacanthidae	2.86	1	0.0274	1.0830	4.2660	0.0000	0.2539
17	Pomacentridae	2.64	1	0.0104	2.4656	21.7750	0.9500	0.1132
18	Scaridae	2.48	1	2.2090	1.1159	14.4560	0.6276	0.0772
19	Scorpaenidae	3.60	1	0.0221	1.2880	3.6930	0.0000	0.3488
20	Serranidae	3.67	1	2.8188	0.8000	4.8660	0.0244	0.1644
21	Siganidae	2.31	1	1.2145	1.0463	14.6480	0.0828	0.0714
22	Synodontidae	3.81	1	0.0283	1.4125	5.3350	0.0000	0.2648
23	Tetraodontidae	2.93	1	0.0092	1.5000	4.2260	0.0000	0.3549
24	Cephalopoda	2.46	1	0.2340	4.6370	36.5000	0.9500	0.1270
25	Palinuridae (lobster)	2.80	1	0.3013	0.9100	6.0670	0.9700	0.1500
26	Portunidae (crabs)	2.66	1	0.0182	6.4100	8.5000	0.7800	0.7541
27	Benthos	2.00	1	0.2930	6.5700	27.4000	0.0108	0.2398
28	Zooplankton	2.00	1	10.0000	21.7600	119.7000	0.9469	0.1818
29	Phytoplankton	1.00	1	60.5608	95.7180	-	0.2093	-
30	Detritus	1.00	1	14.0710	-	-	0.0069	-

Table 4. The relative flows (t km⁻² year⁻¹) of each group by trophic level in the coral reef ecosystem at the coastal area of Ternate Island.

Group \ Trophic level	I	II	III	IV	V	VI
1 Achanturidae		0.1731	0.7380	0.0889		
2 Caesionidae			1.0000			
3 Carangidae			0.4139	0.5799	0.0061	0.0001
4 Dasyatidae		0.2143	0.6063	0.1794		
5 Diodontidae			0.9271	0.0712	0.0015	0.0001
6 Haemmulidae			0.9786	0.0213	0.0001	
7 Hemiscyllidae			0.6163	0.3760	0.0071	0.0007
8 Labridae			0.9688	0.0311	0.0002	
9 Lethrinidae			0.9370	0.0574	0.0056	
10 Lutjanidae		0.0066	0.8724	0.1155	0.0053	0.0001
11 Monacanthidae		0.2600	0.6756	0.0644		
12 Mullidae		0.0110	0.9777	0.0113		
13 Muraenidae			0.8026	0.1916	0.0056	0.0002
14 Ostraciidae		0.0600	0.9400			
15 Pempheridae			1.0000			
16 Pomacanthidae		0.1385	0.8615			
17 Pomacentridae		0.3557	0.6443			
18 Scaridae		0.5200	0.4800			
19 Scorpaenidae			0.4049	0.5862	0.0081	0.0008
20 Serranidae		0.0471	0.2414	0.7037	0.0074	0.0004
21 Siganiidae		0.6874	0.3126			
22 Synodontidae			0.2257	0.7435	0.0293	0.0015
23 Tetraodontidae		0.0780	0.9174	0.0046		
24 Cephalopoda		0.6570	0.2239	0.1191		
25 Palinuridae (lobster)		0.1990	0.8010			
26 Portunidae (crabs)		0.3400	0.6600			
27 Benthos		1.0000				
28 Zooplankton		1.0000				
29 Phytoplankton	1.0000					
30 Detritus	1.0000					

