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Ecological network metrics in assessing sustainability of the Philippine milkfish (*Chanos chanos*) economic resource system

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Abstract. We used an ecological network analytical approach on a simplified, non-trivial and expandable model of the Philippine brackish-pond milkfish (*Chanos chanos*) resource network as an initial attempt in quantifying sustainability of aquaculture systems holistically. The approach defines sustainability as robustness which is the appropriation between systemic efficiency and redundancy of network flow structures. The milkfish resource network model analyzed has five categorized functional compartments: fry source, fry distribution channel, production area, product distribution channel and market consumption. The directed flows in-between compartments are taken as economic values of milkfish fry and products from 1979 to 2001 to exclude other production source in the latter years. The results are compared to previous analyzed global economic and local ecological networks as bench marks. The milkfish resource network exhibit high levels of efficiency and sustainability may be improved by managing production flows of the industry that would optimize robustness through increasing redundancy. The approach can be useful in assessing the effects of policy interventions on the systemic sustainability of resource network systems as demonstrated in the case study.
Key Words: social-ecological system, robustness, resilience, efficiency, milkfish.

Introduction. Aquaculture plays an important role in compensating the stagnating capture fisheries to meet global seafood demand due to population increase that is expected to grow by half by the mid-century (FAO 2014). Fish farming is one of the most rapidly growing food sectors with production volume already approaching half of the total global fisheries supply as catch from capture fisheries continue to decline, only being offset by the increase in fishing efforts (FAO 2014; Anticamara et al 2011). Thus, aquaculture is an essential resource system that needs to be sustained to ensure global food security as the population dependence on farmed fish remains to increase.

In Southeast Asia, aquaculture production of low trophic level species (e.g. tilapia - *Oreochromis* spp. and milkfish - *Chanos chanos*) is expected to meet the protein requirement of the growing population in the area (Marte 2003). Milkfish production in Southeast Asian countries such as Taiwan, Indonesia and the Philippines has traditionally been practiced in saline earthen ponds. In the Philippines, almost half of the mangrove forest loss can be attributed to brackish-pond aquaculture conversion for milkfish production (Primavera 1995). The loss of these mangrove-ecological systems were replaced by human built systems that are still reliant on ecological resources and services, inherently creating a new interdependent social and ecological system (SES) in the form of the brackish-pond milkfish production resource system. A SES can be defined as “an ecological system intricately linked with and affected by one or more social systems" (Anderies et al 2004).

Historically, the growth and development of the brackish-pond milkfish SES could be explained through technological, institutional and cost-return perspectives that involve social, economic and ecological dimensions. Various efforts have been implemented in securing consistent and higher production from increasing production areas to employing research and technology. Although there are numerous research and practices in milkfish aquaculture that contributed to growth and development, these remain focused on specific sections and constraints of an entire system assembly that includes fry supply sources, production areas, consumption market and delivery systems.

In the study of SES, one of the current approach in assessing sustainability is through network metrics. Network approach has a long history of development in the field of ecology and has been used by ecologists to analyze organization, operation and succession of ecological systems (Borrett et al 2014). There are also applications in other fields of study and a network perspective is useful in facilitating comparisons of social and ecological system case studies (Janssen et al 2006). There are emerging efforts towards quantitative analysis of SESs to make apparent the interaction between the heterogeneous social and ecological components (Bodin & Tengö 2012; Gonzales & Parrott 2012) but empirical application across various types of case studies is still necessary to establish merits.

Here we employ an ecological network analytical approach that is grounded on information and graph theories to quantify the sustainability of the brackish-pond milkfish resource system. The approach is well developed in the field of network ecology (Borrett et al 2014) in analyzing ecological food webs (Ings et al 2009; Wulff et al 1989; Banašek-Richter et al 2009), stability and adaptability (Rutledge et al 1976; Ulanowicz 2002), and ecological dynamics (Baird & Ulanowicz 1989). These attempts cumulated to an ecological analytical approach that describes sustainability as systemic persistence termed robustness (Ulanowicz et al 2009; Goerner et al 2009). Robustness of a network flow structure is determined by two complementary traits of systemic efficiency and redundancy. Efficiency is an internal regulatory process of directing flows that optimize output and reduces inefficient redundant pathways. On the other hand, redundant pathways offer alternative routes of energy or material flow during perturbations and provide resilience to the system but are also dissipative. These properties are not evident by analyzing individual compartments but emerge in analysis of network flow structures (Ulanowicz 1986).

The objective of this paper is to apply a holistic approach to assess the sustainability of the brackish-pond milkfish resource system that could potentially integrate the various functional compartments that has been the subject of disciplinary research focus of traditional problem solving science.

