Indian J. Fish., 67(3): 39-51, 2020
DOI: 10.21077/ijf.2020.67.3.88300-05

Ecopath modelling approach for the impact assessment of a small-scale coastal aquaculture system in Goa, India

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ABSTRACT

In this study, the ecological impacts of introduction of cage aquaculture employing small cages integrating shellfish and finfish in coastal water bodies of Goa, situated in the west coast of India were analysed using Ecopath with Ecosim model. A multispecies cage aquaculture system incorporating *Lutjanus argentimaculatus, Etroplus suratensis* and *Perna viridis* was established in an estuarine ecosystem. The Ecopath model identified 12 functional groups starting from detritus (trophic level=1) to large benthic carnivores (trophic level=3.72). The ecosystem statistics such as total system throughput (8672 g m^{-2} $year^{-1}$), gross efficiency (0.001), primary production/respiration (1.4), net system production (1028.2 g m^{-2} $year^{-1}$) and system omnivory index (0.26) indicated that the ecosystem was highly productive and in a developing stage. With a medium rate of recycling (Finn's Cycling Index=11.7%), high system throughput, high system overhead (79%) and moderate omnivory index (0.26), the food web was found to be immature having an organised trophic network with high production. Simulations of the various expanding scenarios for the cage culture within the ecosystem were explored using Ecosim. A scenario in which two cages each for pearlspot and red snapper and 20 mussel ropes was identified as a sustainable solution without sacrificing the threshold biomass for the functional groups of fish species. The study provided useful insights and methodology towards assessing aquaculture in coastal ecosystems in terms of ecosystem structure and function.

Keywords: Coastal cages, Ecopath with Ecosim model, Ecosystem impacts, Estuarine, Multispecies, Simulation

Introduction

The culture of aquatic organisms in inshore waters influenced by the sea, the water area and bathymetry extending to edge of the continental shelf is popularly known as "coastal aquaculture" (Sorensen *et al.*, 1984). Coastal aquaculture using traditional methods is practiced in about 50,000 ha of low lying coastal waters of Kerala, West Bengal, Karnataka and Goa in India (DAHDF, 2018). The state of Goa has 105 km coastline and a continental shelf area of 10 million ha. The coastal water resources of Goa include 0.013 million ha of estuarine area, 0.018 million ha of *Khazan* wetlands and 0.035 lakh ha of brackishwater, that can be utilised for aquaculture (DoF, 2015). The state's fish production from marine and inland sectors are 1.0 lakh t and 4000 t (brackishwater and freshwater) respectively. Since the last decade, marine fish production of Goa has almost stagnated between 0.8-1.0 lakh t (CMFRI, 2014; DAHDF, 2018). Being a tourist destination and with a predominant fish eating population, both finfish and shellfish have great demand among the local population as well as tourists. The state has enormous scope for developing aquaculture including cage culture, bivalve culture and also integrated farming systems by utilising coastal resources (Mohanta and Subramanian, 2001). Presently in Goa, only very few people are engaged in coastal aquaculture activities, even though there is good potential and technological back up for taking up widespread aquaculture activities.

There is enough scope for diversification in coastal aquaculture in Goa, mainly in *Khazan* lands, called *"Khani"*, which are used for aquaculture with locally popular cultivable species. Water movement in these systems is regulated by sluice gates or *Manas*. Fishing in the semi-enclosed *Khazan* areas is considered as a secondary livelihood activity for the traditional fishermen in Goa. These areas are given on lease to groups of fishermen for a certain period (ranging from 1-5 years) for fishing operations. Fishing in these areas is by means of bag nets which are fixed at the *Manas*, opening during the low tide when the water flows out into the estuary. Multispecies aquaculture is found to be an efficient aquaculture system in the *Khazan* lands of Goa which involves cultivating several species from different trophic levels. This has been suggested as a better choice where sustainability can be achieved in the farming practise, not only in terms of maximising resource utilisation but also in minimising the impacts on the environment (Brzeski and Newkirk, 1997). The most pertinent issue in coastal aquaculture is the accumulation of feed waste and faecal matter, which may create eutrophication in the water body. Therefore, experiments on aquaculture systems should take into account the geological, physico-chemical, biological and ecological assessments. A successful ecosystem-based fisheries approach including aquaculture entails the management of existing living aquatic resources within the ecosystem, where aquaculture is practised (FAO, 1995).

An ecosystem based approach (EBA) in coastal aquaculture should consider the long term impacts on biomass, energy flow and nutrient cycling through aquatic living groups such as plankton, fish, apex predators and benthos. Thus, the EBA approach could ensure a sustainable, healthy and productive system in terms of fisheries, other aquatic resources, ecology and environment. Practicing environmentally safe and ecologically sustainable culture technologies is the need of the hour. However, in Goa, there are no concerted efforts to understand the dynamic interactions and impacts of coastal aquaculture on the ecological structure. This study evaluated the sustainability of a small scale multispecies aquaculture system and attempted to predict the consequences of scaling up of aquaculture activities. The coastal aquaculture considered in this paper was small-scale multispecies coastal cage culture system including shellfish and finfish. Ecopath with Ecosim (EwE) model was applied here to construct a trophic mass-balanced model of the ecosystem, where the aquaculture was experimented and using this model, the consequences of different scales of aquaculture were quantified on the ecological compartments.

Materials and methods

An area of 500 m^2 with in a semi-enclosed coastal water body having an area of 0.028 km^2 in *Khazan* lands of Palyem located in Pernem Taluka of North Goa (15° 43' 01.56" N; 73° 43' 23.83" E) was selected for capture-based multispecies aquaculture with continuous stocking and harvesting for a period of two years from 2013 to 2015 (Fig. 1). This semi-enclosed system is connected to Terekhol, an estuarine system situated at the border of Goa and Maharashtra.

