Evolution of the food web in Bandon Bay, the Gulf of Thailand: Ten years of the blue swimming crab stocking program

Amonsak Sawusdee[1], Sontaya Koolkalya[2], Thanitha Thapanand[3] and Tuantong Jutagate[4,*]

1. Walailak University, Thasala, Nakhon Sithammarat, Thailand 80161
   (AS) E-mail: samonsak@wu.ac.th ORCID-iD: https://orcid.org/0000-0003-1286-540X
2. Rambhai Barni Rajabhat University, Muang, Chantaburi, Thailand 2200
   (SK) E-mail: sontaya.k@rbru.ac.th ORCID-iD: https://orcid.org/0000-0001-5596-3400
3. Kasetsart University, Chatuchak, Bangkok 10900
   (TT) E-mail: ffistnt@ku.ac.th ORCID-iD: https://orcid.org/0000-0002-1703-9935
4. Ubon Ratchathani University, Warin Chamrap, Ubon Ratchathani, Thailand 34190
   (TJ) (Corresponding author) E-mail: tuantongj@ubu.ac.th ORCID-iD: https://orcid.org/0000-0002-7179-7913

Corresponding author:

Tuantong Jutagate

Email address: tuantongj@ubu.ac.th

ABSTRACT

The ecosystem in the Bandon Bay, the Gulf of Thailand, has been intervened by the continued stocking of blue swimming crab larvae, also called crab bank, since 2007. In this study, the food web structures in the Bay were constructed in 2007 and 2016, by using the Ecopath model to compare the trophic status, interaction and energy flow among the components in the system, i.e. 10 years after the crab bank intervention. The models were based on the data collected from trawling. There were 20 and 22 fish- and shellfish components used in the models in 2007 and 2016, respectively. A significant increase in biomass was found in blue swimming crab but a decline for other demersal fishes, cephalopods, and Peaneid shrimps. The production: biomass ratios of most components were getting higher in 2016 but the consumption: biomass ratios were relatively constant. The ecotrophic efficiency indicated that the shellfishes were more exploited than fishes. Changes for most of the ecological indices revealed higher maturity and stability during the past 10 years of crab bank. The mixed trophic impact indicated bottom up regulation and, increasing of blue swimming crab negatively impacts only Mantis shrimp. Overall results indicate positive impacts of crab bank activity.

Keywords: crab fisheries; blue swimming crab; crab bank; Ecopath; biomass; impact

INTRODUCTION

The Gulf of Thailand (GoT) is among the most productive large marine ecosystem, in which the marine capture fisheries in GOT, within Thai territory, contributes over 65% of about 2.5 x10^6 tonnes of the country's total marine production each year (Lymer *et al.* 2008). The fisheries in the GoT are intensively both inshore and offshore areas. Thus, declines in biomasses of many fisheries-targeted species are observed, which raise the concern on the appropriate fisheries managements that can be balance both economics and environmental paradigms (Koolkalya *et al.* 2015; Satumanatpan & Pollnac 2017). Within the GoT, Bandon Bay (Surat Thani Province, Southern of Thailand) is one of the most important coastal areas for human activities, including fisheries. The bay has the coastline of 156 km with huge area of intertidal mudflat, i.e. extending 2 km offshore, and received nutrients from numbers of river channels, which makes the Bandon Bay as the epitome habitat and fishing ground of many fishes and shellfishes, including the blue swimming crab, *Portunus pelagicus* that significantly supports the crab-meat industry in Thailand (Jarernpornnipat *et al.* 2003; Sawusdee 2010).

Similar to any other fishery resources in the GoT, *P. pelagicus* has been heavily exploited due to the high demand of crab meat, in which the annual catch is presently around 25000 tonnes a year compared to as high as 40000 tonnes a year in 1990s (Kunsook *et al.* 2014). Due to the decline of the resource, the crab bank program has been introduced. The program is the kind of stocking program, in which the gravid females are placed in onshore storage to release eggs and then the larvae have been reared before release to sea, in which the stage of release vary from site to site, i.e. range from zoea (1-2 days) to 20 days after hatching (Thiammueang *et al.* 2012; Nitiratsuwan *et al.* 2014). Enhancing the fishery resources through release of cultivated species is considered as one of the effective mitigations in fisheries management (Ak *et al.* 2016) and so does the crab bank in the GoT. Since the introduction of the crab bank in early 2000 along both the GoT and Andaman Sea, numbers of study showed the significant increase in abundance and catch rate of *P. pelagicus* at the implemented locations (Thiammueang *et al.* 2012; Arkonrat *et al.* 2013; Nitiratsuwan *et al.* 2014).

