Data Analytical Solutions for Interpreting Bioenergetic Models and Predicting the Tipping Point of Exploited Small Pelagic Fisheries: A Case Study of Sergestid Shrimp

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City Area	351 km^2
City GDP	RM83.2 billion
Climate Zone	Am (tropical monsoon)
ARC3.3 Linkage	Nature-based Solutions Element

Introduction. Using tools that nature provides for solutions to problems related to managing and restoring ecosystems modified by human actions is an effective way of protecting the environment and sustainability of biological resources. Healthy ecosystems have higher resilience against challenges posed by direct human actions and climate change. Small pelagic fisheries represent an important ecosystem service that plays a significant role in the global economy and food security in developing countries. The fisheries are dominated by small, generally schooling species, found in the surface waters of the ocean and coastal river systems. Sergestid shrimp together with sardines, mackerels and anchovies are among the most abundant of this group of species that make up about 28% of world's wild capture fisheries production (MSC, 2021).

Out of the total harvest of 96.4 million tonnes, about 19% is converted into fish meal and oil, mostly for aquaculture feed development (SOFIA, 2020). Overfishing, habitat degradation and climate change are the main pressures threatening the sustainability of small pelagic species, with around 46% of the total stocks being overfished according to the data reviewed by MSC (2021). The consequences of these depleting stocks have still not been fully investigated but are believed to be severe. The reason is that small pelagic species are a vital part of the trophic webs and for the vulnerable coastal communities that rely on low-cost fish for nutrition security (Isaacs, 2016). Biological attributes of small pelagic species such as their short life span, fast growth and reproduction expose them to effects of climate change (Pennino et al., 2020). If stocks of small pelagic species reach a tipping point because of overexploitation and climate change, the resilience of the aquatic ecosystem to environmental fluctuations will further decline. It is important to identify the most vulnerable of the small pelagic species and generate more scientific knowledge of practical importance in sustainable management.

This case study is based on sergestid shrimp that forms a prominent component of pelagic fisheries. Sergestid resources are under immense pressure due to habitat degradation, pollution and overfishing among other factors. Efforts have been made to collect data on the most common species, including *Acetes japonics, A. indicus* and *A. serrulatus*, and apply the tools of data analytics to synthesize information that can help in management of the capture fisheries of this group.

Because of the many similarities among the sergestid species, observations on one species broadly apply to other species of this group as well, at least in the fundamental aspects of their biology and population dynamics. The approach adopted here basically is in the form of synthesis of data backed by direct observations to construct bioenergetic models and frameworks. This approach is necessary to explain the complexities of interaction between various levels of marine organic production and trophic cascades that will yield information of great significance in sustainable management of sergestid shrimp resources. The importance of this method of generating worthwhile knowledge is evident from the work of Orlowski (2020). Such data-driven fisheries models conform to the environmental, social and economic dimensions of sustainable development of associated seafood systems. The modern technologies of the Fourth Industrial Revolution (IR4.0) for processing and interpreting big data and advanced analytics offer solutions for knowing the unknown and balancing fisheries production with environmental concerns that have not been possible by traditional fisheries management systems (Christiani et al., 2019).

This article is a follow up of our review of a vast amount of data on the sergestid shrimp (Stephenie et al., 2021). The main purpose is to present a synthesis of knowledge that has been derived partly from this work to generate information aimed at reforming the management systems consistent with the concept of nature-based solutions for vulnerable stocks of important fisheries. The life history of sergestid shrimp involves migration between lower reaches of the coastal rivers and inshore sea, and both these environments are under enormous urbanization and anthropogenic impacts. This increases their vulnerability to climate change. Conservation of coastal rivers and inshore marine environments can produce better outcomes through an integrated management rooted in the core concepts of sustainability. Managerial interventions aimed at achieving protection of ecosystems adaptively, preserving biodiversity and ecosystem resilience are important nature-based solutions (Berkes et al., 2000).

Shrimp Harvesting Practices and Data Analytics. This study is based on data mining and analysis pertaining to sergestid shrimp (*Acetes spp.*) capitalizing on model projections and expert assessments. Such an approach has been recommended in the technical paper released by the Food and Agriculture Organization (Barange et al., 2018). Before commencement of the data analytics, some direct observations on sergestid fishing grounds were carried out, involving excursions to an intense fishing zone in the sea off Kota Kinabalu (Figure 1) for collection of basic information of fisheries importance.