Species and technology selected for aquaculture

Capture based multispecies cage culture of pearlspot (*Etroplus suratensis*) and red snapper (*Lutjanus argentimaculatus*) integrated with green mussel (*Perna viridis*) was considered as an intervention in the semi-enclosed estuarine systems in Goa for which availability of seeds was assured from the same ecosystem. All the three species selected have high market demand in Goa and fetch high retail price in the local market. Redsnapper in the weight range of 0.6 to 0.8 kg and pearlspot (weighing 0.15 to 025 kg) realises a price of ₹400-500 per kg and ₹250-300 per kg respectively, whereas green mussel (50-60 mm size) yields a price of ₹12-15 per individual in the retail markets. A definite number of fish seeds (proportion of biomass) was extracted from the same ecosystem for cage culture (finfish seeds obtained as bycatch during the normal fishing especially during bag net fishing. Mean length: pearlspot - 50 mm, red snapper - 100 mm) and were stocked independently in three cages made of bamboo poles and nylon (cage dimension - 2.0 x 1.5 x 2.0 m), positioned using bamboo poles in the coastal water body. Pearlspot was stocked in two cages at a density of 200 nos. per cage and red snapper in one cage at 100 nos. per cage), for a period of 8-12 months. Green mussels (28-32 mm size) were hung from the bamboo poles (15 ropes of 1 kg each) used for positioning the cages. Red snapper was fed with chopped discards from the bag nets and pearlspot grazed on periphyton from the surface of bamboo splits positioned inside the cage. Being a filter feeder, green mussel consumed phytoplankton available in the culture system.

Data analysis

Using EwE software, a mass-balanced model was constructed, which was further applied for simulations using Ecosim (Christensen and Walters, 2004; Christensen *et al.,* 2005). The model provides a static mass-balanced profile of the ecosystem during the study period. The model describes the equilibrium between biomass flows through production and losses. The model is built on two basic equations for mass balance and energy flows in each functional group as follows:

$$\text{Consumption } (Q_i) = \text{Production } (P_i) + \text{Respiration } (R_i) + \text{Unassimilated food } (U_i) \quad \text{......(1)}$$

$$\text{Production } (P_i) = \text{Catch } (Y_i) + \text{Biomass accumulation } (BA_i) + \text{Predation mortality } (M_{1i}) + \text{Net migration } (E_i) + \text{Other} \quad \text{......(2)}$$

In equation 2, M_{1i}, which corresponds to predation mortality, can be represented as:

$$M_{1i} = \sum_j^n = 1Q_j \times DC_{ji} \quad \text{......(3)}$$

where, Q_j is the consumption rate for predator j and DC_{ji} is the proportion of prey (i) in predator's (j) diet.

The mass-balanced model can be also given by:

$$\left(\frac{P}{B}\right)_i \times B_i \times EE_i = \sum_j^n B_j \times \left(\frac{Q}{B}\right)_j \times DC_{ji} + Y_i + E_i + BA_i \quad \text{......(4)}$$

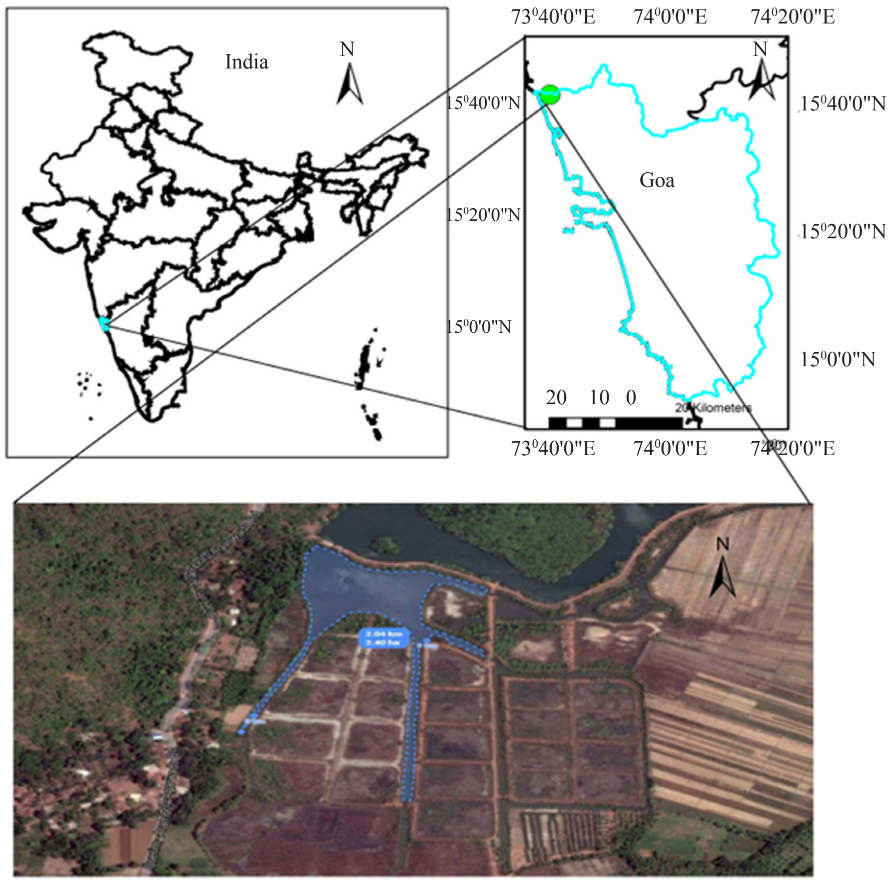

Fig. 1 Site selected for ecosystem modeling

where i is prey and j is predator, $(P/B)_i$ = Production/Biomass , B_i = Prey biomass, EE_i = Ecotrophic efficiency, $Q/B)_j$= Consumption/Biomass, Y_i = Total catch, E_i = Net migration and BA_i = Biomass accumulation.

The functional groups were described after considering the trophic model constructed for Zuari, Sunderbans and Hooghly-Matlah estuaries (Dutta *et al.,* 2017; Rakshit *et al.,* 2017), since there are similarities in the diversity of species collected during this study (Table 1). Among the functional groups, there were nine fishery groups, except plankton and detritus groups, which were exploited by bag nets (Table 1).