For Bandon Bay, most of people, i.e. about 70%, whom live along the coastal area of the bay, are involved in either fisheries or mariculture industries (Sawusdee 2010). Catch composition from combined various fishing activities showed that catch of the trash fishes could be as high as 50% followed by squids, pelagic fishes, demersal fishes, and crabs, in which more than 85% of crab's yield is *P. pelagicus* (Sawusdee 2010). The catch per unit effort of *P. pelagicus* in the Bandon Bay showed a drastic decline in early 2000, i.e. from more than 1 $kg.h^{-1}$ to less than 0.1 $kg.h^{-1}$, incorporate with the average carapace width of the catches was getting smaller, i.e. less than 10 cm compared to about 12 cm in the 1990s (Sawusdee 2010; Niumnuch & Purisumpun 2011). Due to the decline of the resource and according to the initiative, by the Department of Fisheries (DoF), and success of the "crab bank" project in the early

2000s in the demonstrated site in Chumporn Province (Thiammueang *et al*. 2012), this stocking program has been applied to the Bandon Bay since 2007. Presently, this activity has been conducted in the Bandon Bay by many sectors not only by DoF, including private companies, provincial- and district- organizations, NGOs, and even fishing communities.

One of the most concerns on stocking program, such as the crab bank, is whether this stock supplement activity causes in changing the abundances of other species in the habitat, which could consequently lead to the imbalance of the ecosystem and possibly resulting in the loss of other ecosystem values and services (Caddy & Defeo 2003; Molony *et al*. 2003; Bell *et al*. 2006). This imbalance is mainly from two causes, firstly, by competition of food resources both in the intraspecific level, due to increased abundance of the species by the addition of hatchery-reared seeds, and the interspecific level, i.e. competition between hatchery reared seeds and other species with similar ecological requirements and potentially lead to a reduction in abundances of competing species and prey species (Molony *et al*. 2003). Secondly, it is caused by predation, either by or to the stocking species, which may result in the trophic cascade or community-level cascades (*sensu* Polis *et al*. 2000) that impacts to at least three trophic level and could extend to any multilink linear food-web interaction (Caddy & Defeo 2003). Moreover, an exceeding the carrying capacity of the ecosystem due to continued stocking is also considered as a cause of imbalance (Blaxter 2000; Molony *et al*. 2003) Therefore, quantification of the impact of stocking programs, such as crab bank, on the ecosystem is an important step in determining the appropriateness of particular management actions (Fayram *et al*. 2006; Khan *et al*. 2015).

Understandings of food web structure and ecosystem dynamics are important for determining the interactions in an ecosystem and are useful to many ecological studies (Khan *et al*. 2015). Numbers of mass-balance models have been applied for the purpose to understand the ecosystem process and how it governs the living components in the system. Among the mass-balance models, Eopath model (Polovina 1984) is the most popular and widely applied to estimate the biomass budget for each component in the ecosystem, together with their mortality, diet and energetics value. Ecopath partitions the ecosystem into boxes of a component, i.e. a species or a group of species that has a similar life history, and analyze their interactions as well as provide quantitative descriptions of the structure of food webs of the system, in which works under the assumption that the ecosystem under consideration is at equilibrium, i.e. input to a component should equal output for the period being considered (Polovina 1984; Christensen *et al*. 2005). As the steady-state model, it is a privilege to make a comparative study between any considered periods, in particular before and after intervention by human activities such as regulation measures; fisheries, damming, species introduction as well as stocking program (Christensen *et al*. 2005; Fayram *et al*. 2006; Khan *et al*. 2015).

This study, therefore, aims to describe two different situations of the Bandon Bay ecosystem between 2007 and 2016 and investigate the evolution in the ecosystem, through the food web structure and ecosystem functioning, according to the stocking of *P. pelagicus* through the crab bank program, which has been intensively implemented along the coast of Bandon Bay since 2007 (Sawusdee 2010). The study was done by using the Ecopath with Ecosim (EwE) software version 6.2 (freely available at http://www.ecopath.org; Christensen *et al*. 2005). The results can be also further applied for policy development on the sustainable uses of the resources in the Bandon Bay or for management strategy of other blue swimming crab fishing grounds elsewhere. Furthermore, from the findings and obtained ecopath models and the mixed trophic impacts, in particular, it can be further applied if the hypothesis of the balance of the ecosystem and structure of the community are set, if the there is a change in fishing efforts.

