Doctoral Thesis

Quantifying Socio-ecological System Sustainability:

An Ex-post Analysis of the Philippine Brackish Pond Resource Networks

(社会生態システムの持続可能性の定量化：

フィリピンにおける汽水池水産資源のネットワーク分析)

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A Dissertation

by

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ABSTRACT

Keywords: social-ecological system, social-ecological network, resilience, robustness

Sustainability is the new prevailing paradigm of the 21st century where local and global decisions are based upon concerning the viability of co-dependent human and nature constructs. Nonetheless, the idealism of sustainability remains pluralistic and contested. On the other hand, the emerging concept of resilience is sought to define sustainability in terms of persistence whether by withstanding or adapting to perturbations. However, as much as resilience has become an essential discourse in sustainability of interlinked nature and human-built systems, it has also gained the trait of ambiguity. This poses development and practical application of resilience concepts in jeopardy. An objective measure of resilience could contribute to further cumulating knowledge on social and ecological sustainability. This paper contributes to the resilience debate by providing an objective measure of resilience and systemic network characteristics essential for sustainability and to the study in sustainability science. Although there are proposals of the use of network approach in assessing interconnected social and ecological sustainability, empirical evidence is still lacking to support progress. The ecological information-based approach, which is a form of network analysis that measures robustness as a trade-off between resilience and efficiency, is applied on the Philippine brackish pond sector (composed of milkfish and tiger prawn production industries) as an example of interlinked social, economic and ecological systems to gain understanding of systemic persistence.

Resilience is becoming an important discourse both in the academe and society as a whole. It adds a dimension to sustainability that indicates persistence over time in the

presence of adversity and uncertainty. Resilience has their etymological root that means to bounce back. The use of the term resilience can be traced back to the field of physics and material sciences and diffused to other fields such as psychology, engineering and other trans-disciplinary fields. The more contemporary and prevailing concept of resilience comes from the field of ecology. It has been defined as a capacity to absorb shocks and still retain essential properties to persist. Ecological resilience is not just a matter of bouncing back to an original state or configuration, but the ability to adapt to change. In the age of sustainability, resilience is continuously being adopted both by the scientific community as well as society. However, having diverse interpretations of resilience would hinder further development of the concept. A quantitative measure of resilience may provide a foundation for accumulating and creating new knowledge that is relevant to the academe, policy makers and communities. The challenge therefore is developing an approach of quantification to complement qualitative descriptions of resilience.

The main culture species in the Philippine brackish pond sector is the milkfish. The milkfish brackish pond social-ecological system is composed of two major components. The first is the prime system which is the brackish water pond areas. Milkfish are farmed in earthen ponds relying on natural resources and services such as water, land and the natural micro fauna and flora in the culture areas. The second component is the source of milkfish fry for stocking in the ponds. Before the development of hatchery systems, milkfish fry is gathered in the coastal areas by fisher folks. The milkfish fry social-ecological system is an ancillary sector of the over-all brackish pond milkfish social-ecological system. The milkfish fry and the milkfish production systems are expressed into networks. The milkfish fry social-ecological network is composed of the fry source and the various dealers that facilitate the delivery of fry to the grow-out ponds which is also a social ecological system. The milkfish production social-ecological network also has dealers that facilitate the delivery of the culture product to the market. These networks have been reconstructed at the national, main island and regional scales and the ecological information-based approach is used to measure robustness (sustainability), resilience and efficiency. There seven network structures for the milkfish fry system. Four fry networks are at the regional scale and three at the national. The two networks at the national scale or interregional and inter-island trade of milkfish. There are three main island scale and one national scale networks constructed for the milkfish pond production system. There are a total of eleven systems.

Previous studies on ecological systems have determined that self-organizing ecological systems allocate efficiency and resilience to optimize robustness. A system is said to be sustainable if it has enough efficiency to compete in sequestering resources and yet resilient to novel disturbances. Our results show that the network structures of the milkfish system occupy a wider range of efficiency and resilience levels as compared to ecological systems. Our results also indicate that the milkfish networks occupy a wider range of efficiency and resilience allocation as well as robustness levels. The milkfish fry networks at the national scale have the highest resilience and lowest robustness levels. Here I argue that self-organizing ecological systems are effective in managing the allocation of efficiency and resilience in optimizing robustness than human managed systems as the milkfish network does approach boundary limits determined from ecological systems. The interregional and inter-island trading of milkfish fry had the highest resilience and lowest robustness values, the system could benefit from more efficient trading routes in order to increase robustness. The inter trading of milkfish fry is highly redundant that the system is suffering from too much inefficiency. The milkfish networks were also compared to 6 global economic trade networks. The inter-trade of milkfish fry behaves similarly with the economic networks of having high resilience and low robustness levels. The similarity of economic and the inter-trade fry networks perhaps is due to the network construction which does not highlight the delivery component of the system but instead is comprised of point to point exchange of resources and materials. The application of the ecological information-based approach perhaps has its limits of applicability to trading networks that does not highlight special functions of delivery.

The national milkfish-fry resource delivery has also high resilience and low robustness level that it approaches the boundary of the hypothetical limit for optimized robustness. The network structure of that facilitates delivery of fry from the fry-grounds to the pond production areas is highly redundant and multiple pathways render the system inefficient. However, the milkfish fry distribution network at the regional scale has high levels of robustness and tending towards more efficiency relative to the national fry system. This shows that robust sub-systems do not necessarily render a higher scale system sustainable. This is very much counter to our belief that in order to sustain higher scale systems, it is important to guarantee the sustainability of lower level systems. However, in natural systems such as a forest, constant renewal of sub-component continuously occurs to maintain the overall health of the entire system. In the case of the milkfish fry system, perhaps it is necessary to have both highly resilient and highly efficient regional networks to render the entire system more robust. The efficient regions would contribute to the efficiency needed by the national system and resilient regional network could offer redundant pathways in time of perturbations. Having low level of efficiency, the national fry social-ecological system would likely suffer from competition rather than disturbances to the system.

Hatchery systems were established in the 1990s to artificially propagate milkfish fry for stocking into grow-out brackish ponds. It was a concerted effort between the government, research institutions as well as the private sector to meet the demand for stocking material for the expanding growth of milkfish production. Milkfish hatchery directly competed with the milkfish fry gathering system. The milkfish fry social-ecological system had very little efficiency that it could not compete with the hatchery system in supplying fry to the grow-out areas. This transition from wild fry gathering to hatchery bred fry may be considered as a renewal of system component to maintain the overall system of milkfish production. This is a very important insight of how self-organizing renew sub-components in order to maintain the overall structure of the industry.

In the case of the milkfish production social-ecological systems, the four production networks is observed to behave similar to ecological systems where there is allocation of system residence efficiency and resilience that optimizes sustainability. The production network systems at the national and main island scale seem to occupy its own narrow distribution of resilience and efficiency that optimizes robustness. This could be the potential limit for the milkfish industry, the boundary of persistence. The national milkfish production system does not vary greatly from the main island milkfish systems. One reason is perhaps is that the scale difference between the main island and national level is quite small as compare to the scale difference of the national and regional levels in the case of the milkfish fry. The smaller the scale difference, the more likely the system would behave the same. Ecological systems have the tendency to increase efficiency in the absence of disturbances; it is the natural tendency towards growth and development. At three main islands are at different stages of growth and development. The more developed island has higher levels of resilience. This is counter to the ecological concept of ascendency or increasing efficiency. As the main islands grow and develop the milkfish industry, the less efficient it is becoming. Luzon is the main island where milkfish production was initially practiced before spreading to Visayas, then finally to Mindanao. Luzon has the greatest production and Mindanao the least. Ceteris paribus, as these islands develop their milkfish sector, there is an increasing trend of resilience. Luzon has the highest resilience and Mindanao the lowest. It could be argued that restructuring of the network system to increase resilience to support the flow of material as it increases. This is consistent with the ecological concept of resilience where newly perturbed systems increase resilience as it starts to grow and accumulate resources. This would suggest that resource networks that are developed has higher production and requires higher levels of resilience. The different components of the milkfish social-ecological system has been analyzed at different scales and found to have similar characteristics to ecological systems in terms of the general systemic variables of robustness, resilience and efficiency.

The ecological information based approach is also applied on temporal analysis of the milkfish and tiger prawn social-ecological systems from 1970 to 2001. Results show that resilience is a good indicator for the vulnerability of systems. Prior to rapid decline in production of both milkfish and tiger prawn, a decrease in resilience levels could be observed. The causes of decrease in production for milkfish includes market competition of milkfish coming from fish pen production in lakes; shift in fish farming from milkfish to tiger prawn. Disturbances for the tiger prawn includes outbreak of disease and drop in market demand. The measure of resilience is not aimed for any specific disturbance such as what has been mentioned. It is the concept of increasing diversity. Having stated the various disturbances, the measure still responds well to determine if the system is becoming vulnerable to disturbance that may be coming from the social, ecological or economic domains. The main lesson in this research is that social-ecological network systems have traits similar to ecological systems. Many are familiar with the concept of efficiency, but in attaining systemic sustainability, resilience should also be considered. The approach can assist policy makers and practitioners in making informed decisions in maintaining sustainability by deciding over the trade-off between efficiency and resilience of social-ecological systems described as a network.

DEDICATION

I dedicate this research to my family. Even with the great distance, they have supported me. After five years of sacrifice, trials and uncertainties, I will soon be with you all. To my wife, this is our achievement for our family and our future.

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LIST OF TERMINOLOGIES

AMI
Average Mutual Information

BAS
Philippines Bureau of Agricultural Statistics

BFAR
Bureau of Fisheries and Aquatic Resources

DO
Dissolved Oxygen

FAO
Food and Agricultural Organization

IT
Information Theory

PCAARRD
Philippine Council for Agriculture, Aquatic, and Natural Resources Research and Development

PCMARD
Philippine Council for Aquatic and Marine Research and Development

SEAFDEC
Southeast Asian Fisheries Development Center

SES
Social-Ecological System

UN
United Nations

WCED
World Commission on Environmental Development

1. INTRODUCTION

1.1 Sustainable development and sustainability science

The world population is predicted to grow by half by the middle of this century. The continued population growth is simultaneously matched with soaring global temperature brought about by climate change. The situation is further made worse with the increasing demand for food and water while efforts in achieving sustainable development such as the Millennium Development Goals struggled in reducing hunger-afflicted shares of the global population (Morse 2010). This is only one example of the myriad of complex challenges society is facing today and the near future. The economic, social and ecological domains are full with slow persistent problems and fast progressive shocks that pervade throughout global, regional and local scales. For the past recent years, the results of interventions created other problems of greater complexity and of more relevance to the global society. Societies have recognized these heightened social, ecological and economic issues evolving from the old “wicked problems” (Rittel and Webber 1972) to the “new sustainability challenges” with greater societal and ecological implications (Jerneck et al. 2010). Society has a strong reliance on their management skills and technology to address sustainability challenges but the rate of change on the planet is much faster than the rate that society can comprehend such changes (Vitousek et al. 1997) and requires novel methods of analysis and approaches. Interdependent natural and man-made systems are becoming more and more integrated and unstable. The world dilemmas are becoming more and more connected and challenges increasing in complexity and magnitude that society and science need a new paradigm in problem solving. However, traditional scientific and technological responses are no longer enough in providing solutions and attempts in problem solving creates new ones or unintended results.

Efforts have been made to define sustainability, and yet, it still remains as an enigma. Sustainability has been described as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", by the World Commission on Environment and Development (WCED), also known as the Brundtland Commission (1987). The WCED argument of economy and environment interdependencies has received global attention that lead to the sustainability paradigm of growth and development. Sustainability has been further defined as meeting the needs of and improving society without jeopardizing the planetary support systems (Kates et al. 2001; and Clark 2007). A new science has thus been called for as a response to such a challenge of maintaining human and ecological co-dependencies and to ensure a more sustainable future for the planet and consequently, humanity. Thus the impetus for "Sustainability Science" was brought about by the WCED (1987).

Sustainability science is the emerging and evolving scientific field which is the needed response to the complex social and ecological challenges of the twenty first century that could no longer be solved by traditional approaches and technological solutions. As an academic field, sustainability science is described as an institution that postulates direction to understanding holistically various sustainability challenges and provides visions and methodologies in developing a sustainable society (Komiyama & Takeuchi, 2006). It has been more than a decade since the field of sustainability science materialized and could be thought of as an evolution of scientific inquiry. The old 1st mode of scientific discovery and knowledge production is insufficient in solving the complex challenges humanity is facing and the emergence of sustainability science is closely related to the rise of the 2nd mode of science (Gibbons et al., 2003). Sustainability science has been further defined between the "science for sustainability" and the "science of sustainability" or the 1st mode and 2nd mode of sustainability science (Spangenberg 2011). A third mode of science has already been proposed which tries the integration of human well-being and quality of life to academic scientific research (Frühmann et al. 2009). Although this proposed third paradigm is still under conceptual development and contention, it is taken note that there are other emerging conceptualizations of sustainability science. One of the main role of sustainability science as a field of scientific inquiry is to capacitate scholars with competencies in understanding perpetual complex challenges that humanity is facing amidst uncertainty in today's contemporary world. Thus, sustainability science capacitates academicians by applying novel approaches relevant in today's sustainability challenges that traditional sciences are unable to resolve. However, methods of analysis and approaches are deeply rooted according to the traditional sciences and new methods still need to be developed and tested.

Higher education has the objective of producing future leaders in sustainability science in order to create a more sustainable future (Cortese 2003) but these leaders should be familiar with the fundamental questions relevant to sustainability to guide the kind of research relevant to the field. Since the emergence of sustainability science, core questions has been proposed to guide research in addressing fundamental questions related to human and nature interactions. The same core questions raise the concern to what methods and approaches and concepts would be critical in building the science for sustainability. The core questions highlight the importance of understanding human and nature interdependencies, resilience and interdisciplinary efforts. The core questions were proposed to draw the attention on "both the fundamental character of interactions between nature and society and on society's capacity to guide those interactions along more sustainable trajectories" (Kates et al. 2001):

1. How can the dynamic interactions between nature and society – including lags and inertia – be better incorporated in emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?
2. How are long-term trends in environment and development, including consumption and population, reshaping nature-society interactions in ways relevant to sustainability?
3. What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?
4. Can scientifically meaningful "limits" or "boundaries" be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?
5. What systems of incentive structures – including markets, rules, norms and scientific information – can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
6. How can today's operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?
7. How can today's relatively independent activities of research planning, monitoring, assessment and decision support be better integrated into systems for adaptive management and societal learning?

In summary, the core questions 1 to 5 direct research and knowledge creation towards social-ecological interactions and persistence over time. Questions 6 and 7 reflect the fundamental foundation for the need of an interdisciplinary science that transcends traditional science.

1.2 Social-ecological resilience: emergence and challenges

The guiding core questions have become the foundation for an emerging field of research studies in sustainability science focusing on the persistent complex interaction coupled nature and society. As an example, the Resilience Alliance is a research association composed of institutes involved in developing concepts and research methods in understanding human-nature constructs or social-ecological systems (SES). "A SES is an ecological system intricately linked with and affected by one or more social systems" (Anderies et al. 2004). SES is also referred to as socio-ecological and human-environment systems (Gallopin 1991, Turner et al. 2003 and Scholz 2011). There are also journals dedicated to the accumulation of knowledge involving society and ecology (e.g. *Journal of Ecology and Society*). The concept of SES and resilience are applied in other areas of research with their corresponding sets of objectives and epistemological foundations. All have the same recognition that human is an important driver in changing the planet system in the age of the “Anthropocene” (Crutzen 2002 and Glaser et al. 2008). Various conceptualizations of SES are also being adopted by different field of studies and have become widely accepted due to the central concept of resilience which it encapsulates.

Although, resilience is becoming a sustainability agenda (Perrings 2006, Kates et al. 2001, Foley et al. 2005), the concept of resilience has also attained traits of being malleable and connotes a plethora of perspectives and interpretations owing to the adaptations of the different disciplines. The concept of resilience has gone beyond its etymological meaning and has been applied to varying social, ecological and economic contexts. The concept of resilience has gone beyond academic sciences and has also become a pervasive notion in local, regional and global governance (Walker and Cooper 2011) and includes the social, economic and ecological domains. Although the malleability of resilience allows it to be adopted by various disciplines and situations, this may also be the cause of the concept to lose its core idea and efforts in managing resilience becomes incomparable. The descriptive classification of resilience may benefit from a formal (mathematical) definition.

How to build resilience is also becoming important to social processes and adds dimension to the practice of sustainability and setting trajectories for future states. However, resilience has been imbued with subjective normative values, something that is to be desired and implies triumph over adversity. Having multiple subjective interpretations can cause misunderstandings and constrain an effective management of a SES. The abstract form of resilience makes it adaptable in both the academic and social arenas may it be in theoretical or applied discourse and possibly also put it in peril without common knowledge and concrete grounding on its usage. Efforts in attaining resilience would be incomparable if it is based on different standards and standpoints. Most of literature on resilience mainly remains as a synthesis of qualitative definitions and there is the existing gap between the qualitative and quantitative concepts of resilience.

Provided the conditions above, it is the intention of this research to give a formal quantitative expression for the qualitative interpretations of systemic sustainability using the stand point of SES resilience perspective and guided by the sustainability science core questions. The challenge therefore in this research is to empirically measure quantitative systemic traits of sustainability such as resilience. This is an attempt to contribute to the sustainability and resilience discourse that could potentially provide a mathematical understanding of systemic sustainability which remains to be missing in the field of sustainability science. This paper proceeds with the review of current concepts in the study of resilience and how it is defined, applied and measured. Select key concepts are used in order to bridge the qualitative and quantitative interpretations of resilience.