Estimates of parameters

The basic data of the functional group (B_i, P/B_i, EE_i *and* Q/B_i), diet composition, growth input data and fishery data (number of seeds extracted from the ecosystem for each unit of the cage) were the input data for the model. After collating the species-wise data, they were compiled for ecological groups by estimating the weighted (biomass) mean values for the groups (Christensen *et al.,* 2005).

Among the ecological groups, the biomass of fishery groups was estimated following the Gulland (1971) method on the basis of catch data. The abundance data collected were used to estimate biomass for zooplankton and phytoplankton. For detritus group, the formula suggested by Christensen and Pauly (1993) was used for the estimation of biomass:

$$\log D = 0.954 \log PP + 0.863 \log E - 2.41 \quad \text{.....................(5)}$$

where D = Biomass of detritus (g C m^{-2}), PP = Primary productivity and E = Depth of euphotic layer (here as 5 m).

In the input data, *P/B* corresponds to total mortality coefficient (*Z*) (Allen, 1971). Therefore, Z values were estimated for various species using catch curve method in FiSAT (Pauly, 1982). Species for which, length-frequency data were not gathered, the estimates available from FishBase (Froese and Pauly, 2015) were used. *Q/B* values were calculated by applying the equation suggested by Pauly *et al.* (1993) and Palomares and Pauly (1998). Equation 6 was used for functional groups that used caudal fin as the organ of propulsion and equation 7 was used for other groups.

Table 1. Ecological groups defined in the Ecopath model

Large benthic carnivores	Red snapper (*L. argentimaculatus*), groupers (*Epinephelus diacanthus, E. coioides*) and seabass (*Lates calcarifer*)
Medium benthic carnivores	Croakers (*Johnieops borneensis, J. sina, Johnius dussumieri, Nibea albida, Paranibea semiluctuosa, Otolithes ruber, O. cuvieri*); catfish (*Arius maculatus, A. subrostratus, A. arius, Netuma thalassina, Plicofollis dussumieri*); silver sillago (*Sillago sihama*) and goat fish (*Upeneus vittatus, U. sulphureus*)
Pelagic carnivores	Full beaks (*Strongylura strongylura*) and half beaks (*Hyporhamphus limbatus, Hemiramphus lutkei*)
Small benthic carnivores	Silverbellies (*Nuchequuela blochii, Eubleekeria splendens, Leiognathus brevirostris, Photopectoralis bindus, Gazza minuta, Secutor insidiator*); silverbiddies (*Gerres filamentosus, G. setifer*); glassfish (*Ambassis ambassis, A. urotaenia*); cardinal fish (*Yarica hyalosoma*); surgeonfish (*Acanthurus dussumieri*); scat (*Scatophagus argus*) and butterfly fish (*Chaetodon collare, Heniochus acuminatus*)
Clupeids and anchovies	White sardine (*Escualosa thoracata*) and anchovies (*Stolephorus commersonii, S. indicus, Thryssa mystax, T. malabarica, T. setirostris, T. balaema*)
Crabs	Mud crab (*Scylla serrata*), three spot swimming crab (*Portunus sanguinolentus*) and other crabs
Shrimps	Penaeid shrimps (*Penaeus merguiensis, Penaeus indicus, P. monodon, P. semiculcatus, Metapenaeus dobsoni, M. monoceros, M. affinis, Parapenaeopsis stylifera, P. hardwickeii, P. cornuta*)
Cichlids and mullets	Tilapia (*Oreochromis mossambicus*); pearlspot (*Etroplus suratensis*) and mullets (*Mugil cephalus, Liza parsia, L. tade, Chelon planiceps, Valamugil cunnesius, V. seheli*))
Benthic macrofauna	Bivalves (*Anadara formosa, Scapharca pilula, Cardium asiaticum, Villorita cyprinoides, Donax scortum, Perna viridis, Placuna placenta, Marcia opima, Meretrix meretix, Paphia textile*); gastropods (*Babylonia spirata, Bursa tuberculata, Hemifusus pugilinus, Nassarius stolatus, Natica picta, Nerita* sp., *Telescopium* sp., *Tibia curta, Trochus radiatus, Turbo brunneus, Turritella* sp.) and insects
Zooplankton	Copepods, Cladocerans, Amphipods, Fish larvae, Polychaete larvae and Molluscan larvae
Phytoplankton and filamentous algae	Blue-green algae, Diatoms, Dinoflagellates, Euglena and Green algae
Detritus	

$$\log\left(\frac{Q}{B}\right) = 7.964-0.204\log(W_\infty)-1.965T+0.083A+0.532h+0.398d \quad \text{.....(6)}$$

$$\frac{Q}{B} = 10^{6.37}\times0.0313^{T}\times W_\infty^{-0.168}\times1.38^{P}\times1.89^{HD} \quad \text{.....(7)}$$

where, W_∞ = Weight asymptote (g), T = Annual mean temperature of the water body, expressed using T = (1000 Kelvin^{-1}) (Kelvin = temperature in °C+273.15), A=Aspect ratio, h (1 for herbivores, 0 for detritivores and carnivores) and d (0 for herbivores and carnivores, 1 for detritivores): Parameters expressing feeding mode, P=Consumer type variable (one for zooplankton feeders/pelagic predators/ apex groups and 0 for other consumer groups). HD = 0 for carnivores and 1 for herbivores and detritivores. The primary data on mean temperature of the water and size and aspect ratios of fish species were collected and wherever necessary, secondary data were also used (Froese and Pauly, 2015).

For zooplankton and phytoplankton, the count for different groups obtained during the standard sampling procedure were converted into g m^{-2} to estimate the biomass. P/B values for zooplankton were calculated from the empirical formula given by Banse and Mosher (1980):

$$\frac{P}{B} = 0.6547 \times w^{-0.37} \quad \text{.....(8)}$$

Q/B values were collected and modified from other published sources (Shetye *et al.,* 2007; Selleslagh *et al*., 2012; Sreekanth *et al.,* 2020). P/B value of phytoplankton was collected and modified from already published sources (Pitcher *et al.,* 2002; Mohamed *et al.,* 2008; Sreekanth *et al.*, 2020). For benthic groups, the total weight of sample was measured and expressed in t km^{-2}. The P/B values for benthic groups were also calculated as per Banse and Mosher (1980). Q/B values for benthos component was collected and modified from other similar Ecopath models

(Pitcher *et al.,* 2002; Mohamed *et al.,* 2008; Sreekanth *et al.,* 2020).