MATERIALS AND METHODS

The Study Area

The Bandon Bay (9°12' N; 99°40' E), Southern of Thailand (Fig. 1), is the largest estuarine (*ca* 1,070 km^2) and mangrove inlet on the east coast of Thailand, i.e. the GoT. This bay serves crucial nursery and feeding ground of many brackish and marine species is and considered as a textbook example of excessive utilization of coastal resources in the trophic level (Jarernpornnipat *et al*. 2003). Surface water current in the bay shows 2 significant different patterns, according the season as (a) flow counter-clockwise in circular patterns during the dry season, from January to March and (b) flow southwards during the rainy season, from April to December (Wattayakorn *et al*. 1999). The coastal area is a gradual slope meanwhile the average water level in the bay is 2.9 m and be fluctuated between less than 1 m to 5 m (Wattayakorn *et al*. 1999; Jarernpornnipat *et al*. 2003).

The Ecopath Model

Since the first introduction of Ecopath model in 1984 in French Frigate Shoals (Pavolina 1984), this model is widely used to describe the trophic interaction and mass balance in the aquatic ecosystem through the Ecopath with Ecosim (EwE) software, which the model has been progressively developed both in terms of software and techniques by the University of British Columbia's Fishery Centre (Christensen *et al.* 2008; Heymans *et al.* 2016). Detail of the Ecopath model and how to construct it can be obtained from the website, http://www.ecopath.org, or read through over 400 models published in any scientific journals (Colléter *et al.* 2015; Heymans *et al.* 2016). In brief, for the Ecopath model, it is assumed that the ecosystem is in steady-state for each component, i.e. inputs equal outputs, and the basic mass-balance concept (Christensen *et al.* 2005) can be described as

$$Production = catches + predation\ mortality + biomass\ accumulation + net\ migration + other\ mortalities \quad (1)$$

or written as linear equation as

$$P_i = Y_i + B_i + M2_i + E_i + BA_i + P_i \times (1 - EE_i) \quad (2)$$

where, for any component (i), P_i is the total production rate; Y_i is the total fishery catch rate; $M2_i$ is the total predation rate; B_i the biomass; E_i is the net migration rate (i.e.

emigration – immigration); BA_i is the biomass accumulation rate; $M0_i = P_i \times (1-EE_i)$ is the other mortality rate and EE_i is the ecotrophic efficiency, *i.e.* the fraction of the production that is utilized within the ecosystem by predators or exported or fishery.

To construct the ECOPATH, the model is expressed as in terms of utilization of production of each component in the ecosystem at an arbitrary time period, and Equation (2) can re-express as

$$B_i \times (P/B)_i \times EE_i = \sum_{j=1}^{n} B_j \times (Q/B)_i \times DC_{ij} + EX_i \quad (3)$$

where, $(P/B)_i$ is the production/biomass ratio; B_j the biomass of predator j; $(Q/B)_j$ is the relative food consumption of j; DC_{ij} is the fraction of prey *i* in the diet of predator *j*; EX_i is the export from the ecosystem, mostly through fisheries.

From Equation (3), four (4) parameters, i.e. B_i, $(P/B)_i$, EE_i and $(Q/B)_j$, as well as diet composition of each component are required as inputs to construct the ECOPATH. At least 3 out of 4 parameters have to be input to the model for each component and then *n* linear equations for *n* components and solves for the remaining parameter (Christensen *et al.* 2005).

Model Structure

Model components

There were 20 and 22 fish- and shellfish components, i.e. species/ group of species, used for constructed the Ecopath of the Bandon Bay in 2007 and 2016, respectively (Table 1). These components were the catch composition from the trawl survey by the research vessel of the Chumphon Marine Fisheries Research and Development Center within the Bandon Bay area. There were 6 and 10 survey-cruises in 2007 and 2016, respectively.

Model inputs

Input parameters for the basic estimation in the Ecopath model are shown in Table 2 and the details of each parameter as

a) Biomass (B_i): biomass of each fish- and shellfish- component was estimated from the trawl survey data of Department of Fisheries (Chumphon Marine Fisheries Research and Development Center) in 2007 and 2016 by using the swept area method (Sparre & Venema 1992) as

$$B = \left(\frac{\overline{CpUE}}{a \times X_1}\right) \times A \quad (4)$$

where, $\overline{CpUE}$ is the average catch per unit effort of each component; a is the area swept by the trawl per hour (0.09029 km^2) ; X_1 is the proportion of fish in the path of the gear retained by the net (0.5) and A is the total area of the Bandon Bay (480 km^2).