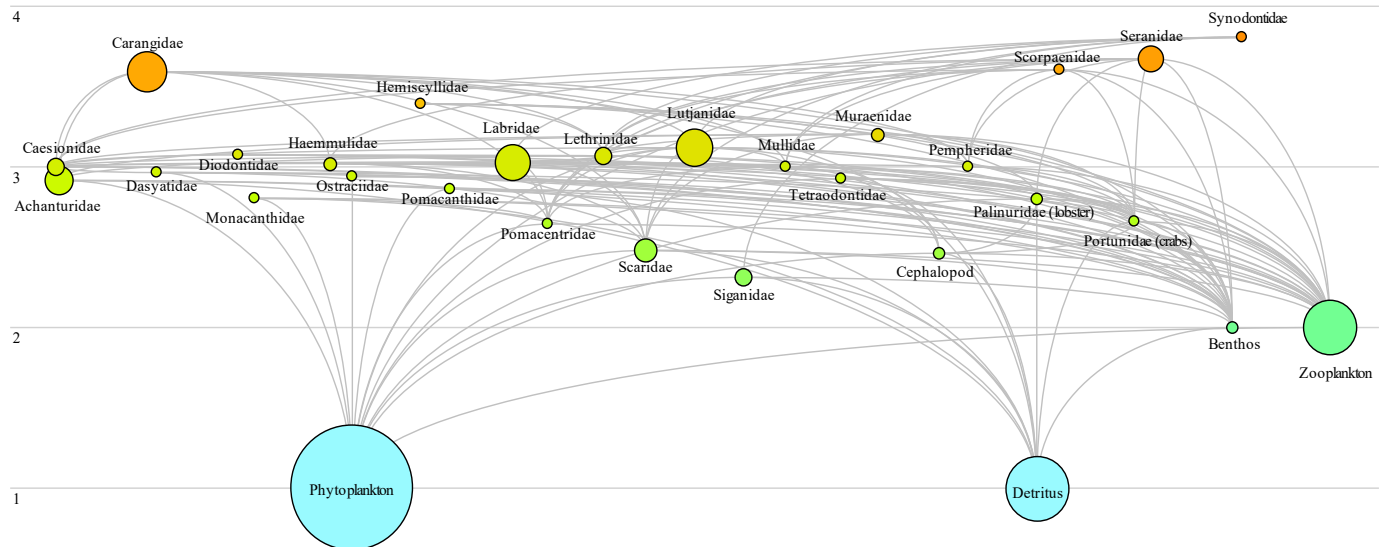


Figure 2. Diagram of trophic networks in coral reef ecosystems in the coastal area of Ternate Island. Trophic levels are shown on the y-axis. The size of the circles represents the proportion of log B (Biomass) values of each functional group.

Table 5. The flows ($t\ km^{-2}\ r^{-1}$) and transfer efficiencies (%) for each trophic level of the coral reef ecosystem at the coastal area of Ternate Island.

Trophic level \ Flow	Consumption by predators	Export	Flow to detritus	Respiration	Throughput		
Trophic level flows from primary producers							
VII	0.0000	0.0000	0.0000	0.0000	0.0000		
VI	0.0000	0.0000	0.0015	0.0028	0.0043		
V	0.0043	0.0004	0.0929	0.1691	0.2667		
IV	0.2645	0.0252	6.7519	12.4060	19.4480		
III	19.2750	0.0515	26.2250	64.2760	109.8300		
II	92.9070	0.0604	255.0700	751.6500	1099.7000		
I	1213.3000	0.0000	4583.4000	0.0000	5796.8000		
Sum	1325.8000	0.1375	4871.6000	828.5100	7026.0000		
Trophic level flows from detritus							
VII	0.0000	0.0000	0.0000	0.0000	0.0000		
VI	0.0000	0.0000	0.0035	0.0067	0.0102		
V	0.0102	0.0002	0.0874	0.1814	0.2792		
IV	0.2741	0.0298	5.6293	10.8000	16.7330		
III	16.6180	0.0606	15.2270	37.9010	69.8070		
II	54.9110	0.0467	9.5627	22.8750	87.3960		
I	33.6220	4868.5000	0.0000	0.0000	4902.1000		
Sum	105.4400	4868.6000	30.5100	71.7640	5076.3000		
Transfer efficiency (%) by trophic level							
Source \ Trophic level	I	II	III	IV	V	VI	VII
Producers		8.4540	17.5970	1.4897	1.7699	0.4587	
Detritus		62.8840	23.8920	1.8160	3.7239	0.4535	
All flows		12.4610	20.0440	1.6406	2.7692	0.4550	
Proportion of total flow originating from detritus: 0.42							
Transfer efficiency (calculated as geometric mean for TL II-IV)							
- From primary producers: 6.0516%							
- From detritus: 13.973%							
Total: 7.4276%							