Figure 1. *Study area in Likas Bay off Kota Kinabalu, Malaysia (2023).*

Shrimp samples were collected at the catch-landing stations around the fishing zone when the traders started marketing the fresh catch (Figure 3). The specimens were randomly sampled and measured for length and weight and refrigerated for subsequent observations for future investigations. Several species of *Acetes spp.* found in this area are geographically widespread. At the time of these observations the predominant species in the catch was *Acetes serrulatus*. The specimens were sampled soon after the catch was landed. No handling and treatment of live specimens was carried out.

This study was designed for analysis of raw data to explore the feasibility of data sorting using statistical methods to be able to disaggregate the voluminous data into sub-categories for establishing trends and drawing conclusions that are otherwise for the purpose of this study pertains to trophodynamics and fishing pressure for suggesting management according to the guidelines for sustainable development of fisheries resources.

Production efficiency analysis and predicting the biomass fluctuations followed the fundamental concept of bioenergetic modelling (Cho and Bureau, 1998; Neill, 1998; Guiet et al., 2020). The bottom-up approach as suggested by Ware and Thomson (2005) was considered appropriate for this study due to exploitation of food resources by the sergested shrimp in the lower trophic levels. The formula proposed by Trites (2019) was used for the bioenergetics-production model. The knowledge generated was integrated to develop the Drivers-Pressures-State-Impact-Response (DPSIR) model for adaptive intervention for sustainable management of sergestid shrimp resources as followed earlier (Patricio et al., 2016; Dzoga et al., 2020).

Figure 2a. *Sergestid shrimp fishing in Likas Bay, off Kota Kinabalu. Fishing operations away from the coastline (2023).*

Figure 2b. *Sergestid shrimp fishing in Likas Bay, off Kota Kinabalu. Fishing operations near the coastline (2023).*

Figure 3. *Freshly landed sergestid shrimp at the landing center in Kota Kinabalu (2023).*

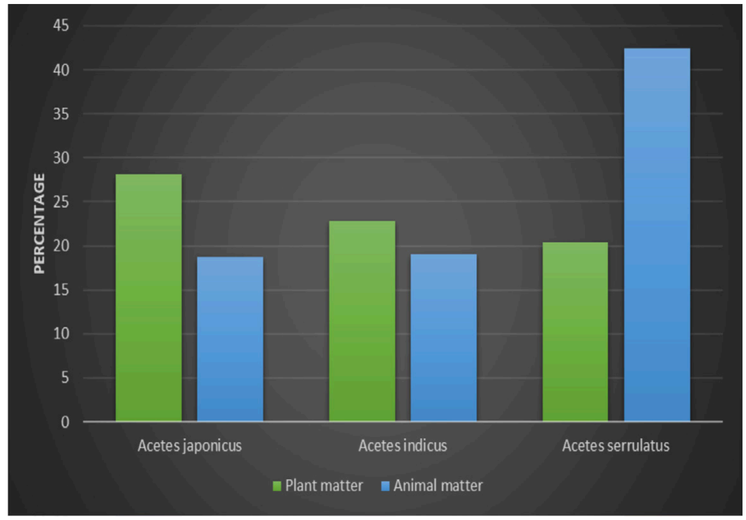

Figure 4. *Relative proportion of the plant and animal matter (unconsolidated) based on volumetric measurement in three sergestid species.*

Position of Sergestids in Ecosystem Energetics. The trophic position of any species in a marine ecosystem depends on the food items that it consumes. Sergestid shrimps are no exception to this fundamental ecological principle, which is the basis of bioenergetic modelling. Information available on the trophic structure of sergestid shrimp provided a basis for constructing bioenergetic models that can be used for a rapid understanding of their role in the energy flow and biomass transformations. Data presented in Figure 4 represents categorizations of different food items known to occur in the shrimp gut into two main categories -- animal matter and plant matter. Because of significant differences in size of the food items (phytoplankton vs zooplankton) that are measured for numerical strength and inclusion of food items where biomass rather than the number (for example, macrovegetation, crustacean body parts, sand, mud, and detritus) is assessed (Amani et al., 2011; Oh et al., 2011), the exact quantification of individual food items has practical difficulties in generating their specific position in the bioenergetic calculations.