b) Production/Biomass ratio (P/B): The P/B ratio is estimated through to the instantaneous rate of total mortality (Z, year^{-1}) as described by Allen (1971). During the survey, catch of each species had been also sampled and length of the individual sample was measured. Thus Z was estimated by Beverton and Holt (1957) as

$$Z = \frac{K(L_\infty - \bar{L})}{\bar{L} - L'} \tag{5}$$

where, L_∞ is the asymptotic length (cm), K is curvature parameter of the von Bertalanffy's growth function, $\bar{L}$ is the mean length in the population (cm), L' represents the mean length at entry into the fishery (cm).

c) Relative food consumption (Q/B): The Q/B ratio is estimated from the empirical relationship proposed by Palomares and Pauly (1989) as

$$log(Q/B) = 7.964 - 0.204 log W_\infty - 1.965T' + 0.083A + 0.532h + 0.398d \tag{6}$$

where, W_∞ is the asymptotic weight (g), T' the mean temperature of the Bandon Bay at 29 ºC (expressed by T' = 1000/K (K = °C + 273.15), A is the aspect ratio (A = H^2/S; H is the height of caudal fin and S is the surface area) for a given fish, h is a dummy variable expressing food type (1 for herbivores, and 0 for detritivores and carnivores), and d is a dummy variable also expressing food type (1 for detritivores, and 0 for herbivores and carnivores). The aspect ratio of each fish as well as Q/Bs for the shellfishes were derived from Vibunpant *et al.* (2003)

d) Diet composition: the input on diet composition of each component was derived from the relevant scientific reports on fish stomach contents in the Bandon Bay and adjacent areas by DoF marine fishery scientists (Table 3).

e) Inputs of non-fishes and non-shellfish components: Biomasses, *P/B*s and *Q/B*s of these components *viz*., benthos, zooplankton, phytoplankton and detritus were derived from the relevant literatures (Supongpan *et al*. 2005a; Sawusdee *et al*. 2009; Premcharoen 2012) and assuming constant during the studied periods.

Model balancing

After input, all required parameters to the model *viz*., biomass, P/B and Q/B, as well as diet composition data, a mass-balance trophic model was performed by balancing the model by modifying the entries until input is equal output for each component (Webber *et al*. 2015). The criterion used for balancing the model was that the *EE* values for each component must be less than 1.0. If *EE* value is more than 1, it indicates that predation on the component is greater than its production. Moreover, the gross efficiency (GE), i.e. food conversion efficiency, in the system, of each component should range between 0.1 and 0.3 (Christensen *et al*. 2005). Thus, to meet the criteria to balance the model, subtle adjustment was made for diet composition.

RESULTS

Except for the stingray, i.e. Dasyatidae, that had not been recorded during the 2007 surveys. The other aquatic resources used for the 2 Ecopath models were similar although some species were included in the group since the minimal in biomass during the 2 surveys (Table 1). The differences in biomasses of the fishery resource components were observed during the 10-years-interval, in which most of the fish groups revealed the increase in their biomasses, including *P. pelagicus*. Significant increase in biomass of the blue swimming crab in Bandon Bay was observed though high fishing pressure to these resources, comparable between the 2 consideperiodriod, which could imply the success of the stocking program (Table 2). On the other hands, there were 3 components that showed significantly decreased in biomasses *viz*., other demersal fishes, cephalopods and Peaneid shrimps. The *P/B* values, estimated through *Z*-value, of most components in the 2016 model were a bit higher in 2007 models, except *Lagocephalus* spp. pony fish, scads and *Upeneu*s spp. This is due to the smaller of the average size of the samples in 2016. Meanwhile Q/Bs was set to be constant in both models, i.e. no difference in feeding rate of each individual component. The trophic level (TL) of all components showed non-substantial changes, i.e. the difference in TL of each component between the 2 considered periods was less than 0.5, which implied their feeding plasticity. The TL of the blue swimming crab was 2.75 and 2.54 in 2007 and 2016, respectively.

The basic inputs with the estimated parameters, i.e. EE and GE, from the Ecopath model for the Bandon Bay for the 2 considered periods were presented in Table 2, meanwhile the diet composition of each component was presented in Table 3. The *EE* values of all components were less than 1 as well as the GE values ranged between 0.1 and 0.3, meeting the requirements of a balanced model (Christensen *et al*. 2005) for both Ecopath models. The EE values indicated that the shellfish components had higher EE (> 0.5) than the fish components (< 0.5), indicated that the shellfishes were more exploited than fishes in Bandon Bay. The blue swimming crab was among the components that had been highly utilized both within (through predation) and outside (through fisheries) in the system since its EE was closed to 1.0. The EEs of the fish component was relatively low indicated they were less predated by the other components in the system. In terms of the gross efficiency (GE), i.e. food conversion efficiency, the value was 0.25 for the blue swimming crab, indicated that the crab 4-times of consumption higher than production. The balance network analysis (Fig. 2) showed the interaction and energy flows among each component in the system. It was clear that the blue swimming crab mostly depended on the detrital-based food chain, i.e. the trophic interactions among recycling organic matter, detritus, predators on detritus (i.e. zoobenthos and zooplankton), and finally to its predators.