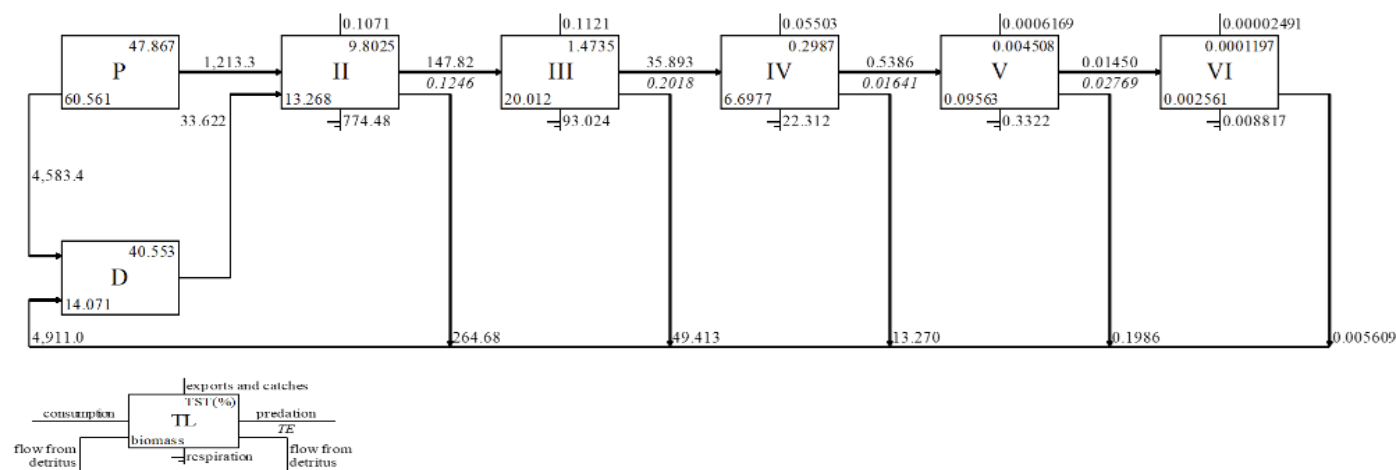


Figure 3. Lindeman spine of the flow network of organic matter and the transfer efficiency (%) from each trophic level in the coral reef ecosystem at the coastal area of Ternate Island. The flow is derived from primary producers (P) and detritus (D). Arrows indicating the trophic level represent export, whereas downward arrows represent respiration.

Mixed trophic impacts (MTI)

The Ecopath models were employed to assess the MTIs utilising the network analysis routine, with the objective of discerning the impact of predation and fisheries activity on the food chain within the coral reef ecosystem at the coastal area of Ternate Island. The findings indicated that fishing activity, specifically hand line, exerted a detrimental influence on the functional groups belonging to the families Siganidae, Carangidae, and Serranidae (MTI = -0.538, -0.472, and -0.470, respectively). The indirect impact on functional groups from the families Haemulidae, Pempheridae, Mullidae, Lutjanidae, Palinuridae, and Achanturidae (Figure 4) was positive, with MTI values of 0.485, 0.440, 0.414, 0.381, 0.328, and 0.244, respectively. This was due to the extraction of their predators.

Meanwhile, based on the predation data, the functional groups that have the most significant impact on other groups are the family Synodontidae (MTI = -0.805) and the family Labridae (MTI = -0.606), followed by the family Serranidae (MTI = -0.498) and the family Haemulidae (MTI = -0.396), the family Achanturidae (MTI = -0.482), the family Caesionidae (MTI = -0.465), and finally, the family Scaridae (MTI = -0.505), all of which impact other groups in the system. Furthermore, the Carangidae have the greatest impact on the Lutjanidae (MTI = -0.565), the Lutjanidae have the greatest impact on the Scaridae and cephalopods (MTI = -0.551 and -0.505, respectively), the Carangidae have the greatest impact on the Pempheridae and Achanturidae (MTI = -

0.498 and -0.482, respectively) (Figure 4). It is also important to consider the impact of predation among groups.

Summary of system statistics

The summary of system statistics from Ecopath models for the coral reef fishery in the coastal area of Ternate Island is shown in Table 6. The model showed that of the total system throughput of 12,102.30 t km⁻² year⁻¹, 11.83% was due to consumption (1,431.21 t km⁻² year⁻¹) and 7.44% was due to respiration (900.27 t km⁻² year⁻¹). Meanwhile, 40.51% was due to detritus (4,902.09 t km⁻² year⁻¹) and 40.23% to exports (4,868.74 t km⁻² year⁻¹). The sum of all production was 6,041.45 t km⁻² year⁻¹. The value of total system throughput described the "size of the whole system in terms of flow" (Ulanowicz, 1986).