Material and Method

Ecological network analytical approach. The ecological network analytical approach is based on the Shannon Diversity Index (Shannon 1948), which integrates both the presence and absence of information into a single metric of measure, where both certainty and uncertainty is crucial in determining systemic persistence. The product summation of known and unknown information in a system under observation provides a single metric H:

$$H=-k\sum_{i=1}^{n} p_i \log(p_i) \quad \text{eq. 1}$$

or aggregate system indeterminacy (Ulanowicz et al 2009), where p_i is information measured as a probability of an occurrence of an observable event event i and $-\log(p_i)$ is the magnitude of uncertainty or the degree of surprise in observing the event. H can be explained as the propensity of a system to change, and provided extreme conditions where there is complete certainty of presence or absence of an even i ($p_i=1$ or $p_i=0$), the system has no propensity for evolution and reflects a constant situation.

Rutledge et al (1976), in the search of defining ecological stability through information theory (IT), further developed the theorem by proposing a decomposition of H into two complementary variables such that X is the resolved uncertainty under the observation of probabilities and Ψ represents the remaining unresolved uncertainty:

$$H = X + \Psi$$ eq. 2

In IT, X and Ψ are are termed "average mutual information" (AMI) and conditional entropy respectively. Thus far, the description of these properties is for general simple observable events. Effectively, for directed weighted networks, the variables in equation 2 are defined by the following equations (Ulanowicz & Norden 1990):

$$H = -k \sum_{i,j} \frac{T_{ij}}{T_{..}} \log\left(\frac{T_{ij}}{T_{..}}\right)$$ eq. 3

$$X = k \sum_{i,j} \frac{T_{ij}}{T_{..}} \log\left(\frac{T_{ij} T_{..}}{T_{i.} T_{.j}}\right)$$ eq. 4

$$\Psi = -k \sum_{i,j} \frac{T_{ij}}{T_{..}} \log\left(\frac{T_{ij}^2}{T_{i.} T_{.j}}\right)$$ eq. 5

T_{ij} represents a quantum of flux from compartment i to j (e.g. flow of currency, carbon, energy, matter, etc.). The dot notation that replaces an index denotes the summation over that index where $T_{i.} = \sum_j T_{ij}$ is the summation of all flux coming from compartment i and $T_{.j} = \sum_i T_{ij}$ is the summation of all flux received by compartment j. The summation of all flux is given by $T_{..} = \sum_{i,j} T_{ij}$ and is called the "total system throughput" (TST). TST represents the system scale in terms of the quantity of material or information contained in the network.

AMI is the mean degree of constraint which determines the capacity of a network to direct and maintain the fluxes while the conditional entropy represents the degree of freedom for flows to occur independently. These network properties are unit-less and the k constant returns a unit of measure to describe the size of the system. The k is taken as the TST ($k = T_{..}$) and gives the transformed equations:

$$C = -\sum_{i,j} T_{ij} \log\left(\frac{T_{ij}}{T_{..}}\right)$$ eq. 6

which is termed "Development Capacity" of the system;

$$A = \sum_{i,j} T_{ij} \log\left(\frac{T_{ij} T_{..}}{T_{i.} T_{.j}}\right)$$ eq. 7

which is the Ascendency or "Systemic Efficiency" and;

$$\emptyset = -\sum_{i,j} T_{ij} \log\left(\frac{T_{ij}^2}{T_{i.} T_{.j}}\right)$$ eq. 8

which is the system's scaled conditional entropy or also known as "Resilience Capacity" which is the system reserve (Goerner et al 2009).

The scaled total system indeterminacy is the capacity of a system for growth and development towards increasing the amount of flux through structural order as well as providing a reserve of redundancy against compartment failures and is termed "Development Capacity" (C). Ascendency represents "Systemic Efficiency" of the system in allocating the flow of resources through the compartments within the network and is the measure of system size and ordered organization (Ulanowicz 1980). Since constraint is embedded in the scaling, efficiency also is an indication of the structural integrity of maintaining the effective performance over long periods of time. The scaled conditional entropy Ø, termed "Resilience Capacity", is the system's ability to absorb disturbances by allowing alternative pathways of flow or an overhead reserve (Ulanowicz & Norden 1990). Resilience capacity opposes efficiency to strengthen the reserve to external shocks. Mathematically, resilience is the average diversity of connections in the network. The two opposing yet complementary properties are essential in maintaining development capacity over time and under the presence of unpredictable disturbances (Ulanowicz et al 2009).