1.3 From resilience to ecological resilience

This section is a brief review the etymological origin and the multiple epistemological variations of resilience. Resilience from Latin ("*re- + salire*") literally means to "spring back" or to return to the original form. The early origins of resilience can be traced in the field of physical and material sciences and diffused to the fields of ecology, psychology and other "inter" and "multi" disciplinary fields. Resilience has been employed in the physical and material sciences to describe a state of material against a particular external force. In the science of physics, resilience is defined as the capacity of a given material to absorb pressure without losing its basic properties upon the removal of pressure. Gordon (1978) has described resilience as a material property to withstand stress by bending and "bouncing back" without breaking. A material that returns to its original shape instead of being permanently deformed is said to be resilient. Resilience is a material property according to its composition and could be understood in terms of the stress and strain applied. Thus resilience is a material property in relation to the external forces being applied and the capacity to return to equilibrium after displacement. In this case, the usage of the term resilience is consistent with the etymological meaning of springing back to the original form. From this stand point, resilience has been applied by various disciplines and beyond scientific fields. Various disciplines have adopted the etymological description of resilience and have incorporated their own epistemological perspectives. Between 1970s and 1980s, resilience was redefined in the fields of psychology and ecology according to their respective core concepts (Norris et al. 2008). Development of concepts of resilience ensued as disciplines continued to solve sustainability issues in the social, economic and ecological domains which are more complex dynamic systems compared to the static nature of materials. The concept has not remained within the scientific fields but has perpetuated to the public domain under the pressures of social, economic and ecological crises (MacKinnon & Derickson 2012). The use of term resilience can be said to have three epistemological strands: 1) mental health and psychology, 2) natural disaster and security and 3) social-ecological systems (Berkes and Ross 2013).

The 1st strand of resilience in the field of psychology gives attention on the ability of an individual which has also been applied to the community. Resilience in the strand of mental health and psychology has its focus of the individual and community capacity to recuperate from adversity (Buikstra et al. 2010; Luthar 2006). The application of resilience in psychological research is defined by risk and vulnerability to humans as an individual or community. Resilience as a human trait in the field of psychology is described as "the potential to exhibit resourcefulness by using available internal and external resources in response to different contextual and developmental challenges" (Pooley 2010). In other words, psychological resilience concerns the individual or community in relation to perturbations and is synonymous to the etymological definition of resilience which considers external pressure to the system. However, there is also the recognition to both external and internal characteristics influencing resilience as applied to individuals and community (Norris et al. 2008).

The 2nd strand of resilience emanating from the natural disaster and security takes the meaning of resilience much more of the etymological sense (Norris et al. 2008) which indicates a capacity of a system to recover to its original state after a disaster or return time after failure (Hashimoto 1982). The disaster and security perspective encapsulates the idea of bouncing-back. This early adaptation of resilience in the strands of psychology and natural disaster considers external shocks and recovery to the original balanced state. The old view of resilience as bouncing-back, springing-back and return to equilibrium has been redefined to "engineering resilience" by Holling (1996). The traditional and etymological meaning of resilience thus exemplifies system maintenance in consideration to perturbations external to the system.

The 3rd strand of social-ecological system studies applies the concept of resilience that is deeply rooted in the field of ecology. The concept of resilience as maintaining a balanced state has also been eminent in ecological studies until the seminal work of Holling (1973) where he challenged the traditional view of ecological stability to one of constant change and adaptation or "ecological resilience" (Holling 1996, Gunderson 2000, and Anderies et al 2006). Social-ecological system resilience studies are increasingly considered in environmental and sustainability issues (Clark et al. 2007; Jerneck et al. 2010; Kates et al. 2001; Perrings 2007). Within this emerging field of study of social-ecological systems, resilience is defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al. 2004). Thus, "engineering resilience" is integrated in the "ecological resilience" perspective where resistance is complemented with adaptation to change. Both properties of resilience are important to persistence near and far from equilibrium.

The pivotal concept of "ecological resilience" or ecosystem resilience (Gunderson and Holling 2002) is a synthesis of observed general characteristics of ecological systems that maintains persistence. Ecological resilience recognizes the etymological definition of resilience as maintenance of an environmental unit, such as a natural forest, according to the consistency of state variables (e.g. maintaining the constant balance between flora and fauna) in consideration to external natural or human-induced disturbances. This internal regulation of maintaining state variables is known as the "engineering resilience" previously described and is recognized to be a systemic property of ecological units essential to maintenance and returning to the original state variables after a disturbance. However, an environmental system also has the trait of changing state variables and yet continues to persist. A forest system is known to have a succession from low density to high density conditions with varying combination of state variables and is able to recover from perturbations by going through this process. An ecological forest system can also have two possible states, one of high tree density and one of high shrub density. Each state can exist over a long period of time and minor disturbances tend to move the system away from the prevailing state, but it is the property of engineering resilience that maintains the state of the system either at high tree or high shrub density configurations. These configurations are said to be close to equilibrium. Thus, ecological systems have both systemic properties of resisting change and undergoing change in the presence of disturbances. This is the general description of the resilience concept that embodies “engineering resilience” and “ecological resilience” that is being applied in various fields with the intent of achieving sustainability of ecological and socio-ecological systems (Anderies et al. 2006 and Folke 2006).

The resilience concept has etymological origins encapsulated within epistemological perspectives and has become a boundary object for the other disciplines that integrates their own epistemological foundations (Brand and Jax 2007). This transition from “engineering resilience” to that of “ecological resilience” is also evident in the adaption of the field of psychology and community development where resilience is also being redefined as the ability to "thrive in an environment characterized by change, uncertainty, unpredictability and surprise" (Magis 2010). As applied to individual and communities, resilience still denotes the capacity to respond to external stress. However, further development of the concept outside the discipline of psychology also included internal changes to the individual as well as the community. For example, there are community development projects aimed to capacitate both personal and collective capacity of institutions to be reflexive to variety of internal and external changes (Canadian Centre for Community Renewal 2000). However, there is the peril of diluting the epistemological value of the resilience concept that originated from the ecological field as it becomes more widely applied to other scientific and applied fields. Having various interpretations promote and allow diffusion into trans-disciplinary application of the resilience concept but put into peril practical approaches and policy implementation. Operationalization of the resilience concept thus remains difficult to implement and hinder advancement in research and application (Pickett et al. 1994, and Brand and Jax 2007).

Thus far, most development of the concept of resilience has remained highly qualitative and defined by the etymological and epistemological stances. A quantitative measure of resilience is equivalently important as having etymological and epistemological meaning. Both qualitative and quantitative approaches have their own benefits and limits in defining resilience being employed in various disciplines. Integrating the advantages of both could provide a better understanding of resilience and how it is applied on social-ecological systems. Qualitative and descriptive analysis of resilience provides an intuitive understanding of SES phenomena which may be difficult to explain quantitatively because of emergent characteristics of system complexity. Quantitative analysis on the other hand can provide better understanding of system behavior according to its components and their relationships (Bondavalli et al. 2009). It is a necessity in this research to utilize current concepts of qualitative analysis as a reference to describe quantitative measure of resilience as an initial attempt to give meaning to the value being measured and to serve as a guide in ensuring consistency in defining resilience in terms of systemic persistence.

1.4 Towards network approach in quantifying ecological resilience

The complex challenges involving social and ecological relations could not be dealt with by traditional scientific solutions and need to be considered with an interdisciplinary approach (Folke 2006, Young et al. 2006 and Binder et al. 2013). Various models and frameworks have emerged based on the imperatives of the sustainability science core questions that illustrate human to nature relationships, resilience, boundaries and limits to prevent degradation. The "Social-ecological Systems Framework" (Ostrom 2007 and 2009) is an example of such approach that "provide a common language for case comparison for organizing the many variables relevant in the analysis of SES into multitier hierarchy that can be unfolded when needed, and for facilitating the selection of variables in a case study" (Binder 2013). Ostrom, who is a Nobel Memorial Prize awardee, developed the framework to capture the hierarchical interaction of social and ecological systems. The application of the framework is intended for a wider community to cumulate knowledge across various researches. Although there are other frameworks and approaches in analyzing SES (e.g. Driver, Pressure, State, Impact, Response - DPSIR; Earth System Analysis-ESA; Human Environment Systems Framework-HES), the "Social-Ecological System Framework" has been regarded as the most suited to allow aggregation of data from other frameworks for analyzing SES due to the equal treatment of social and ecological components as well as identifying variables at different scales (Binder 2013). Efforts are on the way to standardize various concepts and variables at various scales by using the "Social-Ecological System Framework".

Although efforts of standardization and integration contribute to the holistic approach in understanding SES properties and dynamics, the "Social-Ecological System Framework" remains difficult to apply as a quantitative approach having varying variables at various scales and domains (social. economic and ecological). Other frameworks or approaches under the realm of sustainability science used to analyze SES resilience have also not fully included the inherent design structure of systems being considered (Janssen et al. 2006). Likewise, SES resilience analyses are predominantly qualitative and quantitative approach continues to be scant. Other frameworks, concepts and theories are necessarily narrative and descriptive to facilitate intuitive understanding of SES complexity but are also difficult to apply quantitatively. The challenge therefore lies in the quantitative measure of resilience and other traits of SES sustainability to complement qualitative approaches to advance our understanding of sustainability in sustainability science. This manuscript is thus an effort to fill the mentioned gaps in SES analysis by employing a mathematical founded approach to measure SES resilience and sustainability by inclusion of structural design of SES at various scales.

An emerging approach in analyzing SESs is coming from the science of networks (Gonzalès and Parrott 2012; Janssen et al. 2006, Ahern 2011). Network concepts and methodologies have been used to study structure, processes and development of ecological systems. The application of network analysis on food networks, ecosystem properties, species mutualism and dispersal has developed into a sub-field of study of Network Ecology (Borrett et al. 2014). A network is an arrangement of elements and the relationships between the elements. A network structure is a notion well recognizable to many, but there are also network properties that could also be observed by applying network information metrics. A SES represented as a structure of elements that are interrelated could thus be quantified. Jansen et al. (2006) recognized the potential of applying network approach and distinguished social and ecological elements to represent human-related and nonhuman components respectively. Although clear separation of human and nature into components are quite useful in analysis, such distinction remains arbitrary in heterogeneous systems.

Taking a network perspective thus offer a way in managing SES by first understating the interrelationships of the social and ecological nodes and by managing these elements and their connections. Thus far, there is still a shortage of case studies applying network approach to real world SESs as well as considering cases that are embedded in a globalized scenario (Young et al. 2006). There is a need to consider the assemblage of social and ecological elements embedded in a larger scale network that goes beyond physical boundaries of social and ecological systems.

The use of network approach has a long history in scientific analysis in the natural and social sciences. In economic and ecological systems, relationships of components are determined by information that is evaluated by the throughput such as gross domestic product and biomass respectively circulated within the defined network. Although biomass and economic flow could indicate growth they do not reflect the structure facilitating the flow, and hence are insufficient to reflect healthy development (Goerner et al. 2009). In the field of ecology, network approach has been applied by ecologists to study the structure and function of ecological systems (Borrett et al. 2014). The use of networks has also been applied in the field of economics in the form of input-output modelling of economic flows (Leontief 1936) prior to the adoption of contemporary ecologists. The adoption of network approach has spread to other scientific fields as well and may be a useful basis in comparing social, economic and ecological systems across different case studies (Janssen et al. 2006).

The wide adoption of a network perspective (from economics to ecology) may thus have an interdisciplinary benefit for studies in sustainability science. Perhaps the flexibility of the network approach makes it a good candidate in facilitating communication as a boundary object between various fields just like the concept of sustainability and resilience. In a sense, a network approach is also malleable and adaptable in different contexts. A network approach is also useful in studying the heterogeneous social and ecological components of a SES and efforts to develop methods are already underway (see Bodin and Tengo 2012, Janssen et al. 2006, Gonzalès and Parrott 2012). However, empirical studies are still necessary across different cases to verify the applicability and to gather systemic network traits of SESs. This research also acknowledges that there is still limitation in applying the network approach in terms of the arbitrary and qualitative identification of elements and relationships (nodes and links) to determine the network structure of a SES. There is also limitation in joining elements and relationships of varying characteristics in a single network structure such as monetary flow networks and ecological networks.

In relation to the core questions, a network approach can make apparent the relationship between homogenous human and nature components as well as heterogeneous collections of human and nature components. Further testing of these assumptions is required to establish the potential of a network approach in analyzing complex SES networks. It is thus necessary to conduct research in sustainability based on network approach to develop novel methods in understanding human and nature dynamics which could potentially aid efforts towards attaining sustainability.

Based on the previous arguments and in consideration of the limitations, the objective of this research is to **1) employ network theories to analyze a SES described as a network at various scales** as well as **2) determine the applicability of the approach on temporal analysis of SES growth and development**. Furthermore, we seek for general system characteristics by taking the stance of an emerging field of network studies known as “network Ecology” (Borrett et al. 2014) together with the core concepts in SES resilience.

2. CONCEPTUAL FRAMEWORKS

2.1 Adaptive Cycle Narrative

Ecological resilience has always been a descriptive ecological concept developed from observation of real world environment systems (Brand and Jax 2007). The concept has been further developed into formal models, one of which is the “Adaptive Cycle" (Figure 1), based on the natural succession of ecological systems in terms of four phases: 1) exploitation (r), 2) conservation (K), 3) release (Ω) and 4) re-organization (α) (Holling 1986). The distinct phases have their own corresponding combination levels of capital (y-axis; amassed resources), connectedness (x-axis; level of interconnection of elements) and resilience (z-axis), which is described as "the ability of a system to maintain its structure and patterns of behavior in the face of disturbance” (Ibid). The purpose of the heuristic model is to retain general observable traits of systemic events in the course of growth, development and change (Gunderson and Holling 2002).

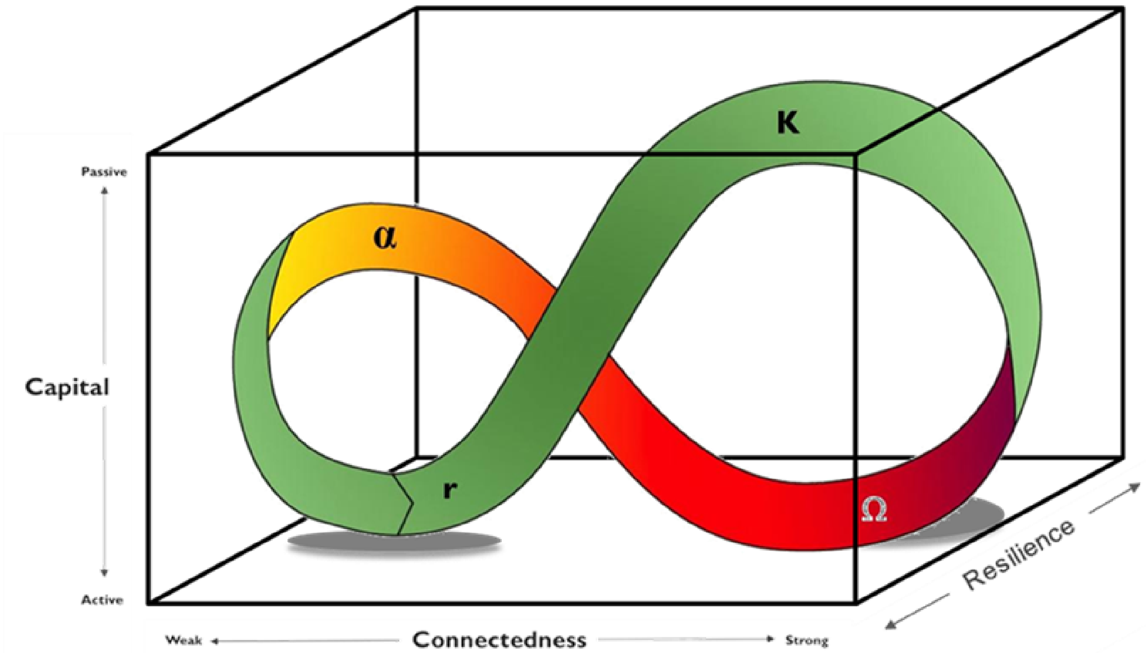


Figure 1. A stylized figure of the “Adaptive Cycle” (based on Holling 1986)

In a given ecological system, the r phase is characterized by fast inhabitation of rapid growing but short lived species (r-strategists) which are efficient in utilizing resources for growth in a newly disturbed area. The K phase on the other hand is characterized by slow growing but long lived species (K-strategists) that accumulates and sequester resources for prolonged periods of time. The transition from the r to the K phase is the transition of the r-strategist dominated state to the K-strategist dominated state which is accompanied by capital (e.g. biomass) accumulation and increasing connectedness of elements in the system. Connectedness refers to the tightly accumulated capital to the existing fauna and flora in the maturing system which increases rigidity thus decreasing resilience (Holling et al. 2002). The r phase is thus characterized by fast resource utilization and growth while K phase is characterized by conservation of the available resources within the maturing system. The r-K transition is the forward loop of the cycle.

The omega (Ω) phase is an added feature to the heuristic model that was taken from Schumpeter's "creative destruction" (1950). The capital accumulation in the K phase becomes tightly bounded to the elements that the system becomes "rigid" and susceptible to perturbations (e.g. pest outbreaks or forest fires). The transition from K to Ω on the onset of a disturbance occurs instantaneously and accompanied by the release of accumulated capital. The alpha (α) phase is the stage of reorganization where natural processes make the natural capital available for the phase of exploitation. The Ω- α transition (backward loop) increase the available capital as connectedness is eroded and initial resilience begins to increase creating a new cycle.

Table 1 summarizes the levels of capital, connectedness and resilience, and cycle speed according to the four phases, as well as the changes from one phase to the next. It could be observed that connectedness and resilience have a direct inverse relationship in the model.

Table 1. Corresponding levels and trends of the variables of the "Adaptive Cycle"

	Capital	Connectedness	Resilience	Speed
		Key variables states		
Reorganization (α)	High	Low	High	Slow
Exploitation (r)	Low	Low	High	Fast
Conservation (K)	High	High	Low	Slow
Release (Ω)	Low	High	Low	Fast
		Key variables trends		
α-r	Decrease	Increase	Increase	Increase
r-K	Increase	Increase	Decrease	Decrease
K- Ω	Decrease	Decrease	Decrease	Increase
Ω- α	Increase	Decrease	Increase	Decrease

2.2 Window of Vitality function

Provided the qualitative conceptualization of resilience in the Adaptive Cycle, there is also another view of resilience emerging from quantitative ecological studies using network, graph and information theories. The "Window of Vitality" (Figure 2) is another general framework emerging from the field of network ecology that attempts to capture the concept of sustainability and resilience (Ulanowicz 2002, Zorach and Ulanowicz 2003, Goerner et al. 2009, and Ulanowicz et al. 2009). This framework, determined by quantifying real ecological networks, is a generic metric for sustainability of network flow systems of matter or energy (collectively called as information).