The calculated net primary production was 5,796.76 t km⁻² year⁻¹, where the ratio of total primary production (TPP) to total respiration (TR) was 6.44, and the ratio of total primary production to total biomass was 57.60. The mean trophic level of the catch was 2.82, reflecting the fact that the fishery is mainly targeting predators. This result is higher than the average estimated trophic level of the catch for global coastal and reef systems (2.5) (Pauly and Christensen, 1995). The calculated net primary production to sustain the system at Ternate Island was 5,796.76 ton km⁻² year⁻¹.

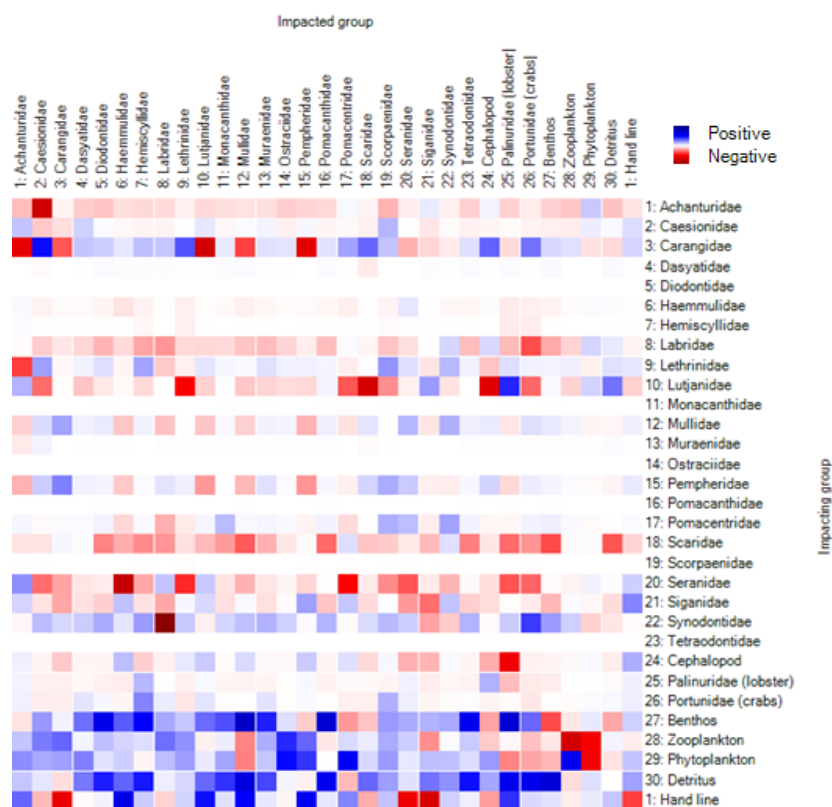


Figure 4. Mixed trophic impact diagram of all functional groups within the Ecopath models, showing the impact of one group on another in the trophic interaction of the coral reef ecosystem in the coastal area of Ternate Island. The y-axis represents the impacting groups and the x-axis represents the impacted groups. The colour gradient shows the influence received by the impacted groups. The blue colours represent positive impacts, while the red colours represent negative impacts. The darkness of the colours indicates the extent of the impact (darker colours mean more affected). The impacts are relative, but comparable between groups.

Table 6. Summary statistics of the trophic model for coral reef ecosystem in the coastal area of Ternate Island.

Parameters	Value	Unit
Sum of all consumption	1,431.21	t·km ⁻² ·year ⁻¹
Sum of all exports	4,868.74	t·km ⁻² ·year ⁻¹
Sum of all respiratory flows	900.27	t·km ⁻² ·year ⁻¹
Sum of all flows into detritus	4,902.09	t·km ⁻² ·year ⁻¹
Total system throughput	12,102.30	t·km ⁻² ·year ⁻¹
Sum of all production	6,041.45	t·km ⁻² ·year ⁻¹
Mean trophic level of the catch	2.82	
Gross efficiency (catch/net p.p.)	0.000047	
Calculated total net primary production	5,796.76	t·km ⁻² ·year ⁻¹
Total primary production/total respiration	6.44	
Net system production	4,896.49	t·km ⁻² ·year ⁻¹
Total primary production/total biomass	57.60	
Total biomass/total throughput	0.01	year ⁻¹
Total biomass (excluding detritus)	100.64	t·km ⁻²
Total catch	0.27	t·km ⁻² ·year ⁻¹
Connectance Index	0.17	
System Omnivory Index	0.15	
Ecopath pedigree index	0.49	
Measure of fit, t*	2.90	
Shannon diversity index	1.59	