From the system statistic estimates (Table 4), it is shown that changes for most of the ecological indices towards values indicating higher maturity and stability during the past 10 yearsof stocking the blue swimming crabs. The throughput value of the 2007 phase (15071.19 t km^{-2} y^{-1}) is a bit larger than the 2016 phase (11304.34 t km^{-2} y^{-1}), which could be due to the fisheries in the Bandon Bay, though mostly artisanal manner, except the commercial fisheries on the blue swimming crabs. The Bandon ecosystem was become more mature from 2007 to 2016 as noticeable by the lower and more closer to 1 of the total primary production per total respiration (TPP/TR) value in 2007 (i.e. 1.30). The development of the Bandon ecosystem toward the maturity in the past 10 years also indicated by higher values of system omnivory index (SOI), total number of pathways and % ascendency in 2016 than those obtained values in 2007. The higher values in total number of pathways and mean length of pathways in 2016 phase, compared to 2007 phase, implied that the food web in Bandon Ecosystem was become more resistant to any perturbation.

The mixed trophic impact (Fig. 3) described the impact to all components in the system when the abundance of any impacting groups infinitesimal increase, i.e. 10%, in terms of relative but comparable between impacted groups. Increased of natural food sources (detritus, zooplankton, zoobenthos, phytoplankton and plant) showed positive impact to most of the remaining components, indicated bottom up regulation in the Bandon Bay ecosystem. Increase in abundance of carnivorous fish, i.e. *TLs* > 3, resulted in negative impact on most fish groups within this ecosystem as well as themselves, i.e. cannibalism. The mixed trophic impacts (Fig. 3) clearly indicated that increase in abundance of the blue swimming crabs had shown the negative impact to only Mantis shrimp by inter-specific concentration, i.e. niche overlap.

DISCUSSION

Applying of the Ecopath model allows describing the trophic interaction and balancing the biomass and annual production of the key components in the Bandon Bay ecosystem for the 2 periods, i.e. 2007 and 2016. Focus of the study is on the blue swimming crab, which continuously release in the studied area since 2010. The comparative Ecopath models showed a difference in the food web structure and ecosystem properties in the Bandon Bay ecosystem during the two considered periods. The major changes in the ecosystem properties of the bay were observed in the summary statistics attributes (Table 4), which showed the improvement of the ecosystem health. Although this improvement, certainly, from multiple causes, this improvement could be translated that there is no negative effect to the ecosystem from the "Crab bank" practice. It can be said that the Bandon Bay ecosystem had become more maturity since TPP/TR in the mature ecosystem should be equal (Odum 1969), and as seen in this study from 2.06 in 2007 to 1.30 in 2016. The connectivity index (CI) and (SOI) were also correlated with system maturity because the food chain was expected to change from linear to web-like as the system matured (Odum 1969; Khan *et al.* 2015). In this study, although CI did not change but the higher SOI in 2016 indicate the more web-like system. All flows and biomasses in the ECOPATH model can be shown in a single flow diagram as in Fig. 2, in which the size of the circles proportional to biomass for each component and Y-axis according represent trophic level. Also according to Odum (1969), they depend more on the detrital pathway and obviously seen in 2016.

The EE values indicated that most components were substantially utilized, both from predation and exploitation in the system. It seems that the EE of most fish components in the Bandon Bay were relatively low, comparable to the whole gulf of Thailand, which are always fixed as > 0.90 (Vibunpant 2003; Supongpan *et al.* 2005a). This could be explained that the bay *per se* is act as the nursery ground and is limited for fishing area and gears used, which mostly in artisanal fisheries (Jarernpornnipat *et al.* 2003; Sawusdee 2010). Moreover, the main fishery targets in the bay are the shellfishes, i.e. squids, mantis shrimp, shrimps and blue swimming crab (Sawusdee 2010; Niumnuch & Purisumpun 2011), which had also observed by that their higher EE than the fish components. The higher EE values for natural food sources (detritus, zooplankton, zoobenthos, phytoplankton and plant), indicated that they were closed to fully utilized by organisms in higher TLs (Khan *et al.* 2015), in particular phytoplankton which seems to be the base food source in the Bandon Bay ecosystem (Lursinsap 1982). The substantially increased in biomass of the blue swimming crab in 2016 showed the consequent increased in EE of the detritus and benthos, because of its bottom feeding behavior (Caddy & Defeo 2003).