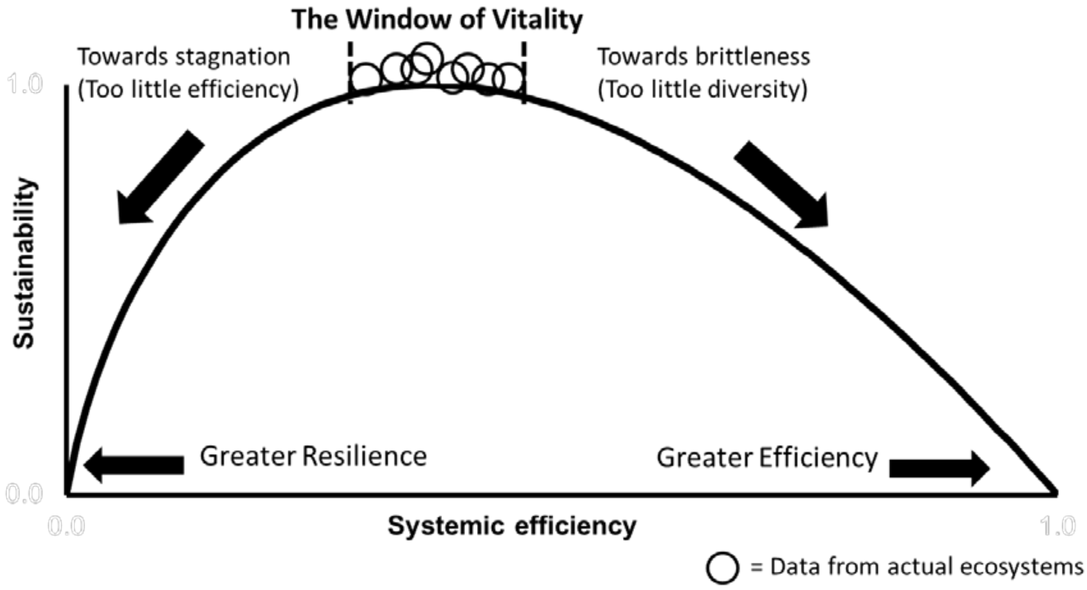


Figure 2. A stylized figure of the "Window of Vitality" (based on Goerner et al. 2009)

The "Window of Vitality" represents sustainability as a function of two opposing but complementary ecological system properties of resilience and efficiency. Sustainability of a given ecological unit is optimized depending on the allocation of systemic resilience and efficiency. Excessive efficiency leads a natural system towards brittleness (Holling 1986 and Ulanowicz et al. 2009) and becomes susceptible to collapse in the onset of novel disturbances. On the other hand, excessive resilience also leads the system towards stagnation that it would not be able to compete with other efficient environmental configurations and would be at risk of losing resources. The system thus is optimized within a hypothetical Window of Vitality which ensures system persistence over long periods of time and under the presence of novel disturbances by having enough systemic resilience and efficiency.

Systemic efficiency as applied in ecological systems pertains to the effectiveness of resource acquisition and utilization which is necessary for growth and development. In a simple input-output model, a given system is said to be most efficient if the input in a certain process is equivalent to its output. The more efficient a given ecological unit, such as a species population, the more resources it can accumulate against other species. In this case, the efficient species would out-compete others in resource accumulation. Efficiency is also related to the processing time of material. In a given span of time, efficient species can process more material than less efficient species and can utilize and accumulate resource much faster. Efficient species out-compete and out-grow slower species and can dominate a given ecological system. Natural systems have the propensity for growth in the absence of perturbations and this is also apparent in the adaptive cycle where efficient r-species surpass K-species in the reorganization phase and dominates the growth phase of the cycle.

The disadvantage of having excessive systemic efficiency is that the ecological system becomes too fragile to disturbances. Taking the extreme case of a single species dominated environment, the ecosystem becomes vulnerable to the weaknesses of that particular species. Given such monospecies organization, there would be a possibility of an entire collapse of a species of flora or fauna due to an outbreak of virus, as a didactic example. The importance of species diversity then becomes necessary in such scenarios of high systemic efficiency. Having multiple species in an ecosystem prevents such brittleness and offers a degree of resistance to novel disturbances by providing some reserve that can maintain the perturbed environment.

Systemic resilience of an ecosystem is very much related to species and functional diversity which operates opposite to that of efficiency. Each species have different response mechanisms to disturbances and increase the chance of the overall persistence of a given ecosystem. In contrast to a simple and efficient monospecies ecosystem, resilience operates by increasing complexity. Ecosystem efficiency and resilience can be thought of as order against chaos or simplicity against complexity that both exist within the same system.

Ecosystems are complex environmental systems composed of multiple interdependent and competing species with overlapping functions. Failure of one functional species can be compensated by others that perform a similar function within the ecosystem in times of disturbances and acts as a reserve that ensure integrity of the system. Similar to efficiency, systemic resilience also has its limits. Excessive resilience is a countervailing force to efficiency that erodes growth of the entire ecosystem. Maintaining diversity of species in a given ecological unit means allowing less efficient flora and fauna to exist together with efficient species. These less efficient species may be seen as ineffective converter of energy and material which may leak out of the system and slows down the growth process. Too much diversity leads to dissipation of resources that could be used within the system for growth. Thus resilience through diversity also has its limits just as efficiency.

An ecological system maintains systemic efficiency and resilience as determined by the window of vitality. It is within this band that persistence of an ecological unit is insured, that there is enough efficiency for growth and enough resilience for disturbances. The focus of these two properties can be identified as internal and external. Systemic efficiency is related to the internal process for growth while the systemic resilience is the reserve for external disruptions to the ecological system. These are two important points when managing towards sustainability. In human built systems, focus has always been on efficiency to increase growth and very little attention is given to the aspect of resilience. These two conceptual components of sustainability may provide a useful indicator against degradation of social and ecological systems as proposed in the sustainability science core questions. The succeeding section of the paper proceeds with the step by step process of building the calculus to measure sustainability, efficiency and resilience by applying information, network, and graph theories.

2.3 Ecological information-based approach

The mathematical foundation of the "Window of Vitality" is the ecological information-based approach which is grounded on network, graph and information theories. The ecological information-based approach is a holistic calculus in formally measuring systemic properties of a given system such as ecological and economic resource networks (Kharrazi 2013). Information theory is credited to Claude Shannon (1948) who proposed a statistical theory that quantifies information and information absence in his influential paper "a mathematical theory of communication". The mathematical expression was derived using communication string texts to quantify levels of uncertainty.

Shannon's index for diversity (Equation 1) is the foundation of Information Theory (IT) which is the basis in quantifying "Indeterminacy" or measure of both presence and absence of information. Indeterminacy "H" quantifies the uncertainty related to a known probability. H has two fundamental components that measure information and the corresponding absence of information. Presence of information for an event "i" is measured by its probability "p_i". One example is the observation of an event that heads would turn up in a given number of coin tosses. In a given probability or presence of information, the absence of information is measured by "-log (pi)", also known as the measure of "surprisal" (Tribus 1961). If probability is the measure of information then it gauges the degree of expectation that an event would occur. On the other hand, surprisal gauges the degree of surprise when an unexpected event occurs. The product of information (probability) and absence of information (surprisal) is the measure of indeterminacy, or the amount of uncertainty one is to expect with a given measure of probability. The summation of all observable and absence of events gives a single measure that is the "Aggregate System Indeterminacy" (Ulanowicz et al. 2009).

$$H = -\sum_{i=1}^{n} p_i \log(p_i)$$

Equation 1: Aggregate System Indeterminacy

Traditional science has always been preoccupied in measuring information (e.g. number of species in a given population) without regard to the valuable insight to the absence of information can provide. Interest has always been on the consistency of the presence of an event. However, that is not how the world operates where the only constant is change. The Aggregate System Indeterminacy measures the potential of aggregated events to change as a holistic measure of evolution potential in a single value. Complete certainty of the absence or presence of events (p_i= 1 or p_i = 0; since probability is a normalized function) results to the surprisal being or approaching to zero and Aggregate System Indeterminacy is zero. Hence, the potential of change decreases as probability approaches either complete certainty on the presence or absence of events. The potential for change is thus bounded between absolute certainty and uncertainty.

Holling (1973) gave a similar argument in his seminal work on resilience which emphasizes the importance of both the presence and absence of observable events. Events such as an extinction of a species (absence of an event), provides fundamental insight to the persistent operation of environmental systems in the presence of unpredictable disturbances. Rutledge et al. (1976), further elaborated on the nature of indeterminacy by decomposing equation 1 into two components (Equation 2). The "Average Mutual Information" (AMI), denoted as "X", is the degree of resolved uncertainty in the observation of probabilities of events (Gallagher, 1968). The "Conditional Entropy" represented by "Ψ" is the residual unresolved uncertainty for every probability determined through observation (Ibid). The AMI and Conditional Entropy are two complementary components that such that:

$$H = X + \Psi$$

Equation 2: Average Mutual Information and Conditional Entropy

The derivation of the equation has been for aggregated observable events of “i” and does not explicitly capture any structural detail of a network. To be able to capture a network structure of flows, it is necessary to designate the source and receiver of information which are designated “i” and “j” respectively. Any flow leaving compartment “i” is received directly by compartment “j”. The designation establishes the relationships between compartments in a given network system of flows of information. For weighted flow networks, the variables in equation 2 are defined by the following:

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

Equation 3: Aggregated Network System Indeterminacy

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

Equation 4: Average Mutual Information

$$\Psi = -k \sum_{i,j} \frac{T_{ij}}{T_{..}} \log \frac{T_{ij}^2}{T_{i.} T_{.j}}$$

Equation 5: Conditional Entropy

The "Aggregate System Indeterminacy" for a network (equation 3) is the sum of the product of all observed flows and corresponding measure of absence. The "k" is a constant used to return a physical dimension to the normalized equation. With regards to weighted flow networks comprised of elemental nodes and weighted connections of flows, T_{ij} is a representation of an amount of information flow (e.g. energy or matter) coming from a specified node i and received by the target node j . The notational "dot" subscript in "$T_{i.}$", "$T_{.j}$" and "$T_{..}$" is used to indicate the index it represents and is a summation of all components over that index (e.g. $T_{i.} (= \sum_j T_{ij})$; $T_{.j} (= \sum_i T_{ij})$ and $T_{..} (= \sum_{i,j} T_{ij})$). The notation T.. is called as the "Total System Throughput" (TST) and is the overall sum of flows occurring in a defined network. As an example, Table 2 is a simple graph of a network with weighted flows. The $T_{..}$ is the summation of all flows from all "i"s to all "j"s (A to A, A to B, B to A, and B to B) which sums up to 10. The $T_{i.}$ is the summation from a given node "i" to all "j"; from A to A and A to B; and from B to A and from B to B); which results to 3 and 7 respectively. Likewise, $T_{.j}$ results to 4 and 6, following the same logical steps of summation over the indices as previously done.

Table 2. A simple graph representation of a network

i, j	A	B	Sum of $T_{i.}$
A	1	2	3
B	3	4	7
Sum of $T_{.j}$	4	6	10

The AMI (equation 4) is a measure of constraint in the network system of flows "T_{ij} ". AMI is a measure that represents the maintaining structure of a network system that provides growth or accumulation of resources. In ecological systems, AMI is "Ascendency" which is the capacity to exercise directed power that ensures the maintenance of the system through time (Ulanowicz et al. 2009). On the other hand, Conditional Entropy (equation 5) is the average degree of freedom or the remaining potential of flows. Conditional entropy represents the extent of the presence of redundant flows. Given that AMI is a network's constraint of flow, then the average degree of freedom is the remaining alternative pathways for the flows of information. The given measures so far are dimensionless without giving the constant "k" a meaningful unit. To return a physical dimension to H, X and Ψ, which are normalized functions, the scalar constant "k" is taken to be the TST which is given as $\mathrm{T}_{..}$ $(= \sum_{i,j} \mathrm{T}_{ij})$. The scalar constant returns the unit of measure to the normalized functions. The scaling results to the following transformation of the equations (Ulanowicz et al. 2009):

$$\mathrm{C} = -\sum_{i,j} \mathrm{T}_{ij} \log\left(\frac{\mathrm{T}_{ij}}{\mathrm{T}_{..}}\right)$$

Equation 6: Development Capacity

$$\mathrm{A} = \sum_{i,j} \mathrm{T}_{ij} \log\left(\frac{\mathrm{T}_{ij}\mathrm{T}_{..}}{\mathrm{T}_{i.}\mathrm{T}_{.j}}\right)$$

Equation 7: Systemic Efficiency

$$\emptyset = -\sum_{i,j} \mathrm{T}_{ij} \log\left(\frac{\mathrm{T}_{ij}^{2}}{\mathrm{T}_{i.}\mathrm{T}_{.j}}\right)$$

Equation 8: Resilience Capacity

The scaled Aggregate Indeterminacy gives the "Development Capacity" (Equation 6) which is the capacity of a system to grow and develop. For a given system to grow and develop, it requires two opposing yet complimentary components of “Systemic Efficiency” and “Resilience Capacity”, to ensure persistence through time and in the presence of perturbations (Ulanowicz et al. 2009). The concept denotes that having greater resilience capacity could result to an un-sustainable state as well as having greater systemic efficiency.

The ecological information-based approach has been applied to ecological systems to determine if such optimal balance does exist. To determine the optimum allocation of resilience capacity and systemic efficiency, the ecological information-based approach was applied to real world ecological network models from previous studies (Ulanowicz et al. 2009). It has been shown that ecological network persistence follows a balanced allocation of degree of organization or systemic efficiency and degree of freedom or resilience capacity.

The said Window of Vitality is obtained by normalizing the system efficiency with the development capacity to represent the relative efficiency of the system denoted as “α”. The relative efficiency measures the relative degree of order of the system. To represent the sustainability of the network system, the Shannon index is applied using “α” as the known order of the system and “$-\log(\alpha)$” the proportioned amount of incoherency or level of disorder in the given system. The normalized value “α” is thus bounded between 0 and 1 and follows the same argument presented previously. The product of the “α” and “$-\log(\alpha)$” provides an indicator for sustainability called robustness or the potential of the system to evolve, adopt and grow. Robustness “R” (Equation 9) thus represents an objective view of sustainability devoid of subjectivity and emphasis is given to the systemic information and the structure holding the information. The “k” constant in this case is taken to be “e” (the base of natural logarithms) to bound the resulting measure between 0 and 1 (Ulanowicz et al. 2009). The amount of robustness (sustainability in terms of persistence) thus represent the capacity of a system to exercise sufficient directed power to grow, develop and still have the necessary fall back of alternative options to withstand disturbances. The measure of robustness is a unit-less measure that can be applied to various networks.

$$R = -k\alpha\log(\alpha)$$

Equation 9: Robustness (Sustainability)

It has been argued by previous research that ecological systems occupy a narrow limit defined by the allocation of efficiency and resilience that optimize robustness or sustainability in terms of persistence (Ulanowicz et al. 2009). The computational approach for robustness has two important systemic variables: 1) the amount of information (matter or energy) within the system and 2) the structure holding the information and the way it is distributed. These are two important characteristics that needs to be considered in the study of SES where element forms structure and structure of elements holds information. Assuming that SES could be effectively expressed as a network, one can then proceed to determine the allocation of SES efficiency and SES resilience accordingly.

It is necessary to verify the applicability of the calculus on a SES expressed as a network configuration and assess against ecological networks to determine emerging systemic traits that could prove useful in monitoring SES robustness or persistence. The following section presents the case study of the Philippine brackish aquaculture system used to represent a SES with varying network components of material structural flows.

3. SOCIAL-ECOLOGICAL SYSTEM CASE STUDY

3.1 Philippine brackish pond aquaculture

Interrelated human and environment units (SESs) come in different forms and can be represented by various models. However, prevailing studies on SES focus on the management of environmental resources by human communities and governance systems that prevent degradation to ensure sustainability. General examples of resource systems are fisheries, forestry and water resource systems (Ostrom 2009). Of all the given resource systems, fisheries has the globally significant role in nutritional provision and significantly decreasing food shortages (FAO 2014) as the world population is expected to reach almost 10 billion by the middle of the 21st century (UN 2013). The world fisheries sector is not only a source of nutrition but a source of income as well to the poorer global communities through the creation of employment and source of income. For countries rich in fisheries resources and specially for developing nations, it is a source of economic gains being one of the highest traded products in the international market. Although expectation on fisheries to alleviate malnutrition and poverty is high, it has its own set of challenges to contend with in terms of human and environmental well-being. Under the realm of food resource production, fisheries remain as one of the rapidly growing industry. The steady increase in fisheries production is due to aquaculture growth and development (Figure 3). For the past 6 decades, the contribution of aquaculture under expansion went from negligible to almost half of capture fisheries production in the year 2012 (see Appendix A). During the same period, output from capture fisheries started to level off even though there has been increasing fishing efforts. These trends created a paradigm shift from capture fisheries to aquaculture production. Further development in the aquaculture sector is intended to alleviate environmental pressure from the world oceans due to capture fisheries.