Mass balancing the model

Diet composition for various ecological groups (Table 2) were estimated based on the gut content analysis in this study and also from the secondary sources of information available from Fish Base (Froese and Pauly, 2015). After compiling all the data on various species, they were pooled for ecological groups. With all these inputs, the model was run in the Ecopath routine to achieve mass balance (EE for all groups should be less than unity). Thus, mass balanced model was developed for the period 2013-15 based on PREBAL routine of Ecopath (EE_i which should lie between 0 (indicates that the groups are neither consumed nor exported) and 1(indicates that the group is heavily preyed upon/exploited by fishing). Besides, the value of respiration, R_i should be non-negative and the R/B_i to be proportional to the liveliness of a functional group (high values for smaller sizes). To balance the model, input parameters *B* and *P/B* were modified and adjustments were made in the diet composition without altering the feeding patterns of the ecological groups.

Performance measures

This mass balanced model was used to find out the basic ecosystem indices. To evaluate the features of the ecosystem, indices like eco-trophic efficiency, total system throughput (TST), gross efficiency of the fishery (GE), net primary production (NPP), net system production (NSP), fractional trophic level of ecological groups, system omnivory index (SOI) and detritivory/herbivory ratio (DH) were used. To identify and measure the ecological interactions among the various ecological groups, a sensitivity analysis known as mixed trophic impacts were used. This analysis was carried out to ensure the efficiency of the model to characterise the ecological interactions. To assess the maturity of the system, NSP, Finn's cycling index (FCI), mean path-length, primary production/respiration (PP/R) ratio and system overhead (SO) were used.

Simulation of impacts of coastal aquaculture on ecosystem

The mass balanced ecosystem model for estuary was explored to determine the impacts of increasing coastal aquaculture, mainly in the number of coastal cages, on the biomass of various ecological groups. In the simulation, it was assumed that the collection of fish seed for the culture is from the same ecosystem under consideration. This was carried out by generating different numbers of coastal cages using the time dynamics module of EwE known as Ecosim (Christensen *et al.,* 2005). Ecosim, a time-dynamic model applied for the simulation, uses the differential equations of basic Ecopath as follows:

$$\frac{dB_i}{dt} \quad g_i \sum_j C_{ji} - \sum C_{ij} + I_i - (M_i + F_i + e_i)\, B_i$$

where, *i* is the functional group, dB_i/dt=Rate of change of biomass, g_i= Net growth efficiency, M_i=Other mortality rate, C_{ji} and C_{ij}= Consumption rates, F_i=Fishing mortality coefficient, e_i= Emigration rate and I_i= Immigration rate

To incorporate the prey-predator interactions, a vulnerability setting was assumed for predator-prey dynamics, which described the position of prey group (vulnerable/protected state) in front of their predators (Christensen *et al.,* 2005). The vulnerabilities were estimated using the Ecosim routine with adjustments in forage time and used as an input for Ecosim. The

Table 2. Diet matrix of all ecological groups used as input for Ecopath

Prey/Predator	1	2	3	4	5	6	7	8	9	10
1. Large benthic carnivores										
2. Medium benthic carnivores	0.15	0.04								
3. Pelagic carnivores										
4. Small benthic carnivores	0.30	0.20				0.05				
5. Clupeids and anchovies			0.40			0.03				
6. Crabs	0.24	0.18		0.15						
7. Shrimps	0.17	0.10	0.20	0.08		0.13				
8. Cichlids and mullets	0.04			0.00						
9. Benthic macrofauna	0.05	0.25	0.15	0.58		0.18	0.25	0.03		
10. Zooplankton		0.04	0.20	0.09	0.60	0.09	0.15	0.10	0.10	0.13
11. Phytoplankton and filamentous algae		0.10		0.00	0.30	0.02	0.02	0.62	0.20	0.62
12. Detritus	0.05	0.09	0.05	0.10	0.10	0.50	0.58	0.25	0.70	0.25
13. Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

vulnerability of a group was assigned corresponding to its trophic level in the model. Ecosim assumed default values defined for tropical ecosystems for all other parameter settings (Base proportion of nutrients: 1.000; minimum foraging time: 0.1, maximum relative feeding time: 2.00, feeding time adjustment rate: 0.5, density-dependent catchability: 1.000). Seven scenarios were constructed and simulated with the incremental fishing effort on the selected ecological groups (Table 3). Certain numbers of cages were considered in the seven scenarios and increment fishing mortality was assumed based on the extra biomass extracted from the ecosystem (Table 4). The simulated relative changes in biomass of all the ecological groups were compared under these scenarios to find out an optimal scenario of cage culture. The selection of the optimal scenario was based on the installation of maximum number of cages without reducing the biomass of all ecological groups (of fisheries importance) beyond 50%.

Results and discussion

Ecosystem features and indices

The results of the ecosystem model indicated that, it is a bottom-upregulated system. The final diet matrix used as an input for the Ecopath model is presented in Table 2. Ecotrophic efficiency (EE) values were observed to be within range (<1) for all the ecological groups (Table 5). The values of EE were very high for small benthic carnivores, benthic macrofauna, shrimps and medium benthic carnivores. EE values were high for most of the ecological groups, which implied efficient utilisation

Table 3. Scenarios considered for simulations using Ecosim

Scenario	Red snapper	Pearlspot	Green mussel
Scenario 1	No change in the system	No change in the system	No change in the system
Scenario 2	100 nos. (1 cage)	400 nos. (2 cages)	15 kg
Scenario 3	100 nos. (1 cage)	200 nos. (1 cage)	15 kg
Scenario 4	200 nos. (2 cages)	400 nos. (2 Cages)	20 kg
Scenario 5	300 nos. (3 cages)	800 nos. (4 cages)	30 kg
Scenario 6	200 nos. (2 cages)	200 nos. (2 cages)	15 kg
Scenario 7	400 nos. (4 cages)	800 nos. (4 cages)	40 kg