To determine the proper distribution of the two opposing yet necessary system network properties of efficiency and resilience, the systemic efficiency is normalized by the development capacity where the ratio of the two gives α, which is the relative efficiency or degree of order of the system. To represent the robustness of the defined network, α is used in line with the Shannon Diversity Index, that is if α is the relative measure of order and what is known, disorder and the unknown is represented by -klog(α), and provides:

$$R = -k\alpha \log(\alpha) \qquad \text{eq. 9}$$

The product -αlog(α) thus represent the potential of a system to evolve and persist. R is defined as robustness and quantifies systemic sustainability. The measure of robustness pertains to the capacity of the defined system to have sufficient directed power to grow and develop and the necessary reserves to withstand disturbances. Going back to the same logic of measurements in equation 1, the equation to measure robustness is used where constant k=e ("e" is taken to the base of natural logarithms). Robustness is an effective measure of allocation between efficiency and resilience to ensure that a system has enough internal regulation against resource competition as well as enough reserve against external disturbances by allowing flexibility of flows. This tells us that in order to persist, network systems should not be overly efficient or overly resilient. The following section applies the calculus in determining the systemic robustness, efficiency and resilience on the Philippine brackish-pond milkfish economic resource system as a network composed fry resources, pond production areas, market consumption and delivery systems.

Resource network modelling. The brackish-pond milkfish resource network is a collection of components that forms a larger scale social-ecological-economic system. In our initial attempt to operationalize the calculus of the ecological network analytical approach, we define a simple network of components (nodes) and connections (flows) to represent the structural configuration of the case study. To identify the components of the system, we define the general functions of the industry with consideration to the basic supply and demand economic resource configuration (Figure 1). The most basic structure of material flow is composed of the supply from the production areas and the demand on the consumption side of the cultured milkfish product. The two basic nodes of supply and demand are decomposed into the procurement, transformation and delivery nodes based on the basic model of the milkfish economic resource system (Smith 1982). The links are established by following the movement of the milkfish from the very initial source of fry to grow-out production and, finally, to the market consumption. The diagram provides the basic composition of a non-trivial social, economic and ecological system. Further decomposition results to the configuration which is composed of 5 compartments including distribution channels. Although the expressed diagram does not constitute a complete network, it does serve as the template for the ensuing step of node disaggregation to complete the network.

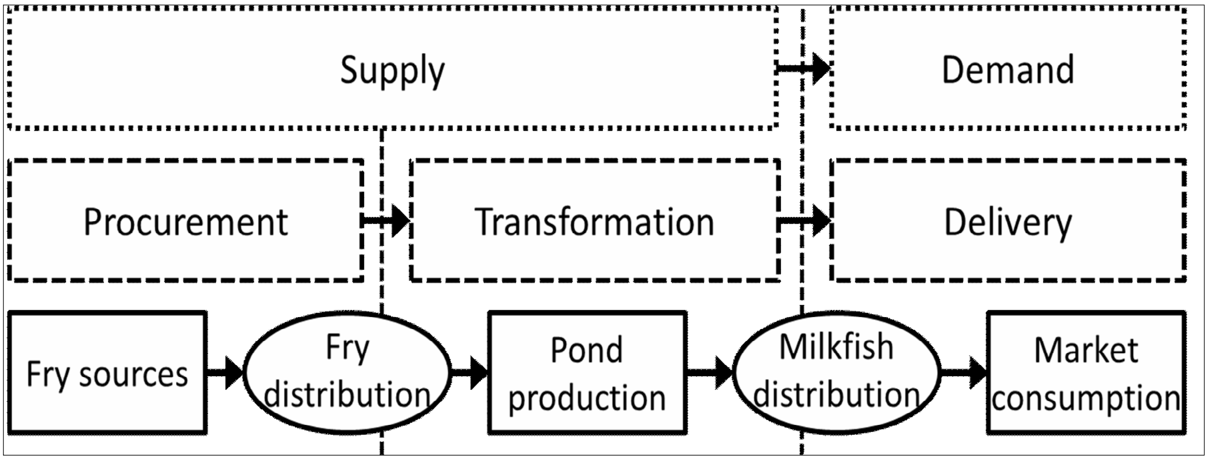

Figure 1. Non-exhaustive classification of the Philippine brackish-pond milkfish economic resource system (product flows in terms of monetary value).

The fry source node is disaggregated into the hatchery and wild fry gathering resources. The brackish-pond production compartments are identified according to the regional divisions of the Philippine archipelago. There are 17 regional areas: 1. National Capital Region (NCR), 2. Cordillera Administrative Region (CAR), 3. Ilocos Region (Region I), 4. Cagayan Valley (Region II), 5. Central Luzon (Region III), 6. CALABARZON (Region IV-A), 7. MIMAROPA (Region IV-B), 8. Bicol Region (Region V), 9. Western Visayas (Region VI), 10. Central Visayas (Region VII), 11. Eastern Visayas (Region VIII), 12. Zamboanga Peninsula (Region IX), 13. Northen Mindanao (Region X), 14. Davao Region (Region XI), 15. SOCCSKARGEN (Region XII), 16. Caraga (Region XIII), 17. Autonomous Region in Muslim Mindanao (ARMM). CAR does not produce milkfish having no coastal areas for milkfish culture. The compartments for the market consumption are defined according to the local and export markets by country of destination. The defined flows in between compartments of the milkfish resource system are the economic flow cycling within the defined core components. The economic flows were constructed using values of milkfish fry and milkfish product from 1979 to 2001 that have been assembled using various data sources and empirical studies. The data has been limited to 2001 to eliminate other possible sources of milkfish exports such as milkfish pens and cages in marine and fresh water areas that could affect the results for the brackish-pond resource system.