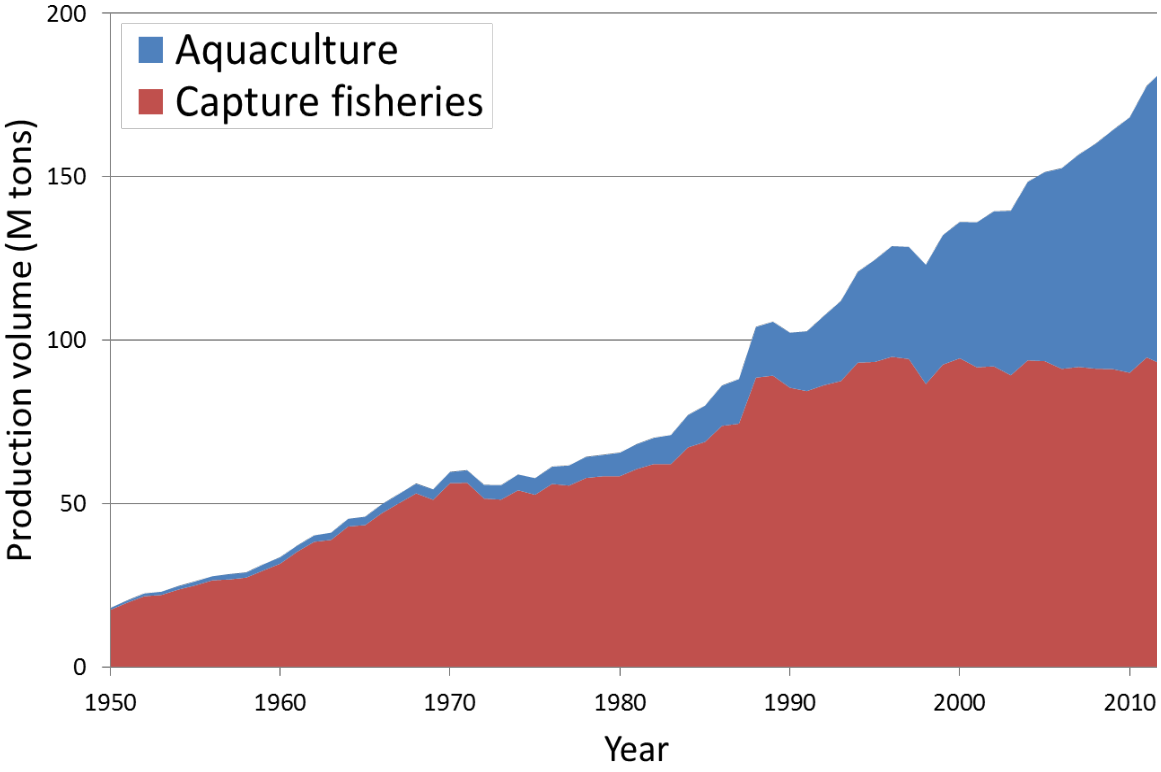


Figure 3. Global fisheries production from the capture and aquaculture sectors

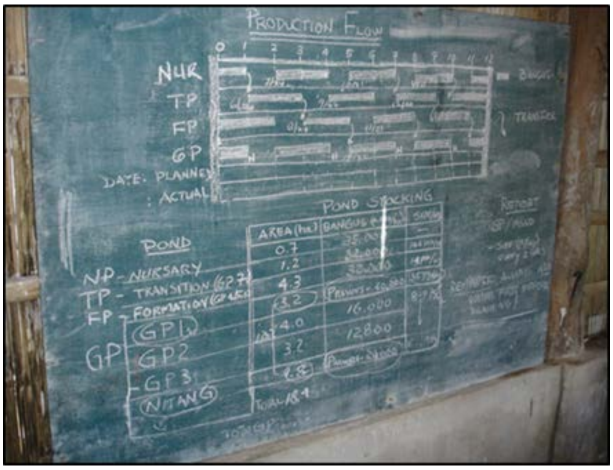
In such a scenario, aquaculture is expected to lighten the pressure of over-fishing on ecological capture areas. However, pressure is transferred to ecological production areas of aquaculture systems as demand for fisheries products increase. The rapid growth of the aquaculture also entails problems such as environmental degradation due to pollution and over production as well as social issues such as marginalization of the poorer communities from resource access. Sustainability of the aquaculture sector is thus a global concern as much as it is a local concern.

The growth in aquaculture production can be attributed to expansion of production areas as well intensification by employing technology and innovation to meet growing demand for fisheries products. Although aquaculture alleviates pressure from the capture fisheries sector, continuous increase in production put pressure on capture fisheries. A fraction of capture fisheries products are converted to fishmeal and fish oils which are used to produce feed materials for livestock as well as aquaculture. Capture fisheries, in this sense, is feeding the growth and development of the aquaculture sector (Naylor et al. 2009). Even though aquaculture could improve the resilience of the overall global food supply, there are still challenges that need to be addressed such as resource efficiency, environmental care, economic equity and proper governance (Troell et al. 2014). It is thus of grave importance to monitor the sustainability of the development of the aquaculture sector to meet the sustainability challenges it is expected to address.

The paradigm shift from capture fisheries to aquaculture production is the blue revolution of the fisheries sector. The blue revolution has also lead to ecological destruction as mangrove and other natural prestine ecological areas were converted to pond production areas. In the wake of the blue revolution, traditional pond production has been lead towards intensification resulting to further environmental degradation of the remaining mangrove areas as well as other natural ecological systems. Early aquaculture development in the Philippines has been traditionally practiced in earthen brackish water ponds converted from natural ecological systems such as mangroves. Although aquaculture has been practiced for over half a century, the first recorded pond was in the Philippine census of 1863 (Primavera 1993). Brackish ponds are earthen enclosures for farming fish and other aquatic species in water that is a mixture of seawater and freshwater (Picture 1). Canals are used to transfer water from the sea and river to control the salinity and water level in the ponds. Filling and draining of ponds take advantage of the natural cycle of tides. Water are let into the ponds during high tide and drained during low tide. Some intensive culture systems also use deep well and water pumps to manage the water quality and quantity during the production cycle.

Picture 1. Traditional earthen brackish water pond culture area

Pond culture practices can be defined as extensive (traditional), semi-intensive and extensive; depending on the ponds design, inputs, technology, innovation and process of management employed. Below is an example of a production flow for a brackish pond "modular" production system (Picture 2). This innovation optimize the output per unit area. The modular method maximizes production output per cycle by optimizing use of area divided into compartments (Agbayani and Ticar 1989). The pond production area are compartmentalized into the Nursing Pond (NUR), Transistion Pond (TP), Formation Pond (FP) and Grow-out Pond (GP). As fry is stocked (Picture 3) and grows, it is transferred through the canal to the next larger compartment (e.g. from NUR to TP). As the compartment source becomes available, it is prepared and stocked again (Picture 4). In a given one year production cycle, all the comaprtments could be stocked simultaneously according to the stage of milkfish growth. This innovative management process can be complimented with other technology such as the use of fertilizer in growing natural food in the pond bottom or water column (Picture 5). Feeding regimes with the use of commercial feeds can also be incorporated to the modular design in intensive methods in pond production.



Picture 2. Production flow process for modular designed ponds

Picture 3. Fry stocking material for brackish ponds

Picture 4. Traditional brackish pond in preparation for fertilization and stocking

Picture 5. Traditional milkfish brackish pond with detached benthic algal community

3.2 Milkfish and giant tiger prawn cultured species

Milkfish (Chanos chanos Forskal) has been traditionally been cultured in brackish pond areas in Southeast Asia even before the onset of the blue revolution Figure 4). Biologically, milkfish is a suitable species for sustainable aquaculture production. Milkfish are benthic feeders and feed on colonies of bethic algae. Being phytophagous, milkfish could be raised in fish ponds without the use of feeds that are produced from capture fisheries by-catch. Milkfish is also euryhaline and could be cultured in a wide range of salinity from fresh to sea water. Most production of milkfish is done in brackish water (mixture of fresh and sea water) ponds where the growth rate is optimized at 40 parts per thousand. Milkfish can be gradually acclimatized and cultured in a wide range of environmental conditions may it be low dissolved oxygen (DO), temperature or other factors. The finfish can also be stunted for late stocking by crowding into small areas in preparation of for grwoth spurts during culture. Milkfish is also biologically resistant to diseases. These resilience characteristic allows milkfish to be biologically grown in high density (Baliao et al. 1999). Milkfish can also be cultured extensively without the use of advanced technologies such as water pump and aeration systems.

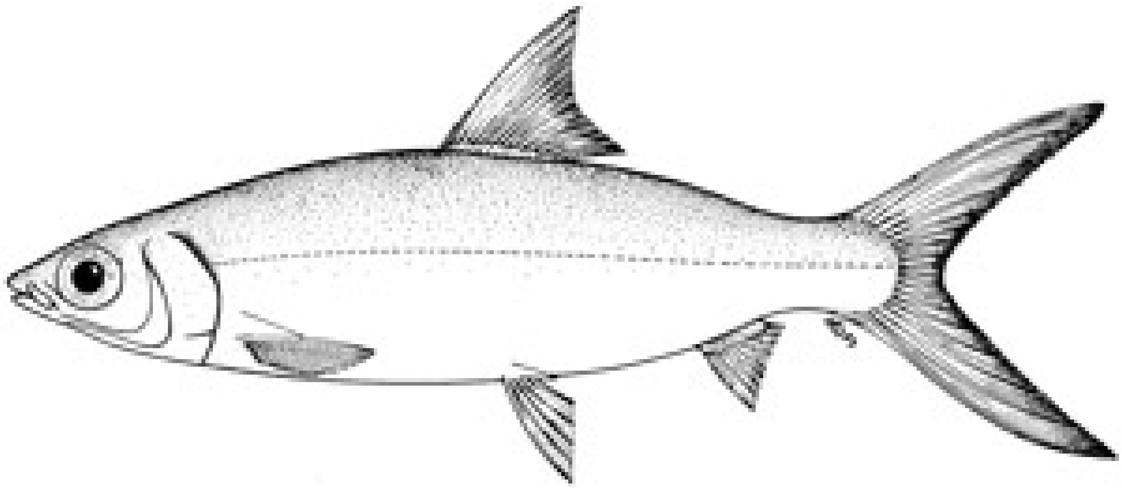


Figure 4. Milkfish, Chanos chanos Forskal (FAO)

Milkfish is an important source of seafood protein for both rich and poor in Southeast Asia. There are three major producing countries of milkfsih in the region: Indonesia, Philippines and Taiwan (Province of China) (Figure 5) (see Appendix B). Taiwan has remained as a low milkfish production country while Indonesia and Philippines has grown and developed the sector producing higher volumes of milkfish. Although Indonesia currently has the highest production volume of milkfish, Philippines has developed the sector at a much earlier stage (1950 to 1980). During the process of growth and development from 1950 to 2012, sharper decline in production can be observed in the production of the Philippines (1983 and 1991) than compared to Indonesia. In understanding sustainability and resilience, it is important to consider disturbances and thresholds retrospectively (Carpenter 2003, and Turner and Dale 1998). The Philippine milkfish production has experienced greater degreee and frequency of perturbations which is important for the retrospective study. Further more, established international fisheries institutions are based in the Philippines and provide important sources of scientific material for reference. Thus, the selected case study is that of the Philippine milkfish production system.

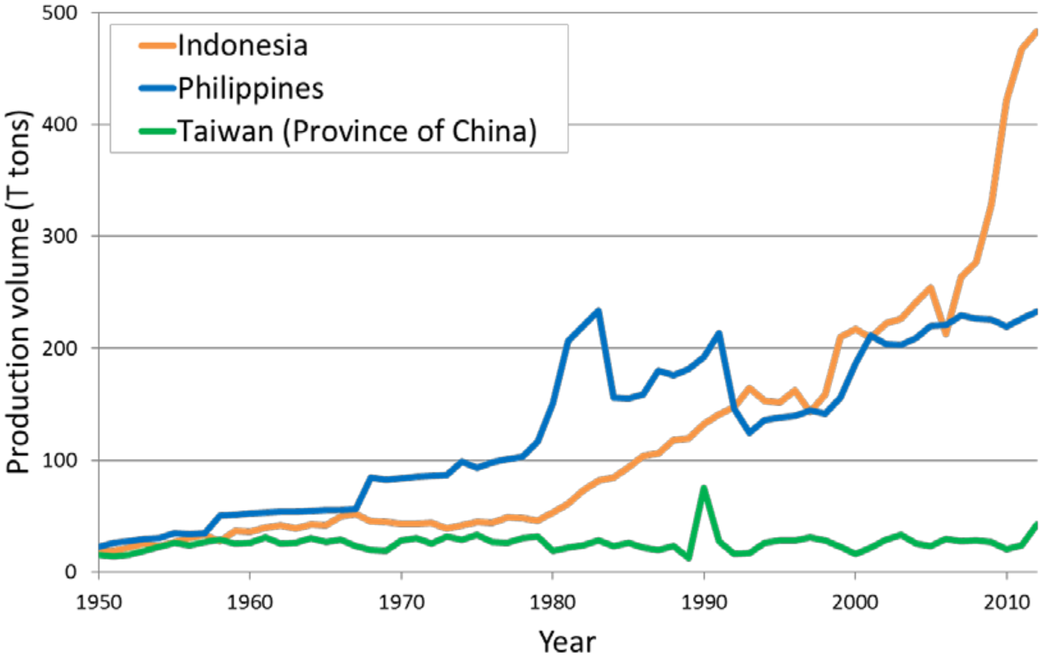


Figure 5. Southeast Asia milkfish production volume

Another culture species in the Philippine brackish pond production is the giant tiger prawn (*Peneaus modon Fabricius*) (Figure 6). Giant tiger prawn has been always a traditional by product in the culture production of milkfish in the earthen brackish ponds. Crustacean larvae enter the pond culture areas through the water canals during water change in the milkfish production cycle. The giant tiger prawn is an aquatic crustacean which is the largest among the prawn species. The biological characteristics of the giant tiger prawn are opposite to that of milkfish. The crustacean is sensitive to changes in the culture environment (e.g. DO, PH, salinity, etc.) and requires a strict regimen to optimize production (Baliao 2000). Any drastic change of the parameters could be detrimental to the crustacean being cultured. The giant tiger prawn is also highly sensitive to a number of diseases such as *Vibrio harveii* (luminous bacteria) and WSSV (White Spot Syndrome Virus) and becomes more susceptible when stressed due to changes in parameters. The giant tiger prawn has been red listed by Greenpeace (2014) as seafood that has been source unsustainably owing to the intensive and semi-intensive production methods. Giant tiger prawn production is also heavily dependent on artificial feeds contributing to pressure on capture fisheries. Mangrove conversion has also been attributed to the rise of tiger prawn production in Southeast Asia.

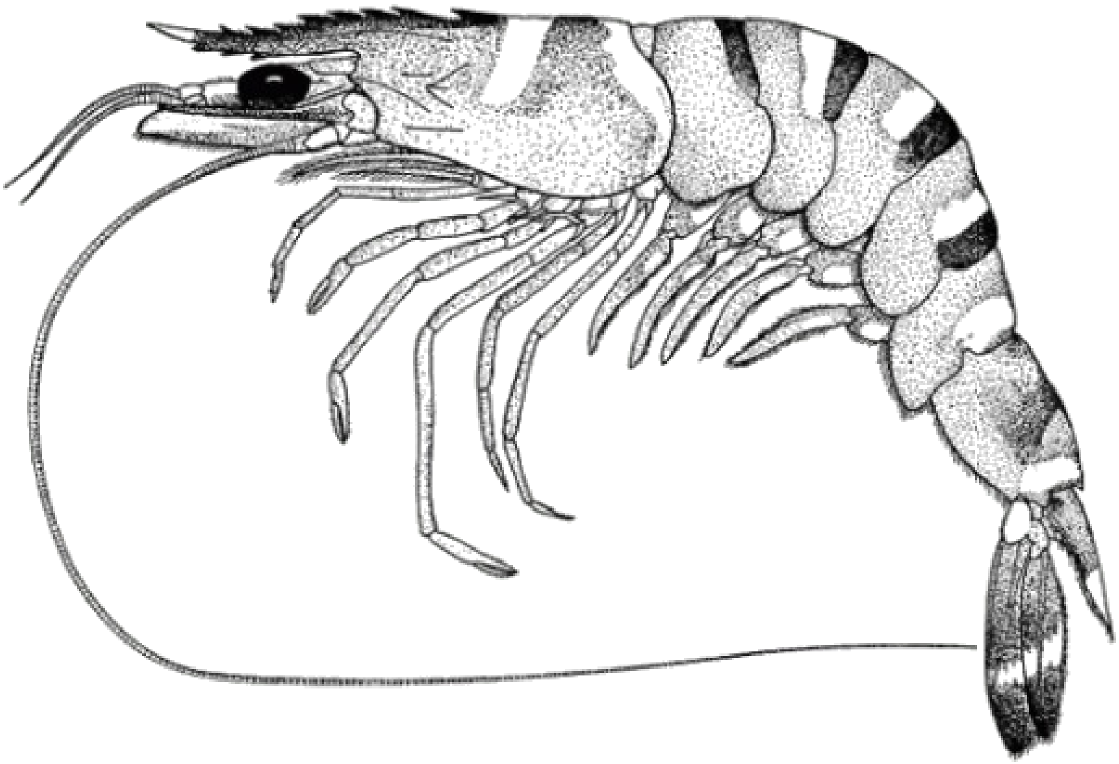


Figure 6. Giant tiger prawn, Penaeus monodon (FAO)

In contrast to milkfish which is important for domestic consumption and food security, the giant tiger prawn on the other hand is a very important export commodity for the country. The history of growth and development of the giant tiger prawn sector is intertwined with milkfish and is considered as a supplementary case study to provide an over-all view and analysis of the brackish water pond resource sector as a larger scale SES.

3.3 Social, ecological and economic conditions

The growth and development of the Philippine brackish pond system can be explained by various factors from social, ecological and economic dimensions. Figure 7 shows the brackish pond volume production from 1950 to 2012 for milkfish and giant tiger prawn. The pattern of growth and development of the milkfish and giant tiger prawn production systems can be narrated by the perspective of the Adaptive Cycle.

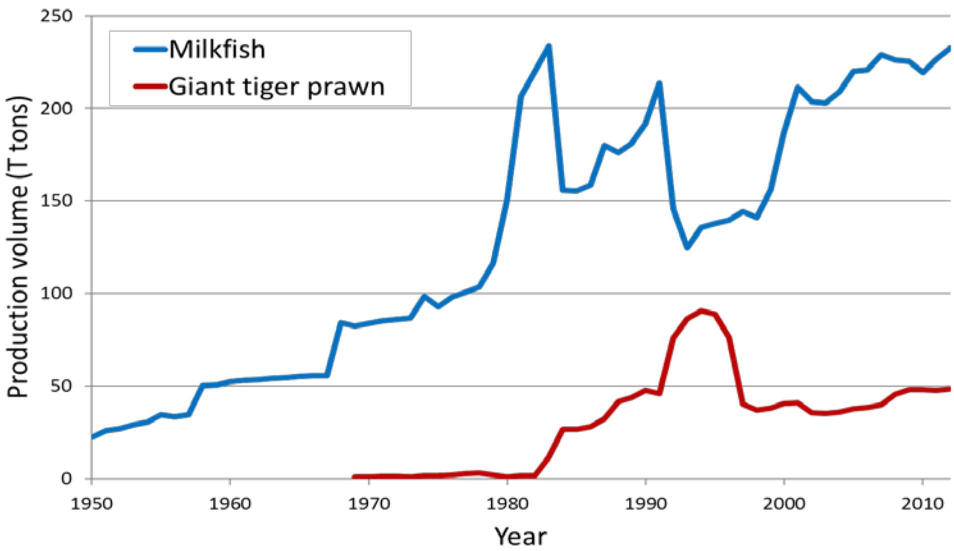


Figure 7. Philippine milkfish and giant tiger prawn production volume

Although milkfish has been cultured for a long time in brackish ponds, it could be observed that from 1950 to 1980, the milkfish system is still undergoing the transition from r to K phase. From 1980 to 1983 there is decrease in growth rate of production which is indicative of the K phase. Post 1983, the system experienced a disturbance and a sharp decline in production could be observed (a sign of the Ω phase). There is the onset of reorganization (α) and growth (r) post disturbance. The milkfish adaptive cycle repeats from 1984to 2001 where there is growth (r) and another major disruption 1991.