Duldic *et al.* (1997) mentioned that coastal areas were usually comprised of low trophic level species with high ecological efficiency and productivity, which support the carnivores within or beyond the system. It is clearly seen that the majority of biomasses in both periods ranged from *TL* between 2 and 3. There was little variation in *TL* for these components in both considered periods, indicating although they feeds mainly on their preferences, they have capability on feeding plasticity (Pannikar & Khan 2008; Duan *et al.* 2009). Meanwhile, decrease in TL of the blue swimming crab in 2016 may be caused by the intra-specific competition since the increase abundance through stocking, which increase chance of individual fed on detritus instead of the common prey, i.e. zoobenthos and zooplankton (Kunsook *et al.* 2014). The mixed trophic impact showed the characteristics of bottom-up control in the Bandon Bay ecosystem, in which changes in abundance of *TL*=1components had shown positive impacts to most of other components in the higher trophic level and dominate ecosystem processes (Dyer & Letourneau 2003; Chassot *et al.* 2005). The possibility of the trophic cascade” in the Bandon Bay could also be considered. High fishing pressure to the shellfish components would consequent in a shift of diet of the high TL (i.e. > 3) components.

Jutagate and Sawusdee (2022) showed that the bottom-set gillnets and collapsible crab traps, the main fishing gears in blue swimming crab fisheries of Bandon Bay, are both focused exclusively in crabs, which contributed over 50% in index of relative importance of the catches. This could be, then, implied that, from the results of mixd trophic impacts, if there were excessive efforts of both fishing gears, imbalance in the ecosystem would occur in the system. Some fishes such as ponyfish and fishes in Family Sciaenidae would impact by losing their feed, i.e. blue swimming crab, and predate more to other invertebrates instead. Moreover, other species those were caught substatntially in both gaers, for example, horseshoe crab for gillnet and puffer fish and *Murex* snail, would be reduced and consequencly affect to their preys and predators. Chassot *et al.* (2005) also stated that fishing generally affects higher trophic levels, which consequently in changes of their population dynamics and eventually modifying the biomass of each component in the ecosystem as a whole.

CONCLUSION

Two ecopath models of the Bandon Bay were constructed in 2007 and 2016. The main attempt was to understand the changes in Bandon ecosystem after the inauguaration of the crab bank after 2007. Changes for most of the ecological indices revealed higher maturity and stability during the past 10 years of crab bank. Differences in abundance of each component between the two models were likely from fisheries. The "bottom-up" control processes in ecosystem of the Bandon Bay was confirmed by the Ecopath model. Understanding on the impacts of fishing activities to the ecosystem as well as examining likely of "top-down" control processes, i.e. fishing control, in exploited ecosystem should be focused for better resources- and fisheries- management of the productive Bandon Bay. Future works should be also taken care on the data quality and certainty of input parameters for the better understanding. Monitoring program on resources abundance is recommended to assess their statuses, in particular the species, which are at risk by changes in crab fisheries in the Bandon Bay.

ACKNOWLEDGEMENTS

This study was financially supported by Agricultural Research development agency (grant number: PRP6405031070) and the Thai Frozen Foods Association under the Fisheries Improvement Project of the blue swimming crab fisheries at Suratthani Province, Thailand.

REFERENCES

Ak O, Ceylan B, Aydin I, Polat H, Küçük E, Eroğlu O and Kapiris K. (2016). Stock enhancement by hatchery-released turbot, Psetta maxima, in the southeastern

Black Sea: capture, migration, growth and diet analyses. *Scientia Marina* 80(2): 163-174.

Allen K R. (1971). Relation between production and biomass. *Journal of the Fisheries Research Board of Canada* 28: 1573-1581.

Arkonrat W, Oniam V, Hengcharoen N and Pradubtham K. (2013). Crab bank implementation: case study of the blue swimming crab bank in Prachuap Khiri Khan Province, Thailand. *Journal of Fisheries and Environment* 37: 30-39.

Bell J D, Bartley D M, Lorenzen K and Loneragan N R. (2006). Restocking and stock enhancement of coastal fisheries: potential, problems and progress. *Fisheries Research* 80: 1–8.

Beverton R J H and Holt S J. (1957). *On the dynamics of exploited fish populations, Fishery Investigations Series II*, Vol. XIX. London: Her Majesty's Stationery Office.