Table 4. Pattern of fishing mortality in correspondence with the collection of seed/spat for cage culture

Red snapper				
Cage no.	Biomass (kg)	Biomass required for cage	% increase in fishing mortality	Fishing mortality
0	13	0.0	0.00	1.01100
1	13	1.5	11.50	1.12727
2	13	3.0	23.00	1.24353
3	13	4.5	35.00	1.36485
4	13	6.0	46.00	1.47606
6	13	9.0	69.00	1.70859
8	13	12.0	93.00	1.95123
Pearlspot				
0	9	0	0.00	1.7500
1	9	2	22.22	2.1400
2	9	4	44.44	2.5200
4	9	8	88.89	3.3075
6	9	12	133.33	4.0775
8	9	16	177.78	4.8650
Green mussel				
Rope No.	Biomass (kg)	Biomass required for cage	% increase in fishing mortality	Fishing mortality
0	137.75	0	0.00000	0.04730
10	137.75	10	7.25953	0.05075
15	137.75	15	10.8893	0.05250
20	137.75	20	14.5191	0.05449
25	137.75	25	18.1488	0.05581
30	137.75	30	21.7786	0.05760
40	137.75	40	29.0381	0.06104

Table 5. Basic estimates observed after mass balancing the Ecopath (habitat area fraction = 1 for all ecological groups)

S. No.	Group	Trophic level	B (g m^{-2})	P/B (per year)	Q/B (per year)	EE
1	Large benthic carnivores	3.72	0.9	1.1	4.8	0.359
2	Medium benthic carnivores	3.281	2.9	0.96	7.8	0.903
3	Pelagic carnivores	3.363	2	0.82	3.8	0.065
4	Small benthic carnivores	3.114	22.2	3.3	9.5	0.999
5	Clupeids and anchovies	2.69	11.6	4.5	14.4	0.837
6	Crabs	2.649	11.9	8.1	110	0.395
7	Shrimps	2.451	20.1	6.8	20.5	0.946
8	Cichlids and mullets	2.148	0.6	5.1	6.5	0.4
9	Benthic macrofauna	2.115	22.8	11.1	60	0.983
10	Zooplankton	2.149	12.3	90	280	0.716
11	Phytoplankton and filamentous algae	1	20.5	195	0	0.556
12	Detritus	1	30.2			0.706

P/B: Production/Biomass, *Q/B:* Consumption/Biomass, *EE*: Ecotrophic efficiency

Table 6. Summary statistics and flow indices for the ecosystem

Parameter	Value	Units
Sum of all consumption	3799.47	g m^{-2} year^{-1}
Total system throughput	8672.1	g m^{-2} year^{-1}
Sum of all production	3682.37	g m^{-2} year^{-1}
Mean trophic level of the catch	2.6	
Gross efficiency (Catch/Net primary production)	0.001	
Calculated total net primary production	4046.25	g m^{-2} year^{-1}
Total primary production/Total respiration	1.4	
Net system production	1028.2	g m^{-2} year^{-1}
Total primary production/Total biomass	25.61	
Total catch	7.4	g m^{-2} year^{-1}
System omnivory index	0.26	
Finn's cycling Index	11.7	
Mean path length	3.2	
Detritivory/Herbivory ratio	1.04	
Ascendency (%)	20.7	
Overhead (%)	79.3	

of these groups in the ecosystem and reduced flows to detritus (Table 5). The basic ecosystem statistics of the system is displayed in Table 6.

The value of total system throughput (TST) was very high (8672 g m^{-2} year^{-1}), which indicated a high turnover of the small sized tropical ecosystem (Table 6). The trophic levels ranged from 1 (phytoplankton and filamentous algae) to 3.7 (large benthic carnivores) and the average trophic level of the catch was 2.6. For the present ecosystem, gross efficiency of the fishery was high (0.001) indicating that majority of the harvested fishes were in the lower trophic levels in the food chain (Table 6).

The ratio PP/R will approach one in a mature ecosystem and the value was more than unity (1.4) in this system, which identified the immature stature and small size of the system (Table 6). NSP, the difference between primary production and respiration will be larger in immature systems and close to zero in mature stems. A value of 1028.3 g m^{-2} year^{-1} for NSP indicated the developing nature of the ecosystem (Table 6). The ratio of total primary production and biomass represents an index of maturity (lower values denote matured systems) and here, the value was 25.6. The value was comparatively high and represented the immature nature of the system (Table 6).

SOI is the weighted (food intake of the individual consumer group) average omnivory index of the consumer groups in the system and the index provides the complexity of feeding interactions between trophic levels (Christensen *et al.,* 2005). The value for this index was 0.26, which showed that feeding interactions among the ecological groups were significant (Table 6). The predation mortality rates stood higher than fishing mortality for shrimps, clupeids and anchovies, small benthic carnivores and crabs. Thus, the patterns in predation show that the other predatory groups exert immense pressure on former groups.

Individual omnivory index (OI) of a consumer is estimated as the variance of trophic levels of its prey groups. If a consumer feeds on a single trophic level, its OI will be zero and a large value for the index shows it preys on various trophic levels. The maximum OI was observed for medium benthic carnivores, crabs, clupeids and anchovies and shrimps. The minimum values were observed for benthic macrofauna, cichlids and mullets, pelagic carnivores and small benthic carnivores. Highly specialised feeding was observed for cichlids and mullets and pelagic carnivores (Table 7). Among the fishery groups, cichlids and mullets, small benthic carnivores and shrimps displayed the highest values of net efficiency, whereas crabs, medium benthic carnivores and benthic macrofauna showed the lowest values of net efficiency (Table 7).