Data collection and handling. The network flow between the production areas through the distribution channel to the market was constructed using milkfish data series of milkfish brackish-water fishpond regional production and exports (1979 to 2001) from the Philippine Council for Aquatic and Marine Research and Development (PCMARD) which was reformed to the Philippine Council for Agriculture Aquatic and Natural Resources Research and Development (PCAARRD), and from Food and Agriculture Organization (FAO) statistics on global aquaculture production (http://www.fao.org/fishery/statistics/global-aquaculture-production/en). The flows from the regional production areas to the milkfish distribution node were based on the milkfish value of production that were converted from Philippine peso to US Dollars (1 USD = 56.04 peso) to be consistent with the FAO values. The flow of values from the milkfish distribution node to the export market by country is taken to be the volume of export (converted to metric tons from net kilograms) and multiplied by the average value per metric tons of each export product obtained from FAO. The types of milkfish exports are dried, salted, smoked or in brine; fresh/chilled; frozen excluding livers and roes; whole/in pieces, not minced; and prepared/preserved in airtight containers. The export products by value where added according to the country of destination to obtain the total export value of milkfish by country. The flow to the Philippine market is then the total value of production minus the total value going to the export market.

There are no time series data for milkfish fry production to base the flow upon. We reconstruct the value flow of milkfish-fry (as stocking material) from the regional production areas to the fry distribution node by using available empirical studies on the cost of milkfish-fry inputs for the years 1979, 1985, 1986 and 1996 (Chong et al 1984; Agbayani et al 1989; Bombero-Tuburan et al 1989; Israel 2000). The other values are taken as the average of in between years.

The milkfish-fry source is disaggregated to two nodes. The first is the areas where wild caught milkfish-fry are caught and the second is the hatchery sources which has been established in the mid-1990s. The initial source of milkfish fry is a SES where fish-fry gatherers are dependent on the coastal environment for collecting milkfish and other fish-fry before the introduction and operation of hatchery systems within the country. The shift from wild caught milkfish fry to hatchery bred milkfish is assumed to start from 1997 and a 5%, 10% and 15% per year increment is used to capture the lower, median and upper bound shift based on the estimated decline rate of wild fry supply at 11.79% (Israel 2000). The distribution channels (fry and milkfish) are used in the assemblage of the network to represent the function that facilitates the distribution of products. Here, we use the term pseudo-node to represent a network encapsulated within a node. At this point, pseudo-nodes are applied as a surrogate to substitute for the detailed process of material distribution. This would allow us to observe the temporal changes of the brackish-pond milkfish resource network system by fixing the sub-network of distribution into a single node.

Results and Discussion. The economic flows of the milkfish resource network were based on the value of production and export as well as modelled milkfish fry flow from empirical studies. Figure 2 is the resulting network robustness measure of the model with 5%, 10% and 15% incremental shift per year from wild fry to hatchery supply starting 1997. The allotted increments do not change the general trend of increase and decrease of robustness from 1997 to 2001. For the ensuing discussions of the rest of the paper, we use the 10% increment shift from wild to hatchery sourced milkfish-fry. For the robustness plotted against the milkfish production value, there is a general decrease in systemic robustness during the earlier growth periods of the industry from 1979 to 1990. Post 1990, there is a general trend of increasing robustness. It can be observed that there is a noticeable decrease in robustness prior to drop in production values. Such disturbance that occurred in 1991 is the shift from milkfish to shrimp (*Penaeus monodon)* production due to market opportunities for the higher valued product for export (Rosario & Lopez 2005).

In the perspective of ecological system evolution, the development capacity of an ecological network consists of two components: ascendency (efficiency), which maintains the structure through time, and resilience capacity (resilience) against perturbations. The temporal changes in the milkfish industry from 1979-2001 indicate a trend of growth and development with minor and major fluctuations that can be attributed to various disturbances within and external to the system as indicated in the development capacity, ascendency and resilience (Figure 3). The development capacity of the system is the sum of ascendency and reserve capacity and it could be observed that there is an almost equal distribution for both in the early development phase of the system and followed by a movement from equal distribution to favoring higher efficiency (ascendency) until 1991 where there is a sudden drop in all systemic indicators. The recovery in development capacity from 1993 is matched once again with increasing ascendency. It can be surmised that growth and development of the milkfish resource network as indicated by the development capacity is coupled with various allocation of efficiency and resilience, and favors higher levels of efficiency relative to resilience in the absence of major disturbances. Since robustness is a function of allocation of efficiency and resilience allocation, it can be said that the decrease in systemic robustness is due to an increasing tendency for the system to achieve greater efficiency over resilience. So far, there is no prescribed distribution of efficiency and resilience for social-ecological systems and we require a benchmark to ascertain where our system lies in reference to other systems that have been previously studied.