Blaxter J H S. (2000). The enhancement of cod stocks. *Advances in Marine Biology* 38: 1–54.

Caddy J F and Defeo O. (2003). *Enhancing or restoring the productivity of natural populations of shellfish and other marine invertebrate resources*. Rome: FAO Fisheries Technical Paper.

Chassot E, Gascuel D and Colomb A. (2005) Impact of trophic interactions on production functions and on the ecosystem response to fishing: a simulation approach. *Aquatic Living Resources* 18(1): 1-13.

Christensen V and Walters C J. (2011). Progress in the use of ecosystem modeling for fisheries management, in: Christensen, V., Maclean, J.L. (Eds.), *Ecosystem*

Approaches to Fisheries: A Global Perspective. Cambridge University Press, Cambridge, 189–205.

Christensen V and Walters C J, Pauly D and Forrest R. (2008). *Ecopath with Ecosim Version 6: User Guide*, Vancouver: Fisheries Centre, University of British Columbia, 1-224.

Christensen V, Walters C J and Pauly D. (2005). *Ecopath with Ecosim Version 5, Help System*, Vancouver: University of British Columbia, Fisheries Centre, Canada.

Colléter M, Valls A, Guitton J, Gascuel D, Pauly D and Christensen V. (2015). Global overview of the applications of the Ecopath with Ecosim modeling approach using the EcoBase models repository. *Ecological Modelling* 302:42–53.

Duan L J, Li S Y, Liu Y, Jiang T and Failler P. (2009). A trophic model of the Pearl River Delta coastal ecosystem. *Ocean and Coastal Management* 52: 359-367.

Duldic J, Kraljevic M, Grbec B, and Pallaoro A. (1997). Composition and temporal fluctuations of inshore juvenile fish populations in the Kornati Archipelago, eastern middle Adriatic. *Marine Biology* 129: 267-277.

Dyer L A and Letourneau D K. (2003). Top-down and bottom-up diversity cascades in detrital vs living food webs. *Ecology Letters* 6: 60-68.

Fayram A H, Hansen M J and Timothy J E. (2006). Characterizing changes in the maturity of lakes resulting from supplementation of walleye populations. *Ecological Modelling* 197: 103–115.

Heymans J J, Coll M, Link J S, Mackinson S, Steenbeek J, Walters C and Christensen V. (2016). Best practice in Ecopath with Ecosim food-web models for ecosystem-based management. *Ecological Modelling* 331: 173–184.

Jarernpornnipat A, Pedersen O, Jensen K R, Boromthanarat S, Vongvisessomjai S and Choncheanchob P. (2003). Sustainable management of shellfish resources in Bandon Bay, Gulf of Thailand. *Journal of Coastal Conservation* 9: 135-146.

Khan M F, Preetha P and Sharma A P. (2015). Modelling the food web for assessment of the impact of stock supplementation in a reservoir ecosystem in India. *Fisheries Management and Ecology* 22: 359–370.

Jutagate T and Sawusdee A. (2022) Catch composition and risk assessment of two fishing gears used in small-scale fisheries of Bandon Bay, the Gulf of Thailand. *PeerJ* submited

Koolkalya S, Sawusdee A and Jutagate T. (2015). Chronicle of Thai marine fisheries in the Gulf of Thailand (1984-2009): variations, trends and patterns. *Indian Journal of Geo-Marine Sciences* 44: 1302-1309.

Kunsook C, Gajaseni N and Paphavasit N. (2014). A Stock assessment of the blue swimming crab *Portunus pelagicus* (linnaeus, 1758) for sustainable management in Kung Krabaen Bay, Gulf of Thailand. *Tropical Life Sciences Research* 25: 41–59.

Lursinsap A. (1982). *Primary production, potential yield and chlorophyll analysis in the southern coast of the Gulf of Thailand*. Thailand: Marine Fishery Environment Group, Marine Fisheries Development Center. 1-45.

Lymer D, Funge-smith S, Khemakorn P, Naruepon S and Ubolratana S. (2008). *A review and synthesis of capture fisheries data in Thailand – Large versus small-scale fisheries*. Bangkok: FAO Regional Office for Asia and the Pacific, Thailand. 1-51.

Molony B W, Lenanton R, Jackson G and Norris J. (2003). Stock enhancement as a fisheries management tool. *Reviews in Fish Biology and Fisheries* 13: 409–432.

Nitiratsuwan T, Panwanitdumrong K and Ngampongsai C. (2014). Increasing population of blue swimming crab (*Portunnus pelagicus* Linnaeus, 1758) through stock enhancement: a case study in Boonkong Bay, Sikao District, Trang Province, Thailand. *Kasetsart University Fishery Research Bulletin* 38: 17-26.