Network analysis

Finn's cycling index (FCI), the amount of recycling of a fraction of TST in an ecosystem, is an important index to show the maturity status of the system (Odum, 1969; Finn, 1976). Mean path length (MPL) is also applied as an ecosystem maturity index (Finn, 1980). FCI and MPL increase with the maturity of the system. In this study, FCI and MPL estimated were 11.7% and 3.2, respectively (Table 6). The detritivory/herbivory ratio and mean system transfer efficiency were 1.04 and 10.6% respectively.

Mixed trophic impact

The mixed trophic impact is a type of sensitivity analysis, which helps to measure the total (direct and indirect) interactions between functional groups and impacts of fishing (Christensen and Pauly, 1992). As per this analysis, an increase in the biomass of phytoplankton and filamentous algae indicated positive impacts on the zooplankton and groups feeding on phytoplankton such as clupeids and anchovies and cichlids and mullets (Fig. 2 and 3). The increase in detritus biomass will augment the biomass of crabs. The increase in zooplankton biomass will reduce the primary producer biomass. Similarly, the increase in crab biomass will reduce the abundance of shrimps, clupeids and anchovies as well as small benthic carnivores. The increase in biomass for small benthic carnivores will deplete crabs significantly (crabs being their common prey group) and thus, it will indirectly increase the biomass of clupeids and anchovies and shrimps. Increase in fishing effort will have negative impacts on the biomass of large benthic carnivores, pelagic carnivores and cichlids.

Ascendency and system overhead

Ascendency measures the competitive advantage of the selected network and the upper limit of ascendency is the development capacity (Ulanowicz, 1986). The deduction of ascendency from the development capacity is known as system overhead (SO) that determines the ability of the ecosystem to resist unexpected perturbations. For the present ecosystem, the ascendency and overhead percentages were 20.1 and 79.3%, respectively (Table 6). The high value of SO suggested that the ecosystem had significant strength in reserve to resist and recoup from alterations in the system.

Simulation of impacts of coastal aquaculture on ecosystem

In the scenario simulations for cage culture, a significant reduction in biomass was considered only when the final biomass reduced to less than 50% of the initial value for each ecological group. This threshold was set with due consideration of population dynamics of fish species in the ecosystems. It was assumed that the biomass

Table 7. Key indices of the ECOPATH model of the ecosystem

S. No.	Group name	Flow to detritus (g m^{-2} $year^{-1}$)	Net efficiency	Omnivory index
1	Large benthic carnivores	1.49	0.28	0.28
2	Medium benthic carnivores	4.79	0.15	0.52
3	Pelagic carnivores	3.05	0.27	0.16
4	Small benthic carnivores	42.28	0.43	0.18
5	Clupeids and anchovies	41.93	0.39	0.32
6	Crabs	320.11	0.09	0.50
7	Shrimps	134.48	0.41	0.31
8	Cichlids and mullets	2.62	0.98	0.15
9	Benthic macrofauna	582.59	0.23	0.12
10	Zooplankton	1802.97	0.40	0.15
11	Phytoplankton and filamentous algae	3589.03		0.00
12	Detritus	0.00	0.00	0.40