A logical approach adopted in the present interpretation is to consider the relative importance of various items in the diet. The proportions of plant and animal matter as shown in Figure 4 have varied not only because of the relative amounts of fragments of macro food items, but also due to fluctuations in the proportions of phytoplankton and zooplankton. This is expected of the sergestid shrimp that are omnivorous and possess opportunistic feeding habits which is an adaptation to deal with the fluctuations in food resources.

The bioenergetic modelling as a scientifically viable tool for quantifying energy allocation in a free foraging marine animal (Deslauriers et al., 2017) is based on the mechanism of the partitioning of energy intake into three main components, namely, metabolism, waste and growth (Winberg, 1956; Ney, 1993). These models have found useful applications in estimating growth as well as environmental constraints (Kitchell et al., 1977; Bevelhimer and Adams, 1993). Through a comprehensive investigation, Yodzis (2001) convincingly demonstrated the dynamics of energy changes in the trophic levels.

The author provided data to show how rapidly and significantly the dissipation of energy takes place in an ascending food chain, with an ecological transfer of energy of merely 0.1. It implies that out of the total amount of energy produced by a species at the base of the food pyramid in the primary production activity, one-tenth (=0.1) is produced by herbivores, and one-tenth of that, or in other words, one-hundredth (=0.01) of primary production, is produced by carnivores, and one-tenth of that, or one-thousandth (=0.001) of energy at primary production level is produced by secondary carnivores.

Trites (2019) has suggested adding a value of 1.0 to the average trophic level of all the organisms that a species consumes to determine its trophic position. In the present article, we suggest a calibrated approach because the energy loss at each transformation is 90% and slight variations in the relative proportions of plant and animal matters produce significant effects in terms of energy flow to the successively higher level of organic production. In the case of sergestid shrimp, the proportion of individual dietary components varies in a narrow range that requires a fine calibration for accurate results. It cannot be defined by a single integer in a discrete level of a food pyramid. Therefore, a trophic level exceeding 2.0 should not be treated as 3.0 but it should rather be calibrated in the range of 2.1-2.9. Going by this rationale, if the diet comprises 50% phytoplankton plus 50% herbivorous-zooplankton mixed component (level 2), the shrimp will have a tropic level of 2.5.

The scope of bioenergetic modelling extends beyond the flow of energy across the trophic levels to include the performance and survival of species of fisheries importance and the overall ecosystem health. Accepting it as a way of quantifying energy allocation in biomass of successive trophic levels, the environmental variables that influence bioenergetic pathways can be used to reflect the fluctuations in ecological modules in a coastal-marine ecosystem, and thus, indirectly relate to the distribution of biomass under the changing conditions of commercial fisheries. Guiet et al. (2020) have followed this approach to explain the historical development and decline in industrial fisheries.

The predictive analytics tools that are now gaining importance during IR4.0 can help in further expanding the bioenergetic domain to be able to contribute to management of anthropogenic pressures on marine fisheries stocks and in examining the effects of climate change as suggested by Jorgensen et al. (2016). Such data analytics models can project scenarios pertaining to population conditions of sergestid shrimp and insights into the pressures that the targeted populations face, and the consequent ecological perturbations (Tomlinson et al., 2014; Mangel, 2015). Knowledge of these aspects can contribute to addressing the complexities in identifying factors that are strong enough to push the individual marine species or ecosystems past some tipping points. These issues are important because of the connectivity and non-linearities among the various ecosystem conditions, and their strong bearing on the social-ecological systems, especially in the tropical developing countries where the role of coastal fisheries in food security cannot be overemphasized.

The bioenergetic models, or for that matter, species-specific relationships between their performance and environment, deserve to be incorporated into predictions of ecological tipping points (Christopher et al., 2017). This has become necessary in view of the heavy exploitation pressure on the sergestid shrimp. They are used as a staple seafood, converted into paste for culinary delicacies, and large quantities are turned into aquaculture feed. During peak seasons of swarming, huge amounts are dried for future use. They are marketed at a very low price of Ringgit Malaysia 2 (=US$ 0.47) per kilogram which is attractive enough for multiple uses described above. There is no dearth of incremental knowledge on their biology and seasonal fluctuations (Omori, 1989; Chiou et al., 2000, 2003, 2005; Collins and Willner, 2003; Hanamura and Ohtsuka, 2003).