Niumnuch N and Purisumpun R. (2011). *Supply chain of aquatic animals from Ao Bandon (Bandon Bay): case study of blue crab, black crab and mangrove crab*. Bangkok: The Thailand Research Fund. 1-93.

Odum E P. (1969). The strategy of ecosystem development. *Science* 104: 262-270.

Palomares M L and Pauly D. (1989). A multiple regression model for predicting the food consumption of marine fish populations. *Australian Journal of Marine and Freshwater Research* 40: 259–73.

Panikkar P and Khan M F. (2008). Comparative mass balanced trophic models to assess the impact of environmental management measures in a tropical reservoir ecosystem. *Ecological Modelling* 212: 280–29

Petchkamnerd J, Rootjanarat T, Ratthanaphron I and Chaikew K. (2004). *Fishing gear replacement project: changing mesh size at bottom side of crab trap in Pakklong subdistrict, Chumphon province*. Bangkok: Department of Fisheries. 1-45.

Polis G A, Sears A L W, Huxel GR, Strong D R and Maron J. (2000). When is a trophic cascade a trophic cascade? *Trends in Ecology and Evolution* 15: 473-475.

Polovina J J. (1984). An overview of the ECOPATH model. *Fishbyte* 2: 5-7.

Premcharoen S. (2012). Ecopath Model of the Mae Klong Estuary, Inner Gulf of Thailand. In: G.H. Kruse, H.I. Browman, K.L. Cochrane, D. Evans, G.S. Jamieson, P.A. Livingston, D. Woodby, and C.I. Zhang (eds.), *Global Progress in Ecosystem-Based Fisheries Management*. Alaska Sea Grant, University of Alaska Fairbanks. 1-27.

Satumanatpan S and Pollnac R. (2017). Factors influencing the well-being of small-scale fishers in the Gulf of Thailand. *Ocean and Coastal Management* 142: 37-48.

Sawusdee A. (2010). Fishing Status and Management Proposal in Bandon Bay, Suratthani Province, Thailand. *Walailak Journal of Science and Technology* 7: 89-101.

Sparre P and Venema S C. (1992). *Introduction to tropical fish stock assessment. Part 1 Manual*. Rome: Food and Agriculture Organization of the United Nations. 1-376.

Supongpan M, Poonsawat R, and Christensen V. (2005a). *Trophic levels of multi-species in the Gulf of Thailand*. Report for the project "Ecosystems, societies, consilience, precautionary principle: development of an assessment method of the societal cost for best fishing practices and efficient public policies”. Bangkok: Department of Fisheries. 1-18.

Supongpan M, Poonsawat R and Christensen V. (2005b). *Introducing ecosystem-based management in the Gulf of Thailand*. Report for the project “Ecosystems, societies, consilience, precautionary principle: development of an assessment method of the societal cost for best fishing practices and efficient public policies”. Bangkok: Department of Fisheries. 1-50.

Sawusdee A, Jutagate T, Thappanand-Chaidee T, Thongkhoa S and Chotipuntu P. (2009). Fishes in the Pak Panang River and Bay in relation to the anti-salt dam operation, Part II: Food web models. *Kasetsart Journal Natural Science* 43: 107-119.

Thiammueang D, Chuenpagdee R and Juntarashote K. (2012). The “crab bank” project: lessons from the voluntary fishery conservation initiative in Phetchaburi Province, Thailand. *Kasetsart Journal Natural Science* 46: 427 – 439.

Vibunpant S, Khongchai N, Send-eid J, Eiamsa-ard M and Supongpan M. (2003). Trophic model of the coastal fisheries ecosystem in the Gulf of Thailand. In: G. Silvestre, L. Garces, I. Stobutzki, M. Ahmed, R.A. Valmonte-Santos, C. Luna, L. Lachica-Alino, P. Munro, V. Christensen, and D. Pauly (eds.), *Assessment, management and future directions for coastal fisheries in Asian countries*. WorldFish Center Conference Proceedings. 365-386.

Wattayakorn G, Aksornkoae S, Tingsabadh C, Sathirathai S, Piumsomboon A and Praphavasit N. (1999). Economic evaluation and biogeochemical modeling of Bandon Bay, Surat Thani, Thailand. Bangkok: Thailand Core Research Sit. 1-103.

Webber M, Persad G, Harris N, Wilmot I and Webber D. (2015). An ecological assessment of Foul and Folly Bays, Morant wetlands area, Jamaica using Ecopath with Ecosim. *Ocean and Coastal Management* 105: 127-137.