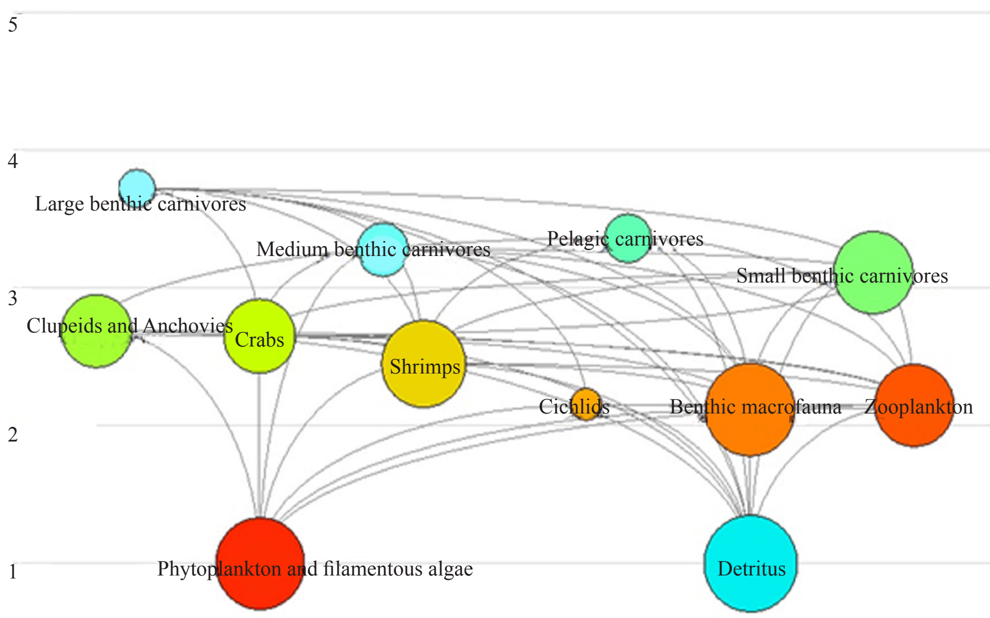

Fig. 2. Network flow diagram for the ecosystem

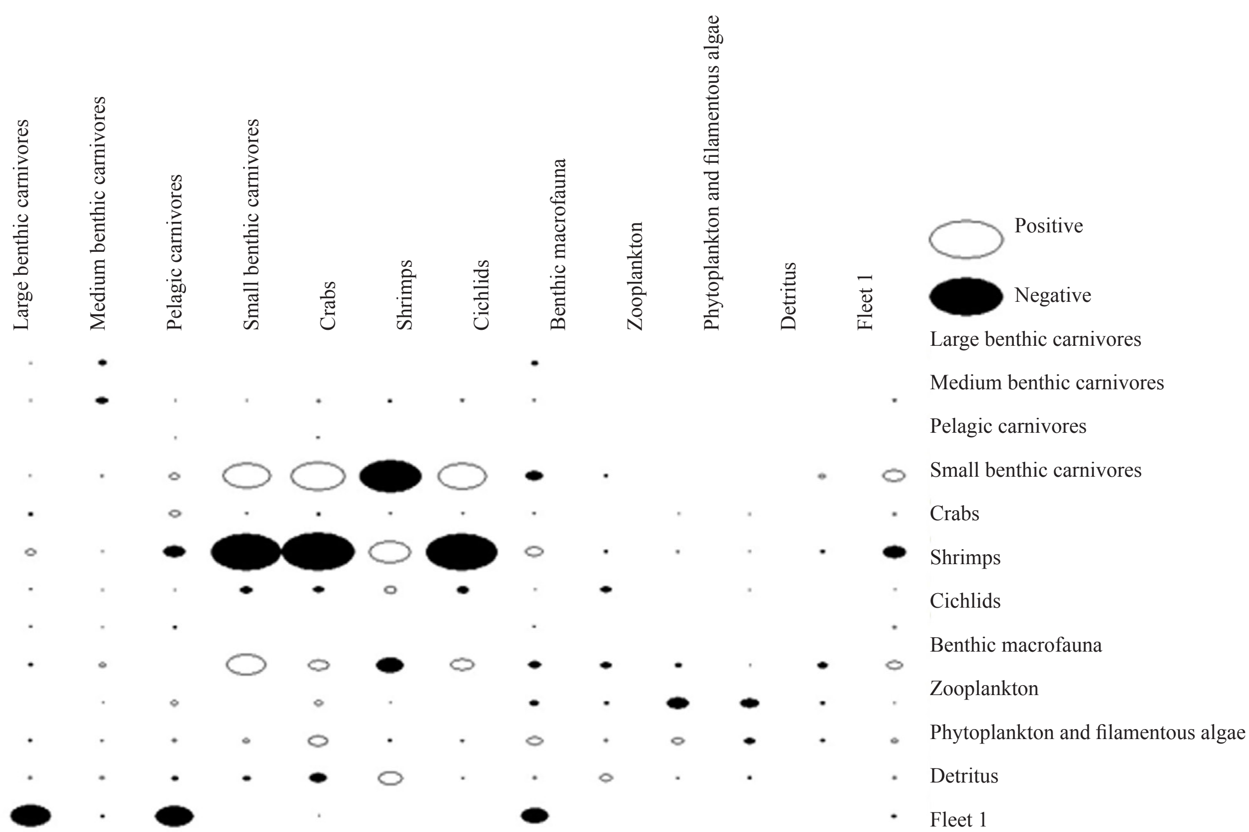

Fig. 3. Mixed trophic impacts between the ecological groups

of ecological groups should not fall below 50% of the initial biomass; otherwise, there will be collapse for these groups in the long term. Results are presented only for selected fishery groups. The relative biomass for selected ecological groups in several scenarios is represented in Fig. 4.

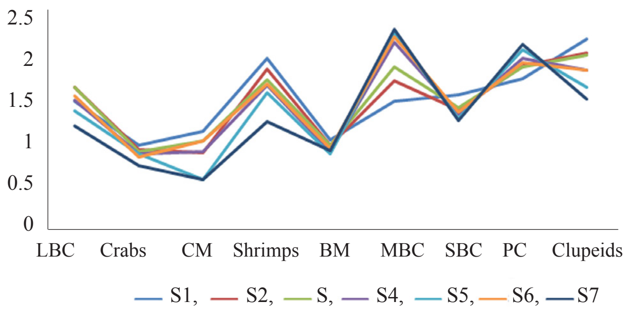

Fig. 4. Relative biomass observed for various ecological groups in different scenarios. LBC - Large benthic carnivores, CM - Cichlids and mullets, BM - Benthic macrofauna, MBC - Medium benthic carnivores, SBC - Small benthic carnivores, PC - Pelagic carnivores

In the first scenario, no cages were considered in the ecosystem and the relative biomass changes for a 10 year period were simulated without altering the fishing mortality of the fishery groups. In this scenario, all the fishery groups maintained relative biomass, significantly higher than the threshold (50% - 0.5) throughout the simulation period. In scenario 2, two cages for pearlspot and one cage for red snapper and 15 kg of mussel seeds were utilised for the culture activity. In scenario 3, one cage each for pearlspot and red snapper and 15 kg of mussel seeds were extracted. All the fishery groups were within the threshold biomass for the entire simulation period in both scenarios 2 and 3. Scenario 4 included two cages for red snapper and two cages for pearlspot and 20 kg mussels. Scenario 4 was identified as the best among all scenarios on the basis of utilisation of the area and ecological sustainability. None of the fishery group was depleted in this scenario beyond the threshold biomass. Moreover, it had utilised the maximum amount of seeds in the cages without disturbing the biomass of the ecological groups in the ecosystem. In scenario 5, there were three cages for red snapper and four cages for pearlspot and 30 kg mussels. In this scenario, due to the extraction of extra biomass for seed, there was a reduction in the relative biomass for cichlids and mullets and crabs lower than the threshold level. In scenarios 6 and 7, the biomass of fishery groups like crabs, benthic macrofauna, cichlids and mullets and clupeids were depleted less than the threshold value (50% of initial) during the 10 year simulation period. Thus, seven scenarios were simulated based on the number of cages, fish seeds and fishing mortality on the fish groups. The variation of relative biomass of fishery groups when the fishing mortality was changed for fishery groups in a span of 10 years is presented in Fig. 4. The mean relative biomass for various fish groups in scenario 4 were 1.48, 0.86, 0.88, 1.65, 0.88, 2.15, 1.32, 1.96 and 1.83 for large benthic carnivores, crabs, cichlids and mullets, shrimps, benthic macrofauna, medium benthic carnivores, small benthic carnivores, pelagic carnivores and clupeids and anchovies. Moreover, the maximum exploitation of the area and maintenance of relative biomass were well above the threshold in this scenario.