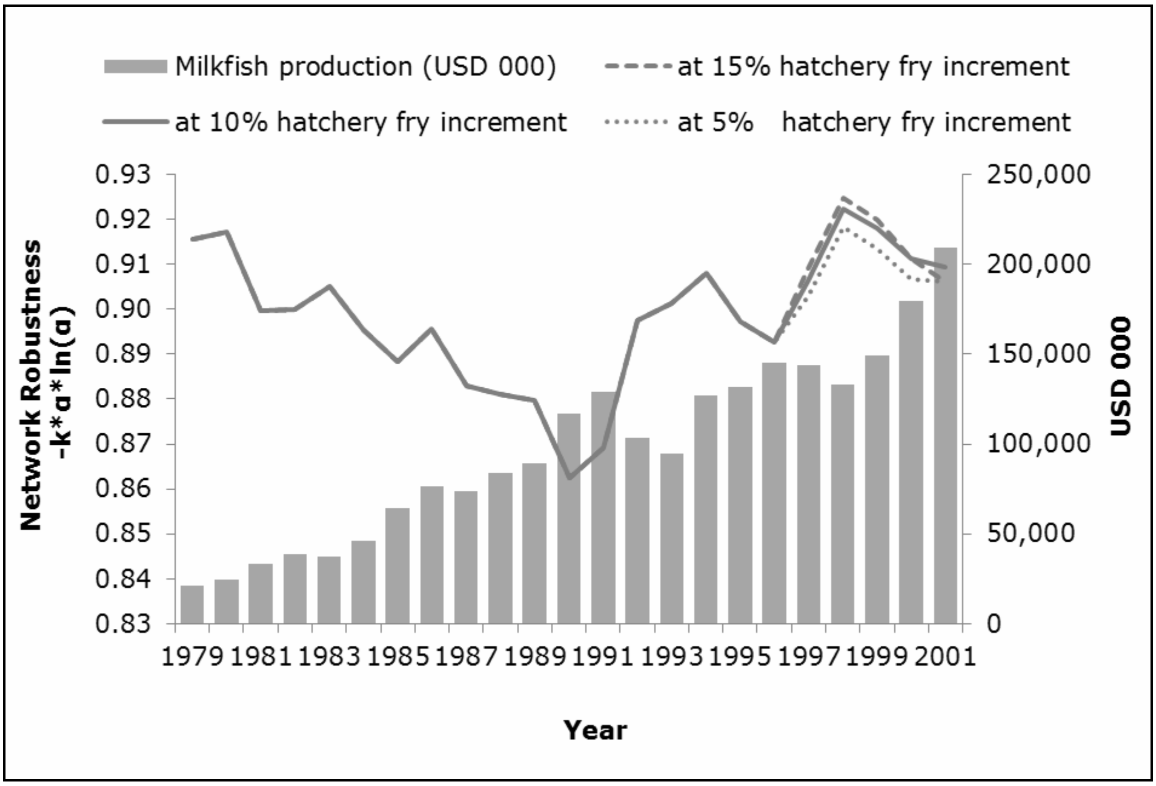

Figure 2. Systemic trend of robustness of the Milkfish resource network with incremental shift from wild to hatchery fry supply of 5, 10 and 15 percent per year.