However, some critical aspects of their production efficiency and population tipping point are still lacking. The approach of using analytical tools outlined in this paper can generate new knowledge from the published information and help in gaining actionable insights for better decision-making in managing the targeted fisheries resources. The issue of tipping points is becoming increasingly important and deserves special attention given the increasing number of incidents of cases of marine ecosystem malfunctioning in localized areas resulting in population depletion and very visible loss of sustainability of exploited fish stocks. The tipping point denotes a critical stage in a situation, or system, beyond which even a small change leads to a significant response in the structure or function of the ecosystem.

Marine ecosystems are inherently complex and characterized by a unique dynamic equilibrium. When resilience of such ecosystems is diminished in terms of population imbalances, ecological disruptions, functional setbacks and socio-ecological attributes, the response can take the form of abrupt, discontinuous shifts, or critical transitions (Vasilakopoulos and Marshall, 2014). While highlighting the numerous factors involved in influencing critical transitions, these authors have emphasized the relevance of multivariate analysis, quantitative resilience assessment and integration of data on multiple aspects to define the mechanisms underlying the tipping points in complex natural systems. The reported decline of 90-95% of the sergestid shrimp catch in an active fishing zone in Melaka as reported by Doraman (2021) points to the ecosystem having crossed a critical threshold. It was linked to the shrimp habitat degradation due to the reclamation work.

However, this matter deserves scientific investigations to identify the tipping point. It is likely that the sergestid habitat degradation was happening over a long time and coupled with pressure of exploitation and other drivers culminated in a situation that tipped the balance to produce a dramatic decimation of the once thriving fishery stock. Such a response of the marine ecosystem is non-linear, and this adds to the difficulty in anticipating and predicting a tipping point (Martone et al., 2017). Despite the constraints and lack of baseline scientific data, predicting conditions leading to tipping points or planning recovery from ones already crossed is important for managing natural resources, especially in a changing climate (Martone et al., 2017). The consequences of collapsed fisheries are devastating to the marine ecosystem as well as the communities that depend on these resources. A reported collapse of sergestid shrimp stocks should be considered as an example of non-linear relationships between the predictor and response variables, including the responses at species, populations, and ecosystem levels, consistent with the views of Selkoe et al. (2015). Earlier investigations on non-linear responses published by Dulvy et al. (2003) highlighted similar conditions resulting in severe depletion or even local extinction of species constituting fisheries.

Investigation of tipping points requires diversifying the sources of knowledge to supplement the data generated by the incremental research. In the case of sergestid shrimp, it deserves far more information and data synthesis than merely the Exploitation Rate (E) is required. The investigations reviewed in this work included the calculation of 'E' following the standard method developed by Gulland (1983) where total mortality (Z) was summation of natural mortality (M) and fishing mortality (F). A separate assessment of fishing mortality for understanding the pressure of exploitation followed the equation: $F = Z – M$. Obviously, when regulation requires a 'no-take fishery' policy for stock conservation, $F = 0$, $Z = M$. For sergestid shrimp, natural mortality has not been separately determined due to practical problems in the mark-recapture technique for these small and swarming crustaceans. Calculation of M, therefore, is by way of subtraction when Z and F are known. Exploitation rate has been reported to be above the optimum level ($E > 0.5$), to be precise in the range of 0.51 – 0.53 (Amani et al., 2011). Obviously, it is a combination of factors, not just the slightly above the optimum exploitation rate, and serves to signify non-linearity in assessing the fisheries status and vulnerability.

The trophic level around 2.5 of sergestid shrimp and other forage species normally found in tropical coastal waters indicates that these animals make use of most of the energy produced in primary production. This makes them the main link between their prey and predators. The rapidly declining available energy for the successively higher trophic levels geometrically decreases the organic production in an ascending pyramid and limits the number of trophic levels (Yodzis, 2001). Any depletion of populations of forage species, therefore, disrupts the energy flow and curtails population of species that are of major significance as a highly valuable human seafood. If the calculations presented by Goldberg (2017) are accepted, the predatory species need 25 – 33.3% of the prey populations to maintain their production potential. This also explains the fragility of coastal marine ecosystems and the need to implement management systems according to the Drivers-Pressures-State-Impact-Response (DPSIR) framework before more tipping points are crossed. It is based on the understanding that Drivers cause Pressures that affect the State of the marine environment which leads to Impact that motivates appropriate Response for managing the situation (Table 1).