A similar narration can be made with the giant tiger prawn using the Adaptive Cycle model. The 1970s is indicative of reorganization where the industry tries to establish itself in the field of aquaculture. The giant tiger prawn has always been a by-product of milkfish production in brackish ponds until the 1970s where it has started to be recognized as a potential aquaculture species for pond production. Unlike milkfish production, operation of prawn production utilizes more technology and operations are intensive. The 1980s vis a vis the Adaptive Cycle is the period increasing growth (r) for the system and a more rapid growth until 1992. The K phase for the giant tiger prawn resource system is represented in the 1990s and rate of growth declines post 1992 and perturbation in 1995 -1997 which is considered as the collapse of the giant tiger prawn industry. Post 1997 shows the phases of reorganization (α) and growth (r). The rapid growth of the giant tiger prawn industry is due to several reasons. One reason is land expansion just like the case of milkfish. Another reason is the shift in culture practice from milkfish to giant tiger prawn. The most overbearing reason for the rapid growth is the use of technology. These factors as well as the high price and demand for the product caused the rapid growth of the system towards the K-conservation stage.

As mentioned before, tiger prawn is very sensitive to environmental fluctuations. To institute more control over the culture environment, technology is heavily employed. Giant tiger prawn is heavily dependent on feeding and strict feeding regimen is practiced in pond production. The use of "catwalks" is standard procedures in sampling of feeds in production areas (Picture 6) as well as the use of feed sampling trays and automatic feeders for more advanced production systems (Picture 7). Sampling is done to determine the feeding rate in a pond area and automated feeding to ensure the proper amount and time of feeding. These efforts all increase efficiency in production and decreases operation losses.

Picture 6. Sampling platforms in prawn production areas (source: Jimmy Balista)

Other technology employed to regulate DO in the water is the use of aeration like paddle wheels (Picture 8). Operation of prawn culture utilizes more inputs which includes electricity. In managing the water quality, the production is reliant on deep well water. Simple innovation, such as the use of netting over production areas prevents bacterial and viral cross contamination from carriers such as birds. Picture 9 shows the netting employed as well as water piping used in water management and disease prevention. These are just a few of the technologies employed in the prawn production that lead to the rapid growth and development (r phase to K phase) of the industry until its shocking collapse in 1997.

There are several reasons for the collapse of the tiger prawn industry in the Philippines. One reason is the reliance on the intensification of culture systems that allowed overstocking of culture materials. Overcrowding resulted to bacterial and viral outbreaks that required the use of pharmaceutical products which raised the issue of food quality and safety for the tiger prawn products. Another reason for such sudden decline in production is the reliance on a single market for export which is Japan. These economic and biological shocks were the prime reason for the collapse of the industry and lead to the shift back to milkfish production.

Picture 7. Feed sampling trays and automatic feeder (source: Jimmy Balista)

Picture 8. Aeration paddle wheels in prawn production (source: Jimmy Balista)

Picture 9. Overhead netting and water piping system (source: Jimmy Balista)

The Adaptive Cycle does offer a good narrative of the cycle of growth and development of the brackish water pond system represented by the milkfish and giant tiger prawn sub-components. However explanatory variables, factors and drivers are still necessary to explain what causes the system to undergo such cycles. The volume production has been taken as equivalent to the capital in the Adaptive Cycle. In an ecological system, capital could be represented by the available resources such as nutrients and biomass. In a complex SES, capital would also include social and economic capital. So far, it has remained as a form of assumption that production volume is an effective equivalent for capital. The following is an account of the variables, factors and drivers that could explain the accounts that constitute the general systemic property of capital in the Adaptive Cycle.

Up until the 1970s, brackish water pond production is essentially synonymous to milkfish production. The initial increase in production volume from 1950 to late 1950s can be attributed to increase in the production area for aquaculture. Production area is a form of capital input for the entire production system. Increase in production area results in increase of production. Production area increased until 1970 at a lower rate as concern for mangrove preservation increased. From late 1950s to 1980s the increase in production could no longer be attributed to area increase alone (Chong et al. 1984).

Increase in production volume in the late 1950s could be attributed to both fish pond area increase as well as increasing use of production technology inputs. It may it may sound low technology but the use of fertilizer in enhancing production is already an advanced during the 1950s. Both application of organic and inorganic fertilizer increases productivity and adaption was said to be the barrier to increasing productivity per unit area (Chong et al. 1982, and Bombeo-Tuburan et al. 1989). Another form of technology and innovation is the modification of pond areas to the modular production type which increases the number of cycle production in a given year as well production outputs for a given area (Lijauco et al. 1979, Agbayani et al. 1989). Application of technology and innovation aims to increase efficiency in production operation and optimize production per unit area by providing control over the culture environment.

The adoption and application of technology and innovation in the development of the brackish pond aquaculture production is a human concerted effort. The establishment of academic and research institution produce scientific knowledge to increase production is critical in promoting production efficiency. These institutions include the Southeast Asian Fisheries Development Center (SEAFDEC), The University of the Philippines in the Visayas College of Fisheries, the Bureau of Fisheries and Aquatic Resources (BFAR) and others. Establishment of these institutions also require capital (human and economic) to be able to operate and produce products that could be used by the industry. The technological and innovation products also need capital for diffusion. For example, training and lectures transfer knowledge and access to credit encourage adoption of technologies (Chong et al. 1984). These are human, economic and knowledge capital that contributes to increase in production.

These examples of natural, human and man-made capital are interacting together to produce an outcome that can be observed as the output of production of the brackish pond system. The more capital that is poured into the given system, the higher the outputs become. Each capital also has its limits in contribution to growth. Capital in the brackish system can be considered effective when it contributes to increase in production. The various capital inputs have interactive outcomes that can be measured by observing the total output for a given production year. Just like environmental systems, capital in the brackish pond system has its levels of being active and passive. Active capital is not completely integrated in the system while passive capital is the effective capital contributing to growth.

Natural resources are important inputs in the aquaculture production process such as land, water and micro fauna and flora. These natural resources have limits in increasing production outputs and are determined by the carrying capacity. The carrying capacity of the natural environment could be augmented by the use of technology and innovation such as use of equipment and chemicals. Equipment would include use of water pumps and aeration units. Chemical would include fertilizers or pesticides to manage pests that compete with the target culture species. The allocation of natural resources and employment of technology and innovation is also dependent upon the social and economic conditions that affect decision on the production process. These examples of factors or variables have a complex relationship that could be difficult to observe and one variable may be limiting to all other variables at one point in time but may be a non-limiting variable at some other time. The interaction of all variables and factors results to phenomena that can be observed. This phenomenon is the measured production level in a given year. The production volume thus could be considered as an equivalent indicator for capital.

Just like the natural environments used as narrative examples in the Adaptive Cycle, the brackish water pond system has its own set of perturbation coming from the social, ecological as well as the economic domain since the system is composed of elements coming from the given domains. These disturbances coming from the different domains causes drop in production levels as well as production rates. Of course, all capital inputs, limiting factors as well as disturbances cannot all become known. Perturbations are also part of the phenomena that is captured in the production levels of milkfish in a given year. Perturbation that are great enough decreases the production level for a certain year. Thus the variables and factors mentioned above, as well as external forces such as natural disasters, determines the production for a given year and the measure is the phenomena of the interactions of all these conditions that could either be known or unknown. However, lacking still is how to incorporate the structural component of a system that holds the given volume flow of capital.

3.4 Brackish water pond social-ecological system

Up to this point, the paper has focused on the grow-out production system of the brackish water pond as a representation of a social-ecological system going through the cycle of growth, development and reorganization in the presence of natural and man-made perturbations. The production areas are only part of a larger system in a world that has been increasing connectivity through the process of phenomena called globalization. This section goes through the process of defining the brackish water pond system, with its critical components and sub-components, as a social-ecological system.

The brackish water pond resource system is a social-ecological system having elements from human, non-human and environmental components whether it is the milkfish or the giant tiger prawn sector that is being considered. Majority of brackish fish ponds come from natural ecological areas viewed before as unproductive areas (Primavera 1995). There is a documented decline in mangrove areas (450, 000 to 132, 500 has) from 1920s to 1990s with accompanying growth in brackish water pond aquaculture areas to 223, 000 has given the same time period (Primavera 1995). Mangrove areas in the Philippine archipelago have been going through its own cycle of adaptive change before the onset of aquaculture growth and development. The Archipelago is divided into three main islands: Luzon, Visayas and Mindanao. The main islands are divided into regional divisions. These patches of mangrove forests have been going through growth, conservation, release and reorganization or its own natural forest succession. Human efforts towards food security and poverty alleviation have become a critical disturbance to the natural cycle of the mangrove systems. From the K-conservation phase of the mangrove and other natural systems, human intervention of land conversion has come as a perturbation to these systems. The clearing of the areas moved these systems to the omega or release phase. In a natural setting, the reorganization phase would take place where species would compete for the released resources (e.g. space and nutrients) to rebuild a new ecological system. However, human activity excluded natural species in utilizing these natural capitals. Humans have converted the areas and have become part of the transformed natural landscape by clearing natural elements and creating earthen embankments for the culture of aquaculture products.

Conversion of the natural landscape into an aquaculture production system is the reorganization phase of the new emerging system which is the brackish water pond system for aquaculture production. As more and more areas are converted and more and more fish farmers begin aquaculture operations, the new system moves from the reorganization phase to the growth phase. The process of land conversion itself requires economic capital in forms of investment on equipment and human resources. The aquaculture production process is still dependent on natural resources such as water, fry sources and the environment where the operation is being carried out. The production areas are thus social-ecological systems with integrated human and environmental elements.

The production of milkfish in brackish pond areas where initially dependent on the natural incoming water form coastal area to provide the fry stock for grow-out. Milkfish fry are naturally present in coastal and estuarine systems where environmental conditions are appropriate for fry development (Smith 1981). During high tide, fish ponds are filled with water from coastal areas that bring in milkfish fry into the ponds. Milkfish fry are grown within the earthen enclosure living off the natural food growing in the fish ponds. In the continuous growth of the sector under pressure of demand for fish products, growth was dependent on the supply of milkfish fry. The fry gathering sub-system thus emerged to supply fry to the increasing production requirements of milkfish ponds. The following section provides an overview of the milkfish fry resource systems that became essential sub-components in the growing milkfish production system in earthen brackish ponds.

3.5 Milkfish fry social-ecological system

To increase production, stocking of milkfish fry in higher density was necessary which could not be provided by the natural inflow of water from the coastal areas. This resulted to the development of a sub-component which is the milkfish fry gathering system. Collection of milkfish fry from coastal and estuarine areas made it possible for fish farmers to increase stocking rates which increase out-put of cultured milkfish product. Milkfish fry gathering (Picture 10) is a human activity of collecting fry from coastal, estuarine and mangrove areas with the use of fry collection gears for the intention of providing stocking materials for fish pond operations.

The milkfish fry and fingerling sub-system provided employment for coastal communities and had become an integral part of the brackish pond aquaculture system. This sub-industry has gone through its own cycle of organization, growth, and demise. The growth and development of the milkfish fry sector included establishment of methods and practices in fry gathering and handling as well as delivery. The increase in area and intensification of production in milkfish grow-out systems had increased demand from the milkfish fry sub-sector. The sub-sector also drew attention from the scientific community to promote efficiency and growth to be able to sustain supply of stocking materials for the grow-out operations. Some of the key problems of the fry sub-sector included efficiency in catch using fry gears, post-gathering handling and storage as well as transfer from gathering grounds to the productions areas. The general method of collection of fry is by filtering fry by either moving or fixed gathering equipment. Gathering also depends on the seasonal availability of the fry sources which depends on the water depth, current, temperature and weather patterns to mention a few factors. The milkfish fry sub-system is a collection of both human and ecological components which forms a social-ecological resource system in which the brackish water pond SES is dependent upon for production (Villaluz et al. 1983).

Picture 10. Milkfish fry gathering (Source: Villaluz et al. 1983)

The milkfish fry social-ecological resource system is unique from fishing exploitation because it is the fish larvae that is being sourced as compared to capture fisheries in coastal areas and traditional stock assessment are most difficult to employ (Villaluz 1983). It is also different from other cases that the gathered product requires another level of transformation before it could be directly utilized. The concern for the continuous supply of milkfish fry for grow-out operations in brackish water ponds have resulted to efforts in developing artificial and spontaneous spawning techniques for adult milkfish in captivity (Vanstone et al. 1977, Chaudhuri et al. 1978, Liao et al. 1979, and Lacanilao and Marte 1980). Science, technology and innovation has led to the establishment of hatchery production sites that later replaced the fry gathering resource system since its operation in the mid-1990s. The following are some of the current hatchery system components from Jamadre Hatcheries Incorporated (see pictures 11-16).

Outdoor algae tanks are used to produce microscopic plankton for feeding milkfish fry. The process itself has a feeding regime where algae are produced to feed planktons that are in turn fed to the milkfish fry. Eggs are collected from the milkfish broodstock maintained in tanks. The eggs are hatched and fed with the cultured feed to larvae stage in the milkfish fry rearing tanks. Once the milkfish fry are viable for pond stocking, they are gathered and counted in preparation for transportation. The milkfish fry are transported in plastic bags filled with oxygen and delivered using various transport methods.

The milkfish fry gathering and hatchery systems are two different components of the milkfish production sector that performs the same function but differ in operations. The hatchery production system exerts more control and predictability in producing and supplying stocking materials and depends less on the natural resources as compared to the milkfish fry gathering system. The hatchery system is an example of efficient production.

Picture 11. Milkfish fry hatchery production site

Picture 12. Milkfish brood stock in concrete tanks

Picture 13. Milkfish fry rearing tanks

Picture 14. Algal tanks used for the milkfish fry feeding regime

Picture 15. Milkfish fry counting for transport and stocking

Picture 16. Milkfish fry in oxygenated bags ready for transport

4. EMPIRICAL ANALYSIS

4.1 Milkfish fry social-ecological systemic boundaries

Given the conceptual theories to be employed and the characteristics of the case study, this section attempts to contextualize the concepts and operationalize the theories. This section is also addressing the 1st objective of the study which is to "employ network theories to analyze a SES described as a network at various scales". To achieve the objective, various networks were reconstructed from peer reviewed papers to represent the milkfish fry and the milkfish production SESs as networks. A total of eleven network configurations were collated and analyzed by comparing to previous studies on ecological and economic resource networks. The ecological and economic networks serve as a benchmark for the milkfish case study. This is to verify if the milkfish systems have similar traits to the benchmark systems. Aside from the difference of natural and man-made systems, the ecological and economic systems also represent different scales at the local and global levels respectively.

Table 3 is a summary of network sources for milkfish fry, milkfish production and the ecological and economic benchmarks. A total of 23 network configurations were used for the analysis. Eleven network configurations were used for the milkfish case study and 12 benchmark networks were used to represent ecological and economic systems. Seven milkfish fry networks have been reconstructed. Three of the milkfish fry networks are at the country level: Philippine milkfish fry resource network; Inter-regional and inter-main island trade. Four other networks at the regional level have been reconstructed for the milk fish fry SES. Four networks have been identified for the Milkfish product at the national scale and three at the main island scale. Six ecological network configurations were used to represent natural systems and six global economic networks for man-made systems.

Table 3. Summary of network sources

Network description	Samples	Source
1. Milkfish fry networks (1976)		
Philippines	1	(Smith 1981)
Intra-regional trade	4	(Smith 1981)
Inter-regional/division trade	2	(Smith 1981)
2. Milkfish product networks		
Philippines (1973)	1	(Creencia 1973)
Luzon, Visayas & Mindanao (1974)	3	(Guerrero 1977)
3. Network bench marks		
Ecological networks	6	(Almunia et al. 1999; Patrício et al. 2006)
Economic networks	6	(Kharazzi 2013)

The milkfish fry social-ecological resource network supplies stocking material to milkfish brackish water ponds. The milkfish fry stocking material goes through a delivery system composed of social-economic nodes that facilitate transfer directly to the production areas or to other social-economic nodes (Figure 8). The system shows that isolated SESs could be connected to other SESs through various actors or dealers facilitating the transfer of information which in this case is the stocking material of milkfish fry. The resulting network is a hybrid SES that is a composition of elemental nodes that are either social-ecological or social-economic in composition.

The Philippine government had implemented a property rights policy over the milkfish fry gathering areas allowing a concession to bid for complete rights over the resource system. Having the rights over the resources, fry gatherers are obligated to sell the milkfish fry gathered to concessionaires. The concessionaires have the exclusive rights to sell the resources gathered over the property to other actors involved in the industry. Runners are smugglers that fry gatherers sell to. Since runners do not have to pay taxes, fry gatherers can fetch better price for their catch however having legal consequential risks. There are areas that do not belong under the concession rules and dealers are the main channel for these areas. Dealers also facilitate inter-regional trade purchasing fry stock from runners and concessionaires. Dealers basically facilitate the distribution of milkfish fry. Brokers are those who facilitate agreements between other actors with regards to purchases of milkfish fry from other actors. Brokers may facilitate direct transfer of fry or simply conduct brokerage without physical handling of fry. Commission man represents a buyer or a seller. Nursery and production pond nodes are hybrid social-ecological systems that grow fry to fingerling size for restocking and market size respectively. The Milkfish fry hybrid social-ecological resource network has high redundancy of material flow just by observing the structure. High redundancy of flows would ensure alternative pathways for the milkfish fry reaching the nursery and production ponds from fry gatherers.