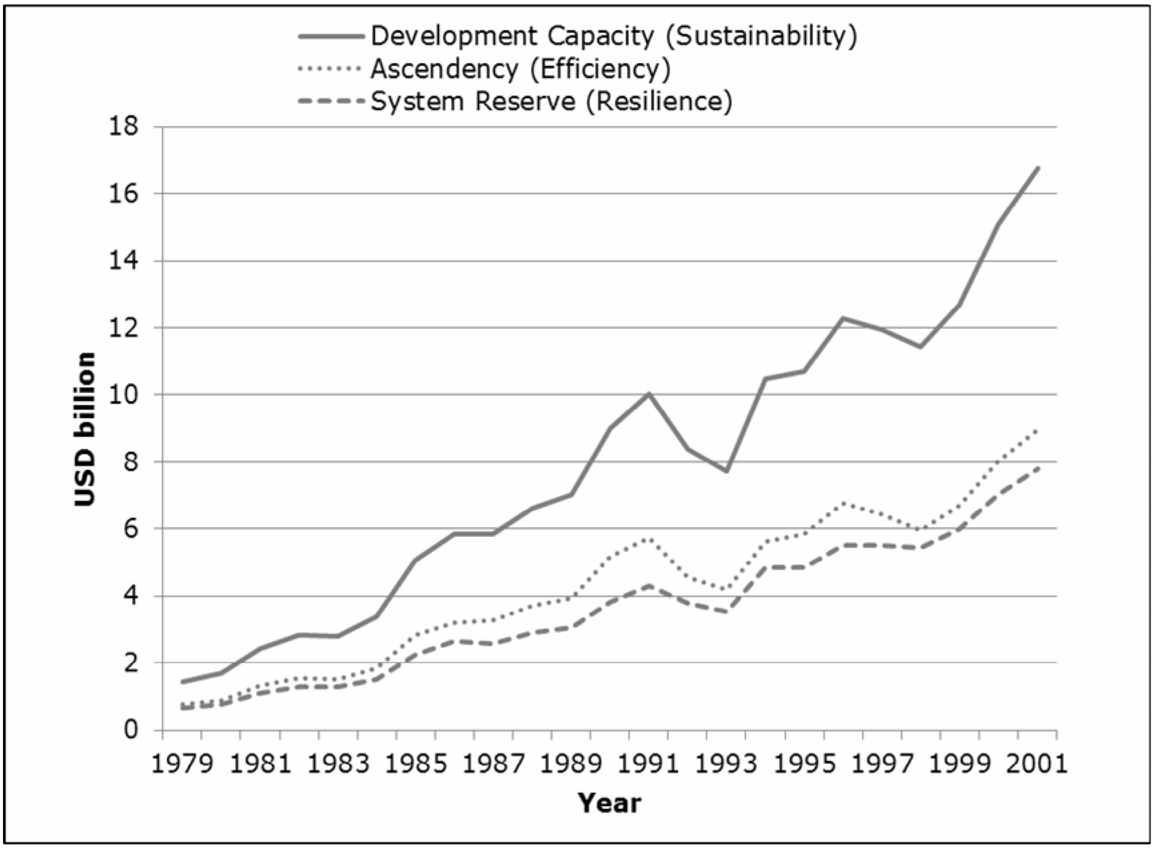

Figure 3. System Development Capacity, Ascendency and Reserve Capacity temporal change.

To examine the implications of the results, it is necessary to establish a bench mark against other systems of ecological and human made constructs. Previous empirical application in quantifying robustness of ecological networks determined a hypothetical window of vitality which reflects the allocation of efficiency (degree of order) and resilience (redundancy/reserved capacity) where robustness is optimal (Ulanowicz 2002; Goerner et al 2009; Ulanowicz 2009). We take the examples of five ecological systems which includes Mondego estuary, Lake Findley, Maspalomas coastal lagoon, Crystal river creeks, and Cone spring (Almunia et al 1999; Patricio et al 2006; Baird & Ulanowicz 1989; Kay et al 1989; Ulanowicz et al 2009). The Modego estuary ecological system included three types of network based on the level of eutrophication. The Maspalomas coastal lagoon had 3 networks based on the stages of ecological development. This gives a total of 9 ecological system networks for reference. Also, we draw upon the study by Kharrazi et al (2013) that attempted to quantify the same for global economic resource networks, to represent human structured systems as oppose to ecological networks. These global economic resource networks are: virtual water, oil, global commodity, Organization for Economic Co-operation and Development – Brazil, Russia, India and China (OECD-BRIC) commodity, OECD-BRIC Foreign Direct Investment (FDI), and iron and steel.

We draw from these studies of essentially ecological and human built systems initially to put bearing on our results. Figure 4 shows the resulting average degree of order (relative efficiency) and corresponding robustness of the milkfish economic resource network in contrast to those of global economic resource and the select ecological networks. The average degree of order of the case study is essentially higher than those of global economic resource and ecological networks while average robustness ranges in between although reaching nearer to that of ecological network robustness. The system of interest thus exhibits a higher degree of efficiency at 0.5 as compared to the two other systems at 0.38 and 0.14 for ecological and economic trade networks respectively. The economic resource trade network could benefit from higher robustness by increasing the degree of order while the increase of robustness for the milkfish network could be achieved by decreasing the degree of order. This suggests that the economic resource and milkfish network lies at opposite extreme with reference to global economic resource and ecological networks. The lesson that could be drawn from the observation is that further increasing the efficiency of the milkfish network will further increase its growth but sacrificing robustness and making the entire network system vulnerable to perturbation. In promoting growth and development of the sector, it is also necessary to manage runaway growth from too much efficiency.