Discussion

The research revealed that the functional groups of organisms within the coral reef ecosystem in the coastal region of Ternate Island exhibited trophic level I to III, with the majority of functional groups occupying trophic level II and III (Table 1). The primary producers within the food web of the coral reef ecosystem along the coast of Ternate Island are at the first trophic level, which is dominated by the functional groups of phytoplankton and detritus. The results of the analysis demonstrated that the primary source of energy was derived from zooplankton and benthos organisms at trophic level II (Figure 2), followed by phytoplankton groups at trophic level I. This highlights the significance of the presence of zooplankton and benthos organisms within the trophic network of the coastal ecosystem of Ternate Island. The majority of biological interactions between different trophic levels or between reproductive populations in aquatic ecosystems occur at the individual level (Sanvicente-Añorve and Alatorre-Mendieta, 2018).

Predatory functional groups are typically found at trophic levels III and II, whereas the organisms targeted by reef fisheries activities on the coast of Ternate Island are predominantly at trophic level III, including the Caesinodae family group (TL = 3), Carangidae (TL = 3.59), Lethrinidae (TL = 3.07), Lutjanidae (TL = 3.12), and Serranidae (TL = 3.67). The family group Siganidae, Cephalopoda, Palinuridae (lobster), and Portunidae (crab) are also the target of capture. They are groups of organisms that are at trophic level II. This indicates that the food web of coral reef ecosystems in the coastal area of Ternate Island is primarily composed of organisms at lower trophic levels. These groups are subject to high levels of predation and fishing pressure in coral reef ecosystem in the coastal areas of Ternate Island (Ullah *et al.*, 2012; Dewi *et al.*, 2018).

As with all living organisms, zooplankton are confronted with the fundamental problems of capturing prey, avoiding predation and finding mates. To illustrate, organisms that await their prey will have a diminished likelihood of locating food sources relative to mobile organisms. However, the process of pursuing prey subjects these organisms to elevated predation risks (Visser, 2007). Menden-Deuer and Kiørboe (2016) posited that global-scale biological processes in the open ocean are driven by microscopic plankton. Marine microbes are the biological engines behind the majority of oceanic geochemical processes, including vertical material

transport and carbon sequestration. Plankton biomass provides a resource for higher trophic levels that support fisheries.

Transfer efficiency declines from trophic level III (1.48%), IV (0.30%), to V and VI (0.0%). These decreases can be ascribed to the decline in biomass of organisms across each trophic level. The transfer efficiency for trophic level II, as proposed by Ryther (1969), was 15% for coastal zones. However, it is commonly observed to range between 10 and 20% (Xu *et al.*, 2011; Ullah *et al.*, 2012). The transfer efficiency for trophic level II was found to be 12.46% (Table 5), indicating that the coastal area of Ternate Island has already reached the standard for transfer efficiency for trophic level II. Conversely, the transfer efficiency for trophic level III (20.04%) is higher than the standard value previously mentioned. This is due to the high energy transfer in trophic level III (see Table 4). Furthermore, the presence of the majority of functional groups with elevated EE values at the trophic level III may serve as the foundation for a high transfer efficiency at this trophic level.

In many marine systems, feeding is highly size-dependent, with large individuals occupying a high trophic level in the food chain (Jennings *et al.*, 2001a; Nash and Graham, 2016). The decline in mean trophic levels in tropical coral reef ecosystems may be attributed to a number of factors, including ambiguous, non-selective fisheries (Mangi *et al.*, 2007), the predation of larger species at lower trophic levels, such as parrotfishes (Scaridae family), and the complexity of trophic cascades based on the exploration rates of predatory groups on coral reefs (Salomon *et al.*, 2011; Nash and Graham, 2016). The presence of predator organisms in natural systems alters food web interactions not only through predatory behavioural mechanisms (Werner and Peacor, 2003; Mooney *et al.*, 2010), but also through consumption (predation). Predator groups can play a significant role in ecosystem processes, particularly when primary consumers are confronted with a multitude of predator groups (Zhang *et al.*, 2004; Jabiol *et al.*, 2013; Ng *et al.*, 2021; Tengvall *et al.*, 2024).