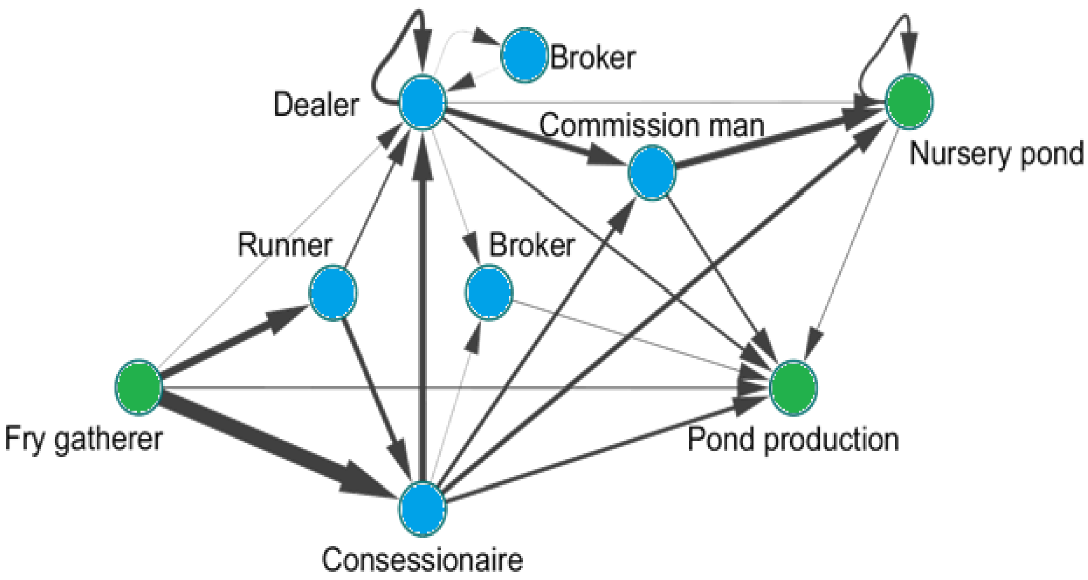


Figure 8. Philippine milkfish fry social-ecological network

Table 4 is the graph of the milkfish fry social-ecological resource network. Each node is represented in the first row and column. The matrix captures the flow of information from one node to another forming the graph of the network of information flow. The unit of measure used in the graph is in terms of percentage volume of milkfish fry being delivered and received by each node.

Table 4. . Philippine milkfish fry social-ecological resource graph

(i,j)	Fry gatherer	Runner	Concessio-naire	Dealer	Commis-sion man	Broker (Dealer)	Broker	Nursery pond	Pond production	Total
Fry gatherer		31	62	2					5	100
Runner			21	10						31
Concessio-naire				29	16		2	20	16	83
Dealer				20	24	1	2	3	12	62
Commis-sion man								28	12	40
Broker (Dealer)				1						1
Broker									4	4
Nursery pond								13	4	17
Pond production										
Total	0	31	83	62	40	1	4	64	53	**(338)**

At the regional level, four networks were reconstructed for Region I, Region VI, Region X and Region XI as represented by Ilocos, Western Visayas, Northern Mindanao and Southern Mindanao accordingly. These milkfish fry networks are sub-components of the national milkfish fry social-ecological resource system network. Figure 9 is the network configuration for the milkfish fry social-ecological resource system of Region I as represented by Ilocos. The network is composed of six nodes, two of which are hybrid SES (green coloured nodes) and the remaining four are socio-economic nodes (blue coloured nodes). The arrow represents the flow of milkfish fry in the defined system. The network configuration of the Region I milkfish fry resource system shows the main structure by the weight of the connections. For example, the prevailing structure is the flow of milkfish fry from fry gatherers to concessionaires to dealers then to outside of Ilocos area. The Region I milkfish fry social-ecological resource network is thus an efficient net-exporter of milkfish fry for the overall system. In the perspective of the Window of Vitality, the remaining flows are redundant pathways or alternative pathways for the flow which helps increase the resiliency of the entire system at the given regional level.

Table 5 is the graph expression of the network structure for the Region I milkfish fry social-ecological resource system which is used for the ecological information-based approach.

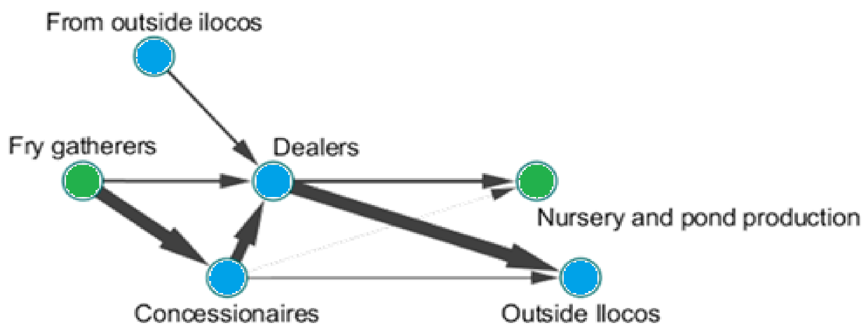


Figure 9. Region I Milkfish fry social-ecological resource network

Table 5. Region I Fry trade in Ilocos

(i,j)	Fry gatherers	Concessio-naires	Dealers	Nursery/pond Production	From outside Ilocos	Ouside Ilocos	Total
Fry gatherers		67	17				84
Concessio-naires			56	2		9	67
Dealers				20		69	89
Nursery/pond Production							
From outside Ilocos			16				16
Outside Ilocos							
Total		67	89	22		78	**(256)**

As compared to Region I, the Region VI (as represented by Western Visayas) milkfish fry social-ecological resource system structure is not as well defined in terms of efficiency (Figure 10). Although the fry gatherers to concessionaires is the prevailing flow, further distribution of the milkfish fry becomes dispersed to dealers, nursery and pond production, and outside of Western Visayas. The network visually indicates a more resilient network than that of Region I because of the more complex flow structure of stocking materials within the system. Table 6 is the graph representation of the Region VI milkfish fry social-ecological resource network that is used for the ecological information-based approach.

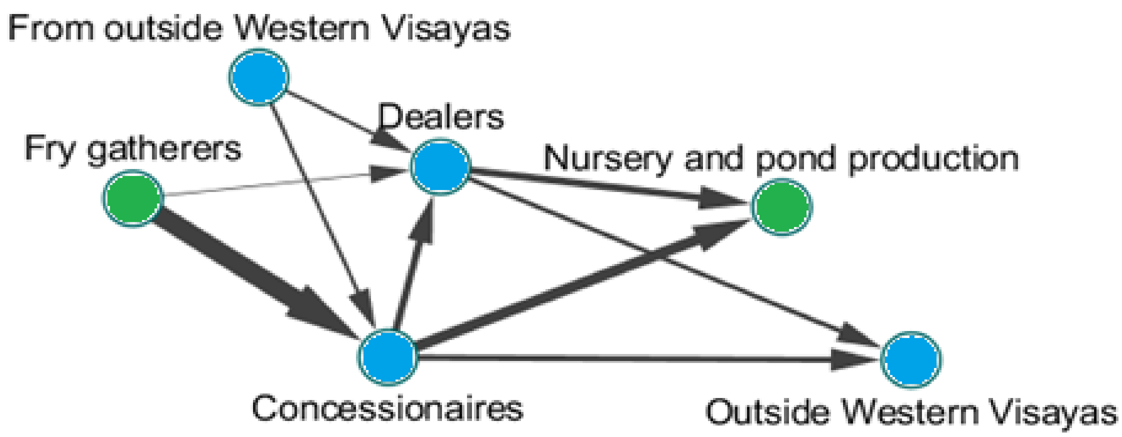


Figure 10. Region VI Milkfish fry social-ecological resource network

Table 6. Fry trade in Western Visayas

(i,j)	Fry gatherers	Concessionaires	Dealers	Nursery and pond production	From outside W. Visayas	Outside W. Visayas	Total
Fry gatherers		70	5				75
Concessionaires			24	38		21	83
Dealers				25		16	41
Nursery and pond production							
From outside W. Visayas		13	12				25
Outside W. Visayas							
Total		83	41	63		37	**(224)**

For Region X, the milkfish fry social-ecological resource network is similar to that of Region I in exhibiting a clearer structure of efficiency (Figure 11). The network shows a structure of efficient export outside of the the region. Perhaps even more efficient than Region I because the flow path only passes one node (consessionaires) before reaching outside of Northern Mindanao as compared to Region I where export has to go through the concessionares and dealers nodes before reaching outside of Ilocos coming from the fry gatherers. Noted also is that the network has less number of nodes as well as flows compared to the prevous milkfish fry networks. Table 7 is the graph of the Region X milkfish fry social-ecological resource network used for the computation of robustness, resilience and efficiency.

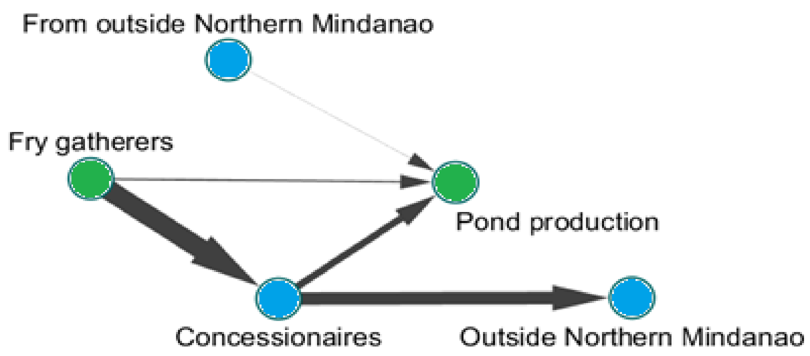


Figure 11. Region X milkfish fry social-ecological resource network

Table 7. Region X Fry trade in Northern Mindanao, 1976

(i,j)	Fry gatherers	Concessionaires	Rearing pond operators	From outside N. Mindanao	Outside N. Mindanao	Total
Fry gatherers		92	8			100
Concessionaires			32		60	92
Rearing pond operators						
From outside N. Mindanao			1			1
Outside N. Mindanao						
Total		92	41		60	**(193)**

The Region XI network for the milkfish fry resource system is similar to that of Region X in terms of efficiency structure (Figure 12). It is the concessionaires that facilitate export of milkfish fry outside of the Region XI. Region XI is also a net exporter of milkfish fry. Pond production nodes rely more on direct transfer of milkfish fry from fry gatherers. Minimal input from outside of Southern Mindanao enters to the system. Redundancy is minimal with the low flows going to the pond production node. Compared to Region X, Region XI does have more redundancy of flows. Table 8 is the graph matrix of the Region XI milkfish fry social-ecological resource network.

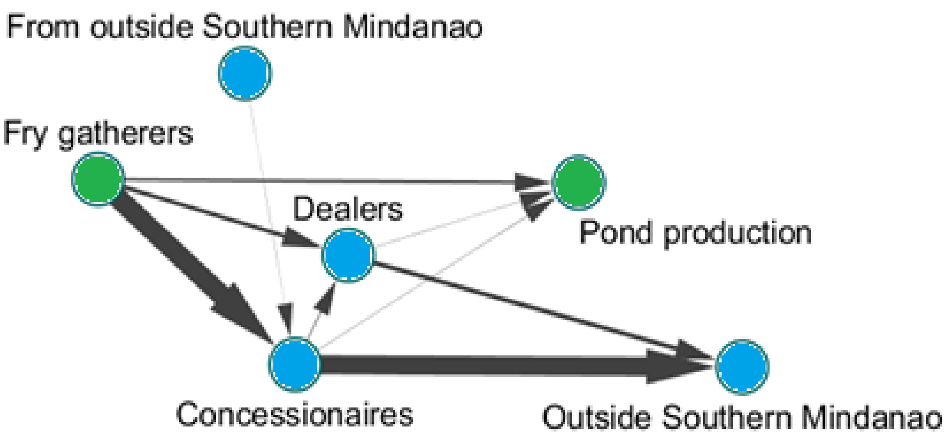


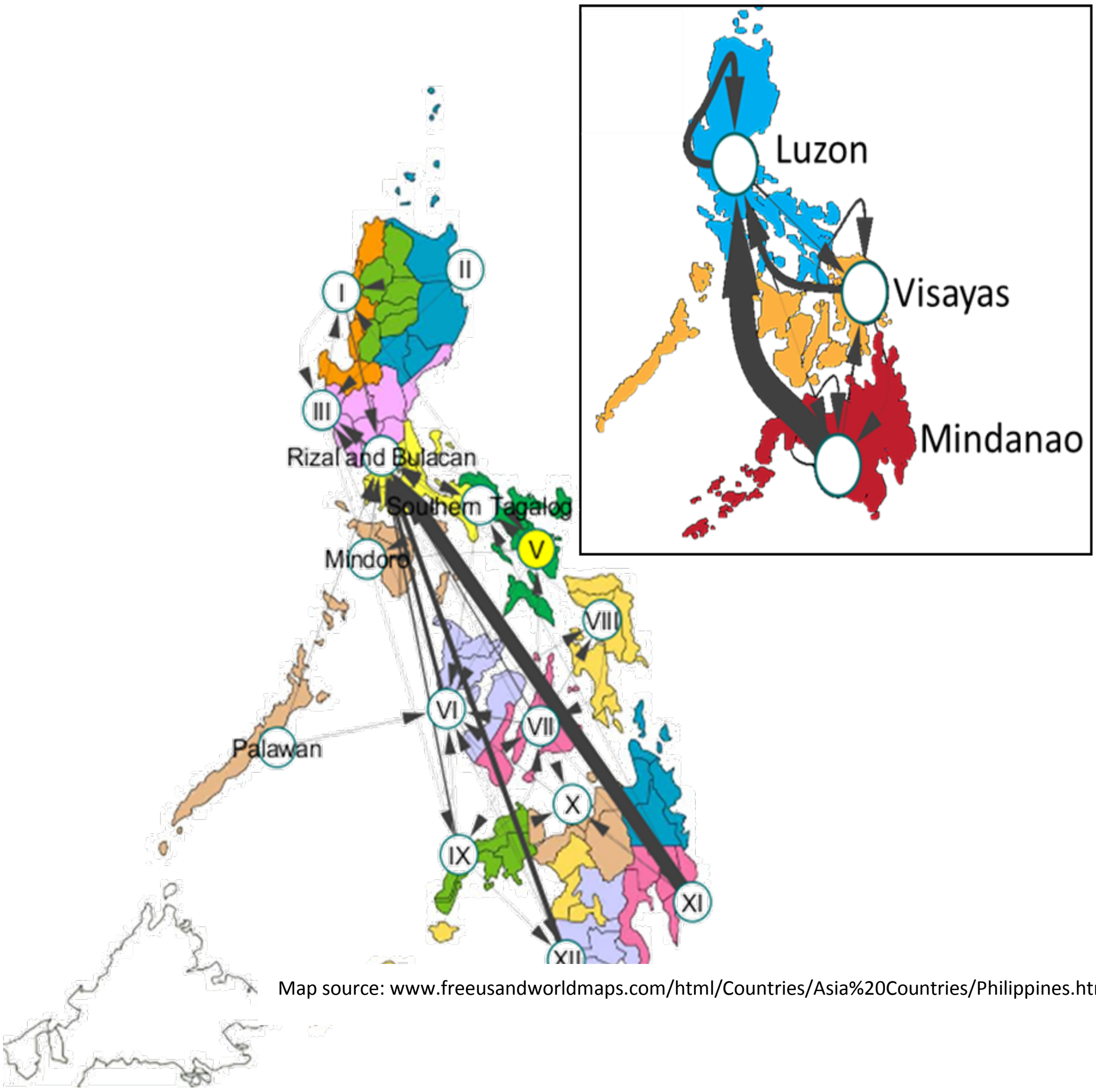
Figure 12. Region XI milkfish fry social-ecological resource network

Table 8. Fry trade in Southern Mindanao, 1976

(I,j)	Fry gatherers	Concessio-naires	Dealers	Pond production	From outside S. Mindanao	Outside S. Mindanao	Total
Fry gatherers		75	15	10			100
Concessio-naires			4	2		69	75
Dealers				2		17	19
Pond production							0
From outside S. Mindanao		1					1
Outside S. Mindanao							0
Total	0	76	19	14	0	86	**(195)**

At the national level, the milkfish fry social-ecological resource system is also expressed in terms of inter-regional and inter-island trade networks (Figure 13). The inter-regional trade network for milkfish fry shows the exchange of milkfish fry from regional sources to regional producers of milkfish for grow-out culture. The inter-regional milkfish trade network depicts the situation in 1976. The figure shows that Region X is the largest source of milkfish fry that supplies the areas of Rizal and Bulacan in the main island of Luzon. It also shows that region VI is the next region of the most inflow of milkfish fry from the other surrounding regions. The inset map shows the three main islands (Luzon, Visayas and Mindanao) and the inter-island trade of milkfish fry. Luzon in a net importer of milkfish fry followed by Visayas and lastly by Mindanao. Intra-island cycling of milkfish fry is highest in Luzon and lowest in Mindanao. The graph of milkfish fry flow for inter-regional trade is provided in Appendix C. The Inter-island trade of milkfish fry is the aggregation of the regional flows according to main Islands. Given the seven network configurations for the milkfish fry social-ecological resource system at the national and regional scales, the paper proceeds to apply the ecological information-based approach to determine if following an ecological perspective would be appropriate in assessing SES sustainability.

The defined milkfish fry social-ecological resource network systems are compared to economic and ecological networks for bench marking. The economic networks are from the previous study of Kharazzi et al. (2013) which are the following: virtual water; oil; world commodity; OECD commodity; OECD foreign direct investment; and iron and steel. These economic networks represent large scale global networks. The ecological networks are the 1) Mondego Estuary (Almunia et al. 1999) and 2) Maspalomas coastal Lagoon (Patricio et al. 2006), representing three different areas and three different stages of growth and development respectively.