To explicitly determine where along the optimal robustness our milkfish network lies, we graph the results together with the two other network types used for benchmarking. Figure 5 summarizes the distribution of the milkfish economic resource network with reference to global economic resource networks and ecological networks in terms of robustness and degree of order. The milkfish industry flow-structure cluster around just beyond the peak of robustness and on the polar side of efficiency. Any increase in efficiency sacrifices further resilience and thus decrease the robustness of the system. The yearly degree of order and robustness of the milkfish network is clustered just beyond the optimum robustness and at the edge occupied by ecological networks leaning towards higher degree of order. Although we consider the milkfish network as an aggregated social-ecological network just as much as the economic resource network we refer to, it occupies the other extreme of increased efficiency as opposed to higher redundancy of its counterpart. It is thus possible for various human and semi-human built networks to occupy both spectrums of high degree of order and high degree of redundancy or resilience.

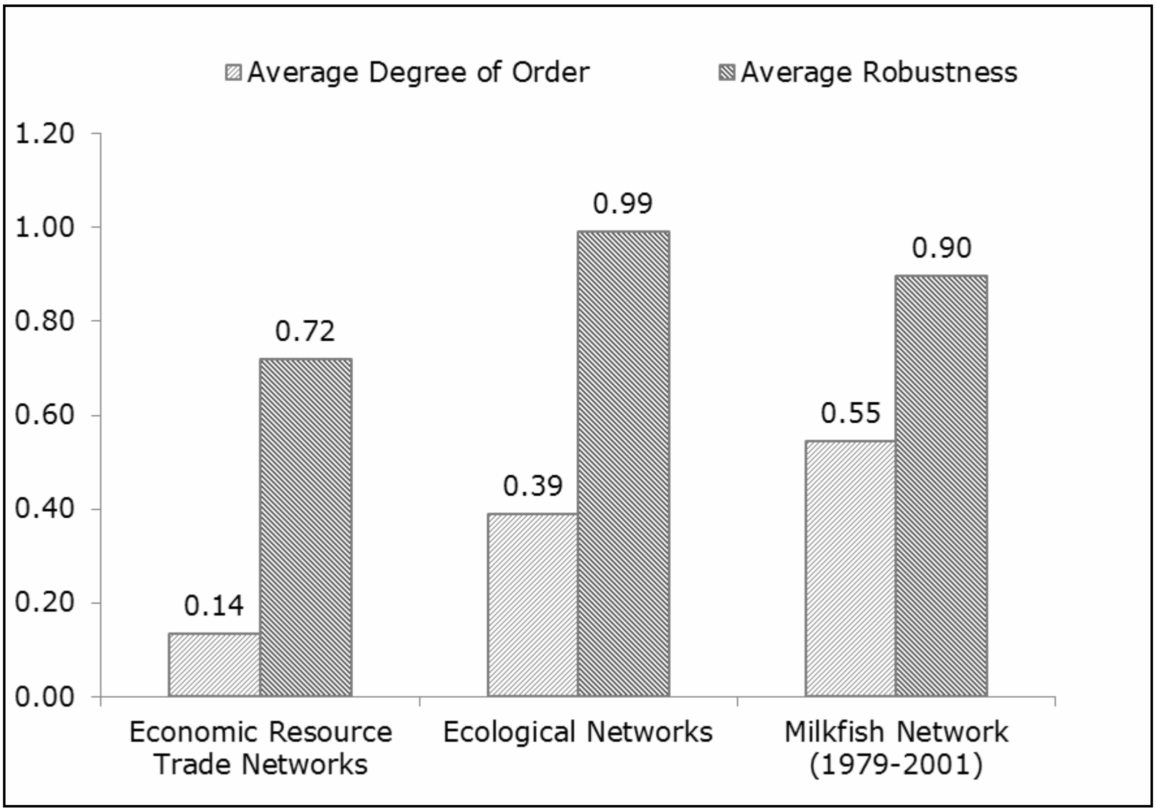

Figure 4. Average and corresponding robustness for the milkfish industry (1979-2001), select ecological and economic resource trade networks.