The concept of mixed trophic impact (MTI) provides a framework for understanding the ways in which any particular group (including fishing fleets) exerts influence over all other groups within an ecosystem in terms of trophic relationships. The MTI concept encompasses both direct and indirect impacts, which may be predatory or competitive in nature (Christensen and Walters, 2024). The MTI analysis allows for the quantification of the combined effects of direct and indirect trophic interactions

among groups. It quantifies the impact of a change in the biomass of one component on other components of the ecosystem (Ulanowicz and Puccia, 1990; Ruzicka *et al.*, 2024).

The MTI result for the coral reef ecosystem at the coastal area of Ternate Island indicates that the majority of groups have a detrimental impact on themselves, which is interpreted here as reflecting increased within-group competition for resources (Christensen *et al.*, 2008; Mohamed *et al.*, 2008; Ullah *et al.*, 2012). As a consequence of predation, some species are compelled to reach the "minimum safe level" in their life span, the requisite level of which is contingent upon the properties of the ecosystem, which are subject to change over time. These properties include the abundance of predator species and the availability of food resources (Dickey-Collas *et al.*, 2014). MTI is a tool that allows the direct or indirect observation (including competition) of a steady-state system. It is not designed to predict the future behaviour of a system in which interactions have been altered. The primary rationale for this is that alterations in abundance can be directed towards modifications in dietary composition, which are not amenable to calculation through MTI analysis (Christensen *et al.*, 2008; Christensen and Walters, 2024).

The modelling results demonstrate that fishing activities in coral reef ecosystems in the coastal areas of Ternate Island utilizing handline fishing gear have a detrimental impact on multiple functional groups that are targeted for capture (Figure 4). However, this has the indirect effect of positively impacting functional groups that become prey for the captured groups. While fishing activities targeting specific species and sizes will result in a reduction in fish biomass rather than abundance per unit area, this will demonstrate the impact of fishing on biomass rather than abundance (Nash and Graham, 2016; Rumagia *et al.*, 2021).

Serajuddin *et al.* (2018) proposed that marine fisheries management must be based on population subdivisions into smaller biological units or stocks. Stock-specific fisheries management encompasses the identification of discrete stocks, their growth, recruitment, and mortality, among other factors. This is conducted on a large scale with the objective of ensuring the sustainability of a population while maximizing its harvest. Information pertaining to morphological, physiological and behavioural variability, in addition to parasite distributions and otolith elemental composition, offers insights into the structure of a given stock. The composition of fish stocks is undergoing alteration as a consequence

of both natural and anthropogenic activities. It is therefore evident that the conservation of fish stocks is of paramount importance for the implementation of appropriate management strategies through the implementation of different stocking strategies.

The summary of system statistics from Ecopath models for coral reef fisheries at the coastal area of Ternate Island (Table 6) demonstrates that the total system throughput from this study is significantly higher than that observed in other ecosystem models using Ecopath in Indonesia. For instance, the study by Dewi (2018) in the Tangerang coastal area of the Western Java Island reported a total system throughput of 34,850.961 ton km⁻² year⁻¹, which is almost three times higher than the value observed in our system. The discrepancy can be attributed to the differing sizes of the research areas and the types of fishing gear employed in the studies, as well as the functional groupings used in the models. The study area covered 143.5 km² of hand line gear and comprised 30 functional groups. In comparison, Dewi (2018) conducted their research in a trawl sweep area of 305.92 km², comprising 42 functional groups.

The ratio of total primary production (TPP) to total respiration (TR) shows that the coastal ecosystem of Ternate Island was in the developmental state (Christensen, 1995). The ratio of TPP/TR represents a crucial indicator of system maturity. A ratio greater than 1 is anticipated during the initial stages of an ecosystem's development, whereas in mature systems, it should approach 1 (Christensen *et al.*, 2008). The value of TPP/TR obtained in this study is evidently greater than 1. The determination of ecosystem maturity is a challenging process, as it is contingent upon a multitude of variables, including biomass, the number of functional groups, and the interactions between them (Vilalta-Navas *et al.*, 2018). Nevertheless, the maturity of an ecosystem can be gauged through parameters such as the primary production/respiration ratio (P/R), which tends towards zero in mature ecosystems, the CI or the total flows of the system (Christensen, 1995).