Map source: www.freeusandworldmaps.com/html/Countries/Asia%20Countries/Philippines.html

Figure 13. National inter-regional and inter-island exchange of milkfish fry

The Milkfish fry social-ecological resource networks are compared to global economic and local ecological networks (Figure 14). High levels of efficiency mean low levels of reliance since efficiency and resilience are inversely related and bounded between the value of zero and one. For example, if efficiency is zero then resilience is one and if efficiency is one then resilience is zero. The global economic resource network occupies the area of efficiency and decreasing sustainability. The ecological networks, as has been previously argued, occupy the hypothetical Window of Vitality which optimizes the allocation of efficiency and resilience to attain high levels of sustainability. In contrast to the global economic and local ecological networks, the milkfish fry networks occupy a wider range of efficiency and resilience levels. The milkfish fry network systems at the regional level (I, VI, X and XI) exhibit higher levels of efficiency as compared to those at the national level. On the other hand, milkfish fry network systems at the national level have lower efficiency as well as sustainability.

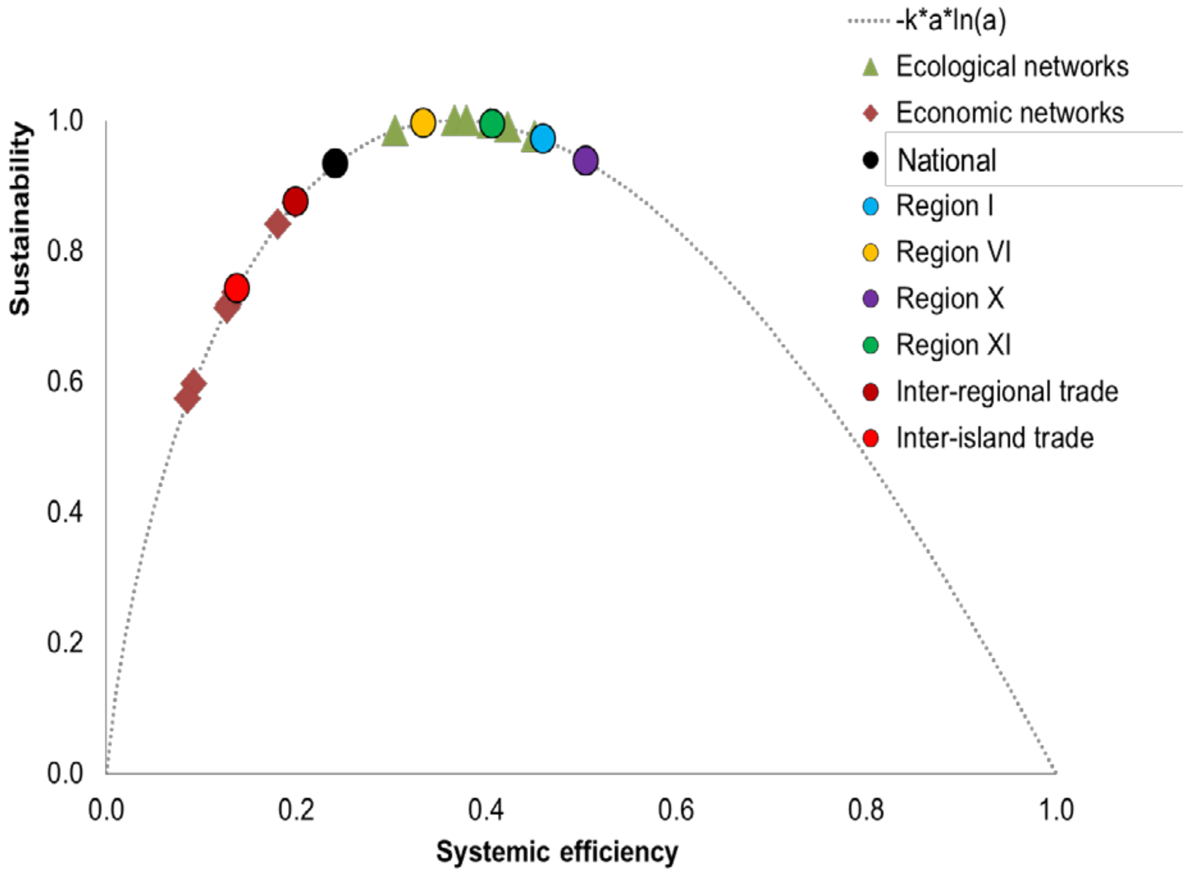


Figure 14. Milkfish fry networks as compared to economic and ecological networks

The four regional networks of milkfish fry social-ecological resource system occupy the distribution of sustainability and efficiency similar to ecological networks. Region X has the highest level of efficiency and lowest level of sustainability or robustness compared to the three other regional level networks for milkfish fry. As previously covered, the Region X milkfish fry structure shows direct flow of fry material from the gatherers to the concessionaires before being redistributed outside the region. The Region X milkfish fry network structure also has less redundant pathways as compared to the other network configurations at the regional scale. Region VI has the lowest level of efficiency, thus highest level of resilience, as compared to the other three regional networks. Region VI has an optimized level of robustness (sustainability) close to that of Region XI. Visually region VI is relatively more complex than all the other networks and has higher redundancy (Figure 10). Given Region VI and XI, high level of robustness could be attained by having either high level of resilience or efficiency. Region I has a higher level of efficiency then Region XI because of lesser redundancy although it is more difficult to distinguish between the two by just observing the network structures. Thus a quantitative measure of networks becomes useful when visually comparing networks becomes difficult.

At the national level, milkfish fry networks manifest lower levels of efficiency as well as sustainability. The inter-regional and inter-island milkfish fry trade networks lie closely to global economic systems that also exhibit lower levels of efficiency and sustainability. One reason for the similarity perhaps is due to the parallel process of network construction. Global economic resource networks were constructed by identifying nodes according to country of source and target of information (economic flow). However, the network construction does not highlight the delivery structure in between sources and receivers. The network structure for the inter-regional and inter-island milkfish fry trade network has been expressed in the similar manner where each area, either by region or island, had been identified as source or receiver of information without defining the delivery structure in between areas. It is thus necessary to consider the network expression in using the ecological information-based approach.

The national level milkfish fry social-ecological resource network, which has a better defined delivery structure of actors and institutions, has efficiency and sustainability level that is between that of global economic and local ecological networks. The milkfish fry resource system, which follows the network identification of the milkfish regional resource networks and similar to ecological networks, occupies the edge of the hypothetical Window of Vitality. Taking the ecological perspective, systems that does not possess enough efficiency losses robustness and is at risk to perish being uncompetitive against other systems in acquiring resources for growth and development. Such is the case of the milkfish fry gathering industry when the milkfish hatchery production system were developed and established in the 1990s. Hatchery produced milkfish fry has been replacing wild caught fry as stocking material for grow out operations. This is the case where similar functions are being performed by two components. Having two sources of milkfish fry is beneficial to the resilience of the entire system but these two components are also in completion.

The results of employing the ecological information-based approach demonstrated the applicability on human-nature resource systems such as the milkfish fry sector represented as a hybrid network of social-ecological and social-economic components. The network can then be transformed into a parallel graph that could be used for computational analysis using the ecological information-based approach. However, it is important to consider how the network is defined that highlight general functions of the systems such as the details of the delivery components between the main sources to the main receivers of material or information. Trade networks (point to point delivery of information) behave differently from ecological systems and do not follow the hypothetical Window of Vitality. Other network analytical tools may be more appropriate in quantifying these types of networks where the defined function is merely production and consumption. As opposed to trade networks, social-ecological resource system network has three defined functions: production, consumption and delivery. The ecological information-based approach is thus applicable in analysing SES sustainability, resilience and efficiency.

4.2 Milkfish production social-ecological system development

The ecological information-based approach has been applied to the milkfish social-ecological resource system in the previous section and has been determined as applicable to other SES expressed as a network. The approach is further tested on the major component of the entire system which is the milkfish production social-ecological system. This system is also a composition of a social-ecological unit which is the pond production areas as well as social-economic elements that facilitate the delivery of the milkfish product from the areas of production to the product consumer. This is a further examination of the applicability of network, graph and information theory on the milkfish production social-ecological resource network systems.

The milkfish grow-out production areas are social-ecological systems where human activity in culture production is highly dependent on the availability and quality of natural resources such as the culture area, seawater, freshwater and the natural benthic micro flora and fauna used in natural food production for milkfish. The grow-out production systems are integrated with the larger economic system of production and consumption. The larger scale system is a hybrid system of social-ecological and social economic components similar to the milkfish fry social-ecological resource system. These components and their interrelationship can be expressed as the milkfish production social-ecological resource network. Figure 15 is a network representing the milkfish production social-ecological resource system at the national scale (Creencia 1973). The green node represents the hybrid social-ecological production unit (brackish water milkfish production ponds) and the blue nodes represent the social-economic components. There are various institutions and actors that facilitate the delivery of the product to the consumer market. The entire network assemblage is composed of pond production, broker, wholesaler, wholesaler-retailer, retailer and consumer.

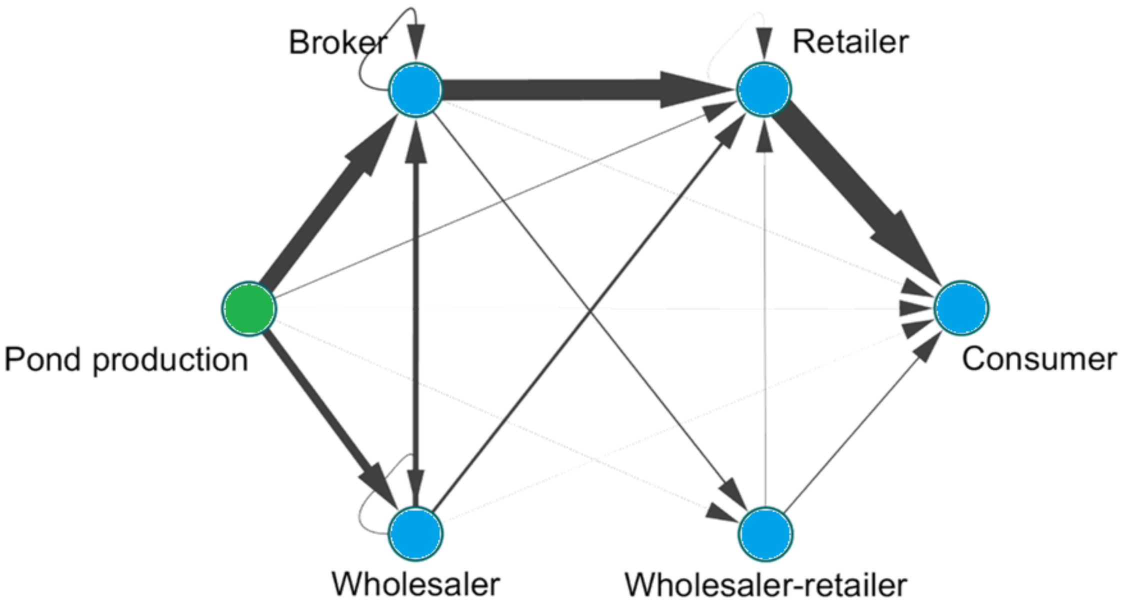


Figure 15. National milkfish production social-ecological resource network

The broker node represents individuals or institutions that facilitate transaction between pond production and other buyers of the milkfish product. Brokers can provide services such as selling and providing credit transactions as well as pricing of the milkfish product from the grow-out ponds. The direct buyers of milkfish are presented as the wholesaler, wholesaler-retailer and retailer nodes. Wholesalers are middle men who sell directly to other sellers for the purpose of reselling. Wholesalers mainly sell to retailers. Retailers on the other hand sell directly to the end-consumer. Wholesaler-retailer performs both function of a wholesaler and retailer. All production flow of milkfish through these various distribution channels eventually reaches the final-user which is the consumer node. The flow is in terms of percentage volume flow of the milkfish product coming from pond production, through the delivery system, until it reaches the consumer. The prevailing structure is composed of the pond production, broker, and retailer and consumer chain. The wholesaler and wholesaler-retailer provide redundancy equivalent to network resilience in the national milkfish production social-ecological resource network. Table 9 is the graph for the national milkfish resource network system used for the calculus to determine sustainability, resilience and efficiency.

Table 9. National milkfish production social-ecological resource graph

(i, j)	Pond production	Wholesaler	Broker	Wholesaler-retailer	Retailer	Consumer	Total
Pond production		33	62	1	4	0.25	100
Wholesaler		4	21		12	0.25	37
Broker			7	7	75	1	90
Wholesaler-retailer					2	6	8
Retailer					0.25	93	93
Consumer							
Total		37	90	8	93	100	**(328)**

The milkfish industry was initially practiced in the main island of Luzon before expanding to Visayas and finally to Mindanao. Taking this into account, the three main islands would be at different stages of growth and development. The ensuing milkfish production networks are for Mindanao, Visayas and Luzon representing the different stages of development.

The Mindanao milkfish production social-ecological resource network is very much similar to the national network in terms of the nodes and the main structural flow connections of pond production, broker, retailer and consumer (Figure 16). The obvious difference is the internal trade occurring at the broker and retailer nodes at the national level. The Mindanao milkfish resource network illustrates lesser degree of flow redundancy as compared to the national milkfish resource network. Another distinguishable difference is the greater role of the wholesaler node for Mindanao in handling higher volume of flow as compared to the national network. Table 10 is the graph for Mindanao. Considering that Mindanao is in its early stages of development as compared to Visayas and Luzon; then the provided network structure is the basic foundation for that stage.

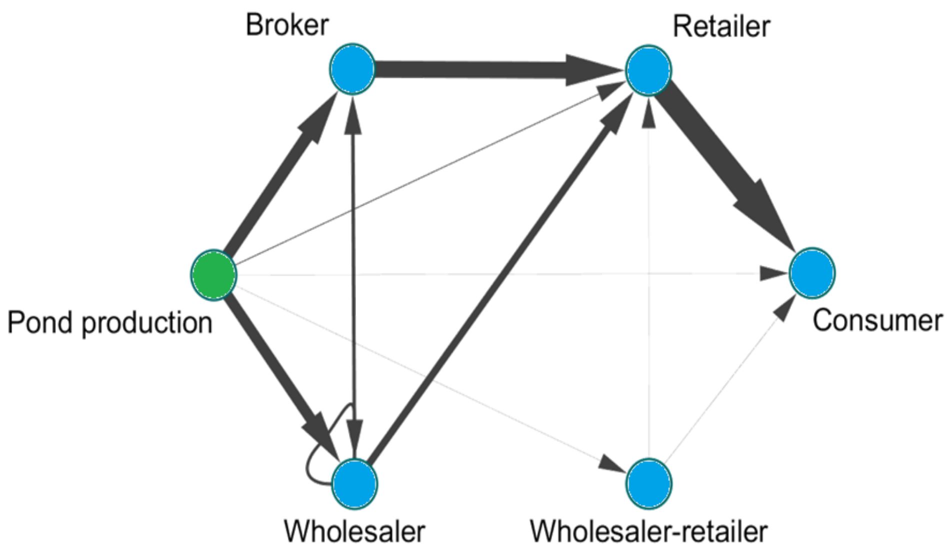


Figure 16. Mindanao island milkfish production social-ecological resource network

Table 10. Mindanao island milkfish production social-ecological resource graph

(i, j)	Producer	Wholesaler	Broker	Wholesaler-retailer	Retailer	Consumer	Total
Producer		45	50	1	4	0	100
Wholesaler		13	15		30		58
Broker					65		65
Wholesaler-retailer					0	1	1
Retailer						99	99
Consumer							
Total		58	65	1	99	100	**(323)**

The Visayas milkfish production social-ecological resource network system (Figure 17) also has the same basic structure as Mindanao with an addition of the cooperative node. Visayas also has more network flows owing to the additional cooperative node as well as the internal cycling of milkfish product for the broker and retailer nodes. Table 11 is the graph for visayas used in for the ecological information-based approach.

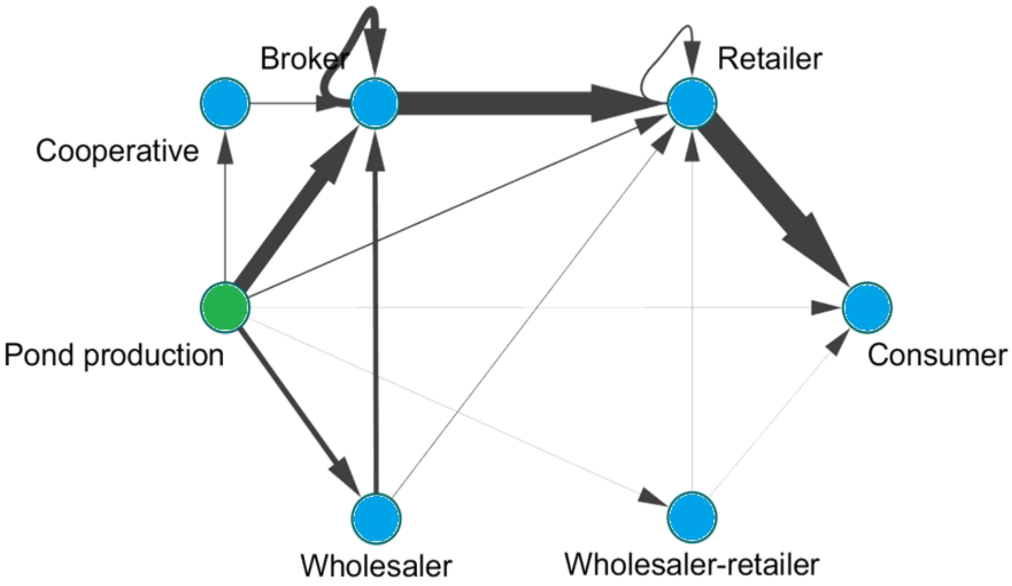


Figure 17. Visayas island milkfish production social-ecological resource network

Table 11. Visayas island milkfish production social-ecological resource graph

(i, j)	Producer	Wholesaler	Broker	Wholesaler-retailer	Retailer	Consumer	Cooperative	Total
Producer		23	63	1	7	0	6	100
Wholesaler			20		3			23
Broker			33		89			122
Wholesaler-retailer					1		0	1
Retailer					9	100		109
Consumer								
Cooperative			6					6
Total		23	122	1	109	100	6	**(361)**

The Luzon milkfish production social-ecological resource network system (Figure 18) is assumed to be the most advanced among the main island in terms of growth and development. Luzon also has the basic nodes with an addition of a node for exporting milkfish products. The network also has the prevailing delivery structure of pond production, broker, retailer and consumer. The wholesaler also plays a substantive role in facilitating milkfish product from pond production and broker to the retailer and finally to the consumer. The Luzon network has a higher number of flows than Mindanao and Visayas and is structurally more resilient. The main deliver structure can be seen as products move from pond production to broker then to retailer and finally to the consumer. The wholesaler node offers an alternate pathway to retailers making the structure more resilient to disruption. Table 12 is the graph for the Luzon milkfish network used to quantify the sustainability, resilience and efficiency of the system.