The current Ecopath model could provide useful ecological data for a coastal aquaculture system along the west coast of India. The studies around the world suggest that the ecosystem based models can be used as an efficient tool to assess the ill effects of aquaculture on ecosystems (DiazLopez *et al.,* 2008). The ecosystem indices showed comparable values for indices and statistics when compared to other major aquatic ecosystems (Pauly *et al.,* 1993; Pauly and Christensen, 1995; Mohamed *et al.,* 2008; Dutta *et al.,* 2017; Rakshit *et al.,* 2017; Sreekanth *et al.,* 2020). The system is smaller in size and seems to be highly productive in which the freshwater is well mixed with the saline water (Shetye *et al.,* 2007; Manju Lekshmi *et al*., 2018). Here, a detailed discussion is provided on the ecosystem indices, network flows, maturity and the simulated impacts of various scenarios of aquaculture on ecological groups and ecosystem as a whole.

The higher values of EE indicate that the system's secondary productivity is efficiently used up by the consumers and top predators. The average transfer efficiency was found to be 9.5% for the system indicating that the value for the ecosystem is close to the theoretical value of 10% (Odum, 1971). The gross efficiency was found to be 0.001 which denoted the dominance of the lower trophic levels in the system. Pelagic carnivores, large benthic carnivores, crabs, cichlids and mullets exhibited low EE values indicating that only a minor proportion of their biomass was consumed and the rest was going to detritus. EE values for fish groups were highest, which suggested that these groups were utilised efficiently in the ecosystem. The fractional trophic levels for ecological groups were also estimated by the Ecopath model (Levine, 1980; Ulanowicz, 1995). Among the fishery groups, the highest trophic levels in the ecosystem were represented by large benthic carnivores, medium benthic carnivores, pelagic carnivores and small benthic carnivores and lower trophic levels were represented by cichlids and mullets, shrimps, crabs and clupeids and anchovies.

The ratio between detritivory and herbivory was estimated as 1.04, which indicated that the detritus group was equally important as primary producers in the ecosystem. Thus, in this ecosystem, the two main pathways were the detritus-based pathway and phytoplankton based pathway. Therefore, the food cycle of the estuary was controlled by the detritus, phytoplankton and lower trophic level groups depicting a bottom-up regulated food web in resemblance to other estuarine and coastal ecosystems (Flint and Rabelais, 1981; Longhurst, 1983; Gearing *et al.,* 1991; Mendoza, 1993; Lin *et al.,* 2011; Mohamed *et al.,* 2008; Meier *et al.,* 2012; Mukherjee *et al.,* 2019).

The mixed trophic impacts provide trophic interactions between the ecological groups (Christensen *et al.,* 2005). The efficiency of the ecosystem model is defined based on its ability to capture the direct/indirect interactions of one ecological group on the other. In this study, the ecosystem model was able to capture these interactions among the ecological groups and thus, the efficiency of the model was confirmed.

FCI and MPL are applied to evaluate the maturity of a system (Odum, 1969; Finn, 1976; Finn, 1980). The low values of these indices showed that this ecosystem was in an immature developing stage. The PP/R ratio was significantly greater than unity and thus, the system is expected to be an immature one. In this study, this index (1.3) was found to be significantly greater than one and thus the ecosystem was an immature ecosystem in its development stages. A moderate value for SOI indicated that feeding interactions were intermediate between the trophic levels and the system was in an immature developing stage. Detritus and plankton components had positive impacts on many of the ecological groups in mixed trophic impacts routine.

The introduction of aquaculture activities in a natural system could result in variability of biomass of different living components and also increase nutrient discharge into the ecosystem that could result in greater biological activity and active interactions between pelagic and benthic components (Jiang and Gibbs, 2005; DiazLopez *et al.,* 2008). It has been reported that Ecopath model could be an efficient tool to analyse the impacts of different species and how their interactions could alter the ecosystem (Pauly *et al.,* 2008). The stability of an ecosystem is determined using a system overhead index. A greater value of overhead (near to 80%) underlines that the ecosystem is small and could overcome the unexpected perturbations within the system.

In the scenario simulations for cage culture, a significant reduction in biomass was considered only when the final biomass was reduced to less than 50% of the initial value for each ecological group. This threshold was considered with consideration of the population dynamics of fish species in ecosystems. In this study, simulations were carried out to identify the optimal aquaculture practice (in the number of cages) which would not hinder the ecosystem balance and ensure sustainability for a long period (10 years). From the results of the simulations, an ideal solution would be a system with the maximum area utilisation without obstructing the sustainability of the ecological groups. For this, the average values of relative biomass for the fishery groups in each scenario was analysed and we found that the fourth scenario (2 cages each for pearlspot and red snapper and 20 mussel ropes) was an ideal solution (maximum feasible number of cages without losing the threshold biomass for the fishery groups) where maximum utilisation of the area and maintenance of biomass would be well above the threshold level.

The semi-enclosed water bodies in the coastal belt of Goa, which were utilised for shrimp aquaculture, faced a serious setback due to disease outbreaks. Thus utilising these semi-enclosed water bodies for multispecies aquaculture will provide an alternative solution for the fishers. From the Ecopath model, it was clear that the system was immature in nature and having adequate strength in reserve to adjust to perturbations. That means at the present aquaculture scenario, the system can adjust itself to the changes coming through culture practices. Considering various scenarios and the relative biomass change for various fishery groups for a period of 10 years, a sequence of two cages for red snapper and two cages of pearlspot with 20 kg of mussel seeds was considered as an optimal scenario for coastal aquaculture in the selected study area. The results presented in the simulations are predictions for a period of 10 years only and hence, it has to be validated with proper experimental trials. Results of this baseline study shows how simulation models can be used in an aquaculture system to identify optimal capture based aquaculture practice, which will not hinder the ecosystem balance and ensure sustainability for a long period.

Acknowledgements

We express our heartfelt gratitude to the Director, ICAR-CIFE, Mumbai; Director, ICAR-CIFT, Kochi, Director, ICAR-CMFRI, Kochi and ICAR-CCARI, Goa, for the scientific and technical support. We also convey our heartfelt thanks to the fish farmers of Goa for their kind co-operation. The paper was presented in 11th Indian Fisheries and Aquaculture Forum (11 IFAF), 21-24 November 2017, Kochi.

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Date of Receipt : 30.03.2019
Date of Acceptance : 11.08.2020