The mean trophic level of the catch (2.82) is similar in value to that observed in the Tangerang coastal system (2.78) (Dewi, 2018), as well as in ecosystem models of Jurien Bay Marine Park in Western Australia (2.9) (Lazano-Montes *et al.*, 2011). However, it is higher than that recorded in other ecosystem models, including those of Galápagos rocky reef systems (2.27) (Okey *et al.*, 2004), the rocky coastal ecosystem in Bahía Tortugas, Mexico (Morales-Zárate *et al.*, 2011), the Bay of Bengal, India

(Ullah *et al.*, 2012), and the Lidao artificial reef in the Shandong Peninsula of China (Wu *et al.*, 2016) exhibited similar values. Conversely, the outcome was found to be lower than that of other ecosystem models, as evidenced by the findings of Mohamed *et al.* (2008) in the Karnataka Arabian Sea (3.04), East Brazil large marine ecosystem within mean trophic level of 3.4 (Freire *et al.*, 2008), the coral reef ecosystem at the Eritrean Red Sea coast was found to have a mean trophic level of 3.84 (Tsehaye and Nagelkerke, 2008). Similarly, the Gulf of Cadiz ecosystem at south-western Spain exhibited a mean trophic level of 3.32 (Torres *et al.*, 2013), while the North-west Mediterranean Sea demonstrated a mean trophic level of 3.13 (Corrales *et al.*, 2015). The mean trophic level of the catch serves as a crucial indicator of the overall level of exploitation of fish groups situated at the lower levels of the food web, and its impact on predator and prey species (Ullah *et al.*, 2012). The question thus arises as to whether the decline in global mean trophic levels of catches is a consequence of fishing down the marine food web, whereby fishing fleets increasingly target species low in the food web (Ruzicka *et al.*, 2024). The lower value assumes that lower-order invertebrate consumers are significant components of the fisheries, particularly in the coral reef fisheries in the coastal area of Ternate Island, where they are primarily targeted (Ahmad *et al.*, 2020).

The gross efficiency of the fishery exhibited considerable variation between different systems. Systems with a fishery harvesting fish at the lower levels of the food chain (e.g., an upwelling fishery) demonstrated higher values than those whose fisheries concentrated on apex predators (e.g., oceanic tuna fisheries) (Ullah *et al.*, 2012). The gross efficiency of the fishery was defined as the ratio of catch to primary productivity (Christensen *et al.*, 2008) and was found to be 0.000047 (Table 6), indicating that the fishery may play a significant role in structuring the ecosystem due to its targeting of a majority of predator fish species. It should be noted, however, that this estimate was based solely on official statistics, which are presumed to be significantly lower than the actual yield of the fishing activity in the coastal area of Ternate Island.

The connectivity index (CI) and system omnivory index (SOI) were found to be 0.17 and 0.15, respectively. Furthermore, the CI is employed as an indicator of the maturity and stability of an ecosystem (Vilalta-Navas *et al.*, 2018). In our model, the ecosystem exhibits a CI value of 0.17, indicating that only 17% of potential ecosystem connections have been established (Table 6). The connectance index is

defined for a given food web as the ratio of the number of actual links to the number of possible links. The act of feeding on detritus (performed by detritivores) is included in the count, but the opposite links (i.e. detritus "feeding" on other groups) are disregarded (Christensen and Walters, 2024). Coll *et al.* (2009) posited that as ecosystems develop, their biomass, information, and complexity tend to increase. Conversely, when ecosystems are perturbed, for example, by fishing, these trends reverse. In order to contextualise ecosystem development, it is possible to compare indicators across different modelled systems or to compare them within the same system at different time points. Such indicators include a variety of coefficients pertaining to flows and biomasses, such as total primary production/total respiration and total biomass/total production. Additionally, there are nutrient recycling indexes, such as Finn's cycling index and predatory cycling index, as well as the SOI and indices related to the information theory of Ulanowicz (1986).

Conclusion

The coral reef ecosystem at the coastal area of Ternate Island was characterized by a low trophic level system, with zooplankton and benthic organisms playing a significant role in maintaining the ecosystem. The fishery activity is focused on a limited range of target species, due to the lack of diversity in fishing gear employed. A series of system attribute parameters indicated that the ecosystem exhibited a relatively low level of maturity, stability, and disturbance resistance, and was thus classified as a developing system. In general, this model provided information about the coral reef ecosystem properties based on their trophic interaction in the eastern part of Indonesia, especially in North Maluku Province, using the Ecopath model. This may lead to further research that can be compared with the findings of this study.

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