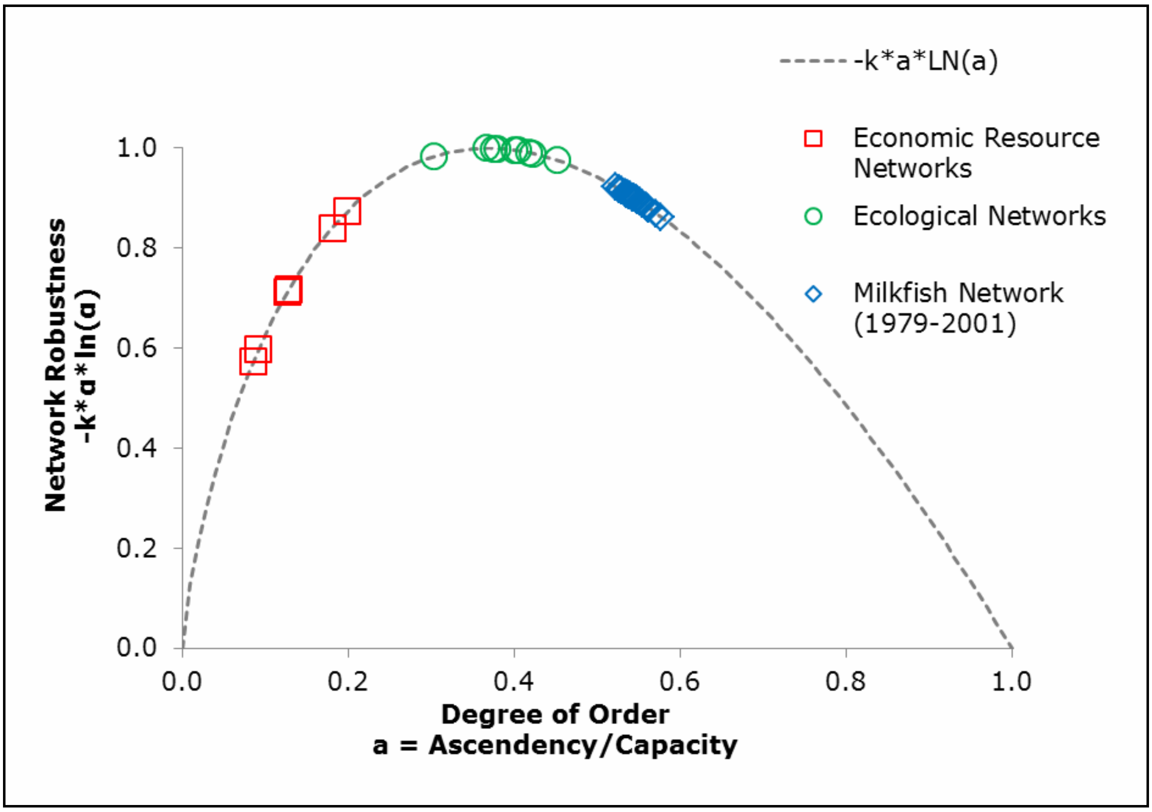

Figure 5. Degrees of order and robustness of the milkfish network from 1970 to 2001 as compared to global economic networks and select ecological networks. The milkfish network shows higher efficiency (degree of order) and clusters on the right side.

We must consider the scale of the milkfish network to that of the economic resource networks. The scope of the latter is global in scale while the milkfish network is at the country scale which only includes international connections by country. We could only assume that the economic resource network has a more complex network structure where countries can both be a supplier and consumer of the resource being considered. It would be interesting to consider the country level analysis of these global resource networks if each country of interest would have the tendency to have higher degree of order or remain in the same area of high resilience. This leads us to question whether systems of high resilience could be composed of sub-networks that are more efficient in structure. This would have implications on the scalar differences of systems that larger robust systems may be composed of efficient sub-networks, but at the moment, it is beyond the scope of this research. In order to increase the robustness of the milkfish economic resource network, it is necessary to increase its resilience by decreasing efficiency. This has important implications to policy in promoting increased production of the sector which are most always oriented in production efficiencies in culture methods of the milkfish sector through technological advances.

Conclusions. Robustness, efficiency and resilience are important considerations for the sustainability of social-ecological systems that remain mostly qualitative in perspective. The ecological network analytical approach is a potential method in quantifying these systemic indicators particularly to network flow and structure persistence. This quantitative measure of these indicators is meant to complement qualitative dimensions developed under the rubric of sustainable aquaculture.

The case study of the milkfish economic resource network revealed patterns comparable to environmental successions where early development of the system experiences decrease in resilience and corresponding overall systemic robustness. We also establish that social-ecological and economic systems occupy a wider range of efficiency and resilience distribution as the cases shown in the global economic resource network and that of the milkfish network. The approach could contribute to the knowledge of social-ecological dynamics of aquaculture resource systems. The systemic indicators can be used in navigating aquaculture systems towards a more robust state by considering not only resilience but the proper allocation of systemic efficiency as well.

As for policy implications, we have described the milkfish network according to the political and geographical division where interventions are usually implemented according to the defined boundaries and which is more relevant to policy makers,. We have chosen a country level of analysis and put emphasis on geographical boundaries to define the network of interest to cater to the academic demand of analysis as well as the potential of acceptance of application within the socio-political structure of governance. The remaining challenge in the temporal assessment of social-ecological resilience and other properties is the difficulty in data availability. We used a simple representation of the network but nevertheless have tested the approach to show the possible application in measuring robustness, resilience and efficiency of the case study. The proposed application is to serve as a model for other possible case studies measuring robustness of interlinked socio-ecological systems and offers a possible assessment of policy implications for sustainable aquaculture growth and development.

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