Table 1. *DPSIR framework for sergestid shrimp.*

Drivers	Human activities that affect the sergestid resources or the marine ecosystem: Demand of sergestid shrimp as an affordable food item and feed for aquaculture industry. Economic downturn due to reduced income opportunities turning impoverished coastal communities to easy harvest from the sea and buy low-cost food. Interest in reclamation of nearshore areas for a more lucrative business investment. Climate change.
Pressures	Direct environmental effects of the Drivers: All the processes and activities by which the drivers bring about change in the state.
State	Condition of sergestid stock or the marine ecosystem: Attributes of the marine ecosystem reflecting its condition or abilities for specific issues or purposes: Decline in ocean health. Diminished resilience. Poor water quality due to eutrophication and pollution. Reduced capacity of the ocean to provide ecosystem services.
Impact	Impact on human welfare attributable to change in the state of the marine ecosystem: impaired ocean structure and functions. Decline in biodiversity. Threat to sustainability of fisheries resources. Long-term impact on society.
Response	Initiatives or measures to reduce impacts: Policies and targeted actions to improve the state of sergestid shrimp stocks and ecosystem resources. Enhancing community resilience. Alternative livelihoods such as sustainable aquaculture. Real-time marine monitoring system. New knowledge. Improved governance.

The DPSIR framework as described above provides a structured system, the effectiveness of which can improve by developing the indicators needed to enable feedback to decision-making institutions on specific issues and the resulting impact of the policies made, or likely to be made in the future to address the identified problem (FAO, 2021). Establishing a DPSIR framework that appears as a chain of casual links is a complex task as it entails analysis of the various cause-and-effect relations attributed to a problem such as the threat to sustainability of sergestid shrimp resources. Mustafa et al. (2021) have highlighted the need for mainstreaming sustainability concepts in protecting the marine natural capital, especially the affordable fisheries resources for maintaining the livelihoods of the coastal communities. Managing fisheries is a viable component of food security because of the reliance of the growing population on seafood. Fish provides macro-and micro-nutrients that combat hunger and malnutrition. FAO sustainably managing the capture fisheries to optimize production, improve nutrition and poverty reduction and increased resilience of the marine ecosystem against the effects of climate change that cumulatively contribute to food security.

Resource Exploitation to Tipping Point. Sergestid shrimps, by virtue of their biological attributes and patterns of blooming that are known to coastal communities engaged in fisheries, are prone to overexploitation. On a regional basis, their population has been exploited to a stage that can be considered as a tipping point. While this assessment might not apply to all the sergestid populations across the world, it certainly deserves to be considered as being close to or having reached the tipping point. Although the observations targeted on one species are vitally important but tropical marine ecosystems that support mixed fisheries and witness intense exploitation have inherent complexities and non-linearities that need in-depth analysis.

Erosion of resilience of targeted populations is also related to an imbalanced marine ecosystem and changing social-ecological systems. Coastal ecosystems under pressure of overfishing over a long period of time could respond to even small perturbations that they have endured in the past with abrupt changes not seen or anticipated before. We should accept that the marine ecosystems are in a critical transition, the consequences of which are not properly understood. It requires going beyond incremental research to disruptive approaches of generating knowledge that can provide a basis for concerted action to manage fisheries as a viable component of global sustainable food security. Biomass predictions from simple bioenergetics models can be used to develop calibrations for models for estimating fisheries productivity and impacts that need to be addressed by DPSIR frameworks. Data analytics and other tools of the fourth industrial revolution provide the way forward in designing new management frameworks that protect the marine natural capital for the welfare of human societies.

Small pelagic species such as the sergestid shrimps are an important component of marine biodiversity and tropical ecosystem dynamics due to their role in food chain and interaction with other species. Sustainably managing these resources not only improves the socio-economic well-being of the people, especially food security, but also helps balance the coastal-marine ecosystem which is necessary for conserving biodiversity and facing the stress of climate change (Bauer, 2021). The importance of addressing the challenges linked to urbanization in areas such as river catchments and coastal sea in terms of pollution, habitat degradation and overexploitation of marine populations as highlighted by Maasri et al. (2021) deserve serious attention.

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Additional Data

• **Population Density:** 1,492 people/km^2

• **Gross National Income (GNI):** 15,020 USD (Higher-Middle Income) [2023]

• **Gini Coefficient:** 36.1 [2023]

• **Human Development Index (HDI):** 0.728 (High) [2025]

• **Type of Climate Intervention:** Hybrid (Both Adaptation and Mitigation)