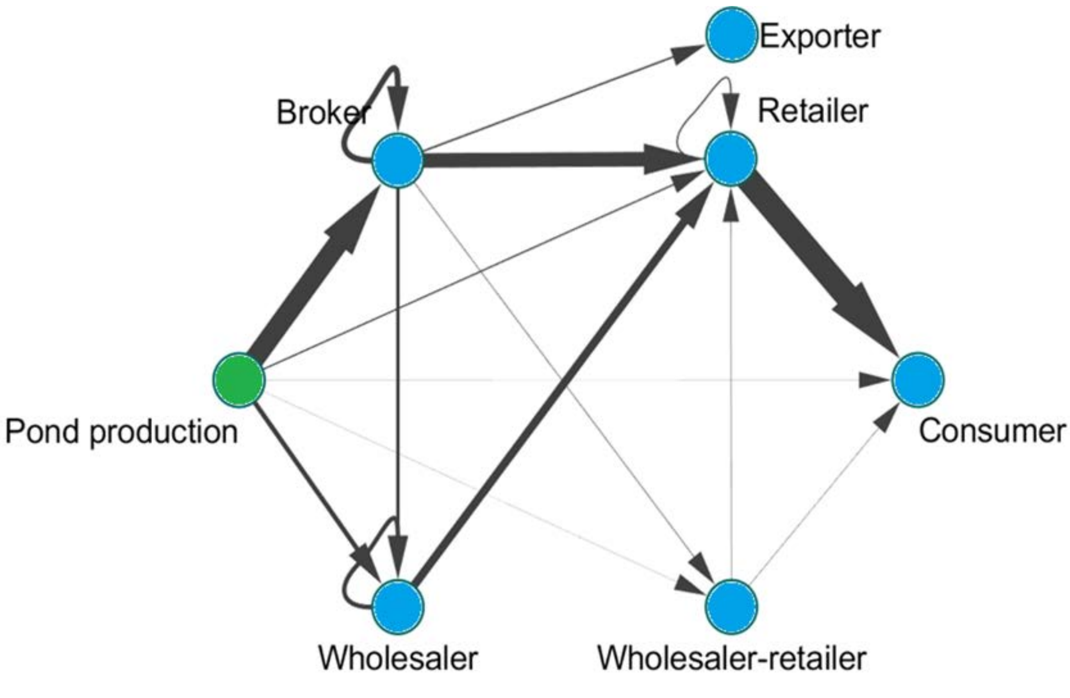


Figure 18. Luzon island milkfish production social-ecological resource network

Table 12. Luzon island milkfish production social-ecological resource graph

(i, j)	Producer	Wholesaler	Broker	Wholesaler-retailer	Retailer	Consumer	Exporter	**Total**
Producer		18	75	1	6	0.25		100

Wholesaler		17			31			48
Broker		13	22	3	52		7	97
Wholesaler-retailer					2	2		4
Retailer					6	91		97
Consumer								
Exporter								
Total		48	97	4	97	93	7	**(345)**

The milkfish production social-ecological resource system has been modelled at the national and main island scales. Three network representations have been provided for Luzon, Visayas and Mindanao that is hypothesied to be at different growth and develoment stages with Luzon being the most advanced and Mindanao as being at the early stage. The matrix graphs of the four networks is used to determine the Window of Vitality (Figure 19). The resulting figure provide a snapshot of the possible Window of Vitality for the milkfish production social-ecological resource networks. At the main island scale, the Mindanao production social-ecological resource system has the highest level of efficiency and lowest level of sustainability followed by Visayas then Luzon. Luzon and Visayas has comparabe levels of robustness even though luzon has the lowest level of efficiency or higher resilience. The milkfish networks behave similarly to ecological networks in allocating resilience and efficiency to optimize sustainability in terms of network robustness. At the national level, the milkfish prodcution social-ecological resource system lies within the range of the levels of the main islands. The results show the initial range of efficiency and resilience for the milkfish production resource network that behaves similar to ecological network systems in the optimization of sustainability.

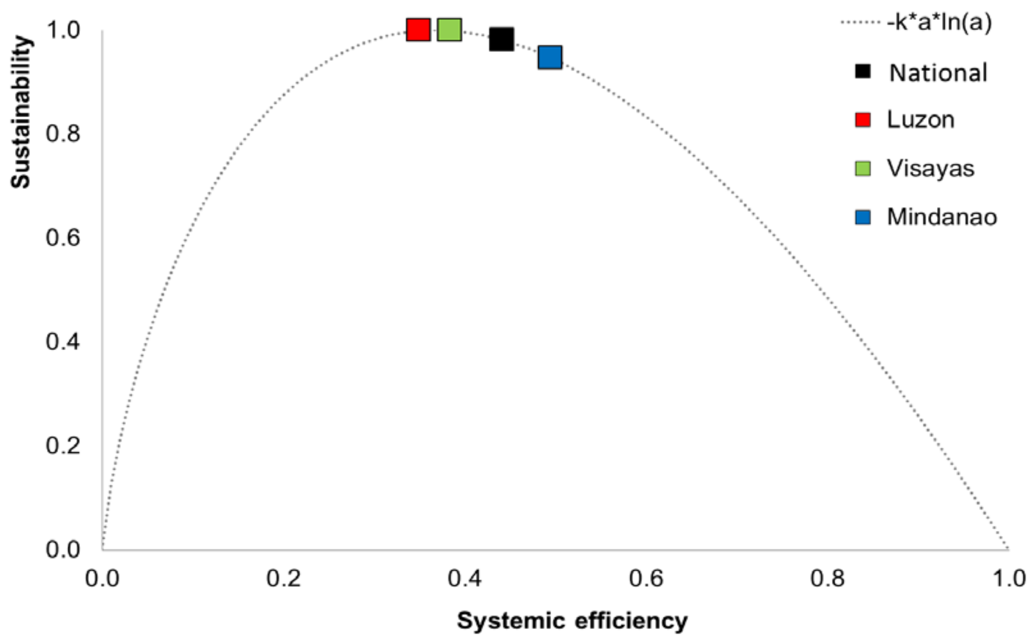


Figure 19. The Window of Vitality for milkfish main islands and national networks

Ecological systems are said to have the propensity to accumulate resources for growth and development. Known as system ascendency, it is a measure of the overall activity in a system with consideration to structure and interaction of elements (Patricio et al. 2006). In the absence of disturbances, ecological systems have the tendency to increase ascendency. Greater ascendency results to faster resource accumulation and growth of the entire system. The theory of ascendency is also evident in the adaptive cycle, where ascendency is crucial in the early stages of growth at the r phase. However, given limited capital and increasing connectivity, ascendency would start to decrease as it approaches the K phase. In the ecological information-based approach, systemic efficiency is equivalent to systemic ascendency (Goerner et al. 2009). As efficiency increase, resilience decreases and vice versa. Given the two qualitative and quantitative ideas of growth and development taking the ecological perspective, it would be possible to have an estimate of the phase of a system descriptively and numerically.

The milkfish production social-ecological resource systems for Luzon, Visayas and Mindanao have different levels of efficiency. Considering that Luzon, Visayas and Mindanao are at various stages of development, the arguments above is applied in explaining the differences in efficiency levels. Mindanao represents early stages of brackish pond development followed by Visayas. Luzon is at the most advanced stage of development of the milkfish industry. The decreasing efficiency (from Mindanao to Luzon) of the three different stages shows that the milkfish sector is already approaching the K phase in the Adaptive Cycle. If the systems were in the growth phase, there would be increasing levels of efficiency from Mindanao, Visayas and Luzon. This initial use of the ecological-information based approach together with the Adaptive Cycle proves to be useful in monitoring the sustainability and resilience of systems at various stages of growth and development. This has implications in the possibility to assess interventions on large scale social-ecological resources.

Figure 20 is the Window of Vitality summary for the milkfish fry and production social-ecological resources systems at the regional, main island and national scales. The networks, just like ecological systems, occupy a similar hypothetical Window of Vitality that optimizes sustainability by appropriating efficiency and resilience levels. Although there is the observed optimization, components of the milkfish social-ecological resource system do have the tendency to lean towards systemic efficiency. It can be observed that the network configurations are from national to regional scale behave differently from global scale economic networks which occupy high resilience. This is just an initial observation and more samples are needed to verify if higher scale networks have higher resilience compared to lower scale systems which are relatively easier to manage. This would also reflect the human dimension of managing resource and delivery systems towards greater efficiency.

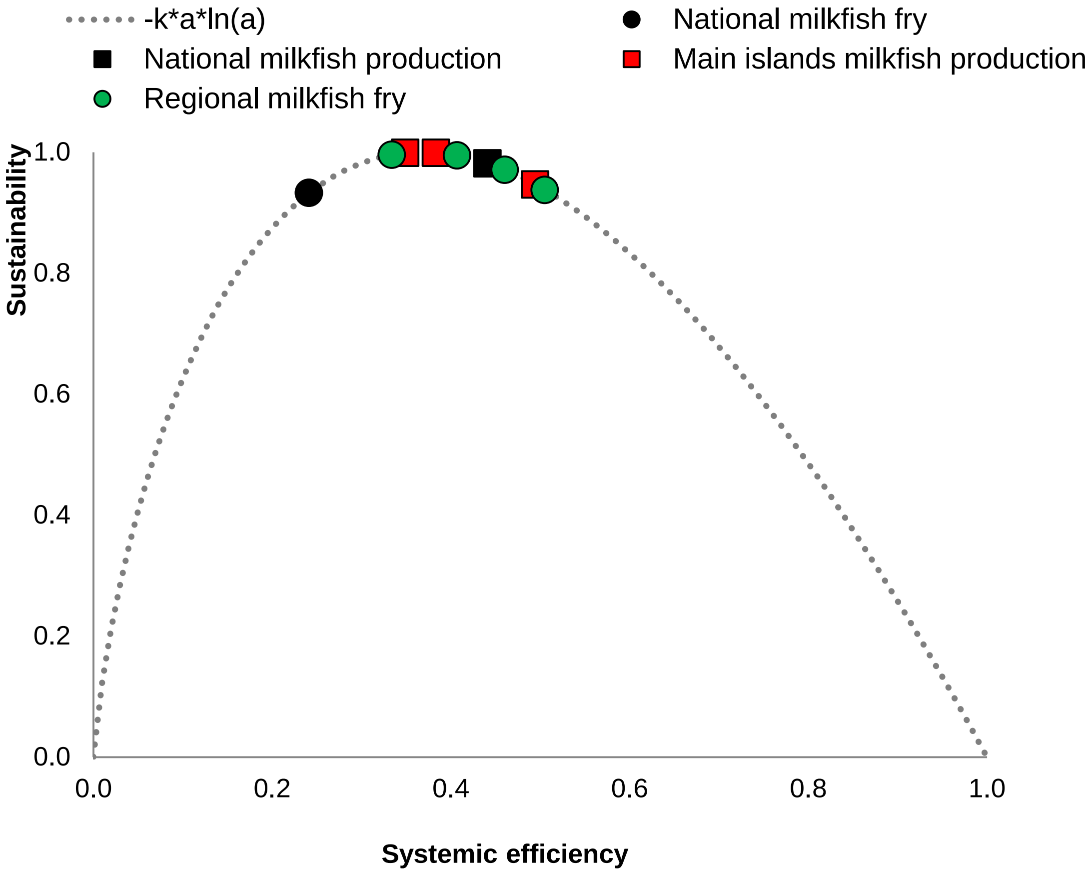


Figure 20. Window of Vitality for the milkfish fry and production at different scales

Highly efficient systems become prone to disturbances which push the system back towards greater resilience. On the other hand, as observed in the national milkfish fry social-ecological resource network, systems that have low levels of efficiency (high resilience) becomes uncompetitive and have the risk of being replaced by other systems (such as the hatchery production system). Such replacement phenomenon is also present in ecological systems and is known as "autocatalysis" (Ulanowicz 2009). Autocatalysis is a selection pressure in ecological networks that enhances ascendency (efficiency) for the entire system. The hatchery system is more efficient in producing and delivering milkfish fry and promotes greater production in the grow-out areas. Autocatalysis is the process of selection where highly resilience and inefficient components (such as the milkfish fry resource system) is replaced by the hatchery system as the main source of fry stocking material for the entire assemblage of the brackish pond milkfish social-ecological resource system. The use of the ecological-information based approach and the Window of Vitality on the case study of the milkfish social-ecological resource system becomes more relevant when complemented with the qualitative description of the Adaptive Cycle. Origins of both the Window of Vitality and Adaptive Cycle come from studies on ecological systems and have complementary and parallel conceptualization that has not been integrated before.

Application on the case study establishes that the Window of Vitality and the Adaptive Cycle are both consistent and complimentary in providing qualitative and quantitative description of the phenomena of growth and development for the milkfish social-ecological resource system. There are limitations though in the application, for example, the detail of network construction should be similar to those used in ecological networks and not just point to point exchange network without highlighting the delivery components involved in the system. Further studies are necessary to explore the applicability of the ecological information-based approach on such trade networks but this is currently beyond the scope of this dissertation. The use of the calculus can also be used on networks at various scales such as applied to the case study (national, main islands and regional) and are still comparable because the measure of sustainability, resilience and efficiency are scale free and unit-less. This provides further potential not just comparing studies at different scale but also different systems. The following section covers the temporal progression of social-ecological network to determine the behaviour of the system throughout the growth and development stages.

4.3 Brackish pond social-ecological system growth, development and sustainability

The ecological information-based approach and the corresponding Window of Vitality has been found to be applicable not only for ecological and economic networks but also on hybrid social-ecological resource systems as for the case of the milkfish resource systems expressed as a network structures of product flows at different scales. This has been the first objective of employing network theories to analyze a SES described as networks at various scales. The second objective of the research is to determine the applicability of the approach on temporal analysis of SES growth and development. This section is the temporal analysis on the systemic characteristics of the brackish water pond system of the Philippines which is composed of the milkfish and giant tiger prawn social-ecological resource systems. The systemic characteristics remain to be sustainability, resilience and efficiency that has been described under the concept of the Window of Vitality and measured by the ecological information-based approach. The temporal changes in the systemic properties are narrated using the Adaptive Cycle.

The gap in the analysis of the first objective is that the milkfish social-ecological resource system has been conducted on two main components: 1) the milkfish fry and 2) the milkfish production social-ecological resource systems. In investigating the temporal changes in the growth and development of the given case study, it is necessary to integrate the two components together to be able to obtain a holistic observation of the system and not just compartmental inspections. In order to integrate the two critical components together, a definition of the network structure is required. The brackish water pond system can basically be described as a production and consumption or supply chain model that includes the delivery processes that integrated the auxiliary system of fry supply to the grow-out system.

The milkfish resource system can be defined as a composition of supply and demand nodes (Smith et al. 1982). The same can be applied to the brackish pond resource system. Figure 21 represents the brackish pond resource system elements and disaggregation of these elements. At the highest tier the system is described by two elements of supply and demand nodes. The supply node is where the elements and processes of production occur. The demand node represents the end user of the product produced from the supply node. At the lower tier the supply node is horizontally disaggregated into the procurement and transformation nodes. The transformation node represents the brackish water pond culture areas which have already been explained as a social-ecological resource system. The procurement node is the component providing stocking or input materials for transformation production. At the last tier, the nodes are further disaggregated and critical nodes identified as fry sources, brackish pond productions areas and consumption of the grow-out products. It has been established that it is important to consider the distribution channel between key functions of production and consumption. The distribution channels are included in the supply chain resource system as the (milkfish) fry distribution and the milkfish (production) distribution nodes.

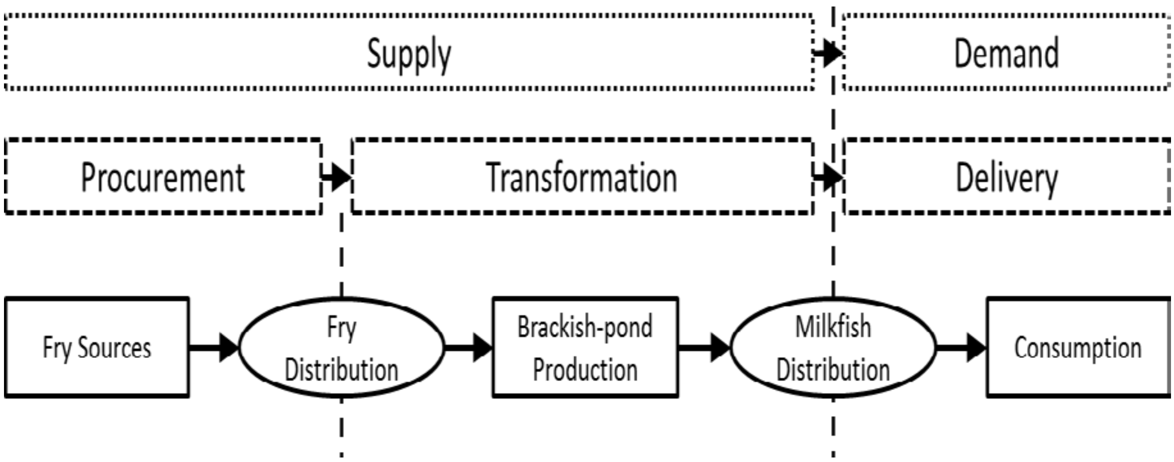


Figure 21. Brackish water pond resource system (based on Smith et al. 1982)

The given brackish water pond resource system depicts an integrated structure of social, ecological and economic components. The fry source is a hybrid of element of social and ecological elements as well as the brackish pond production component. The milkfish fry and milkfish (production) distribution nodes contain social and economic elements. The consumption node is the end user of the in the overall system that determines the demand for the milkfish product. The basic structure of the brackish water pond water system is further disaggregated to provide more detail and to construct the network configurations for the analysis using the ecological information-based approach. Figure 22 is the network system of product flow for the milkfish and giant tiger prawn sectors that comprises the brackish pond social-ecological resource system used for temporal analysis of systemic growth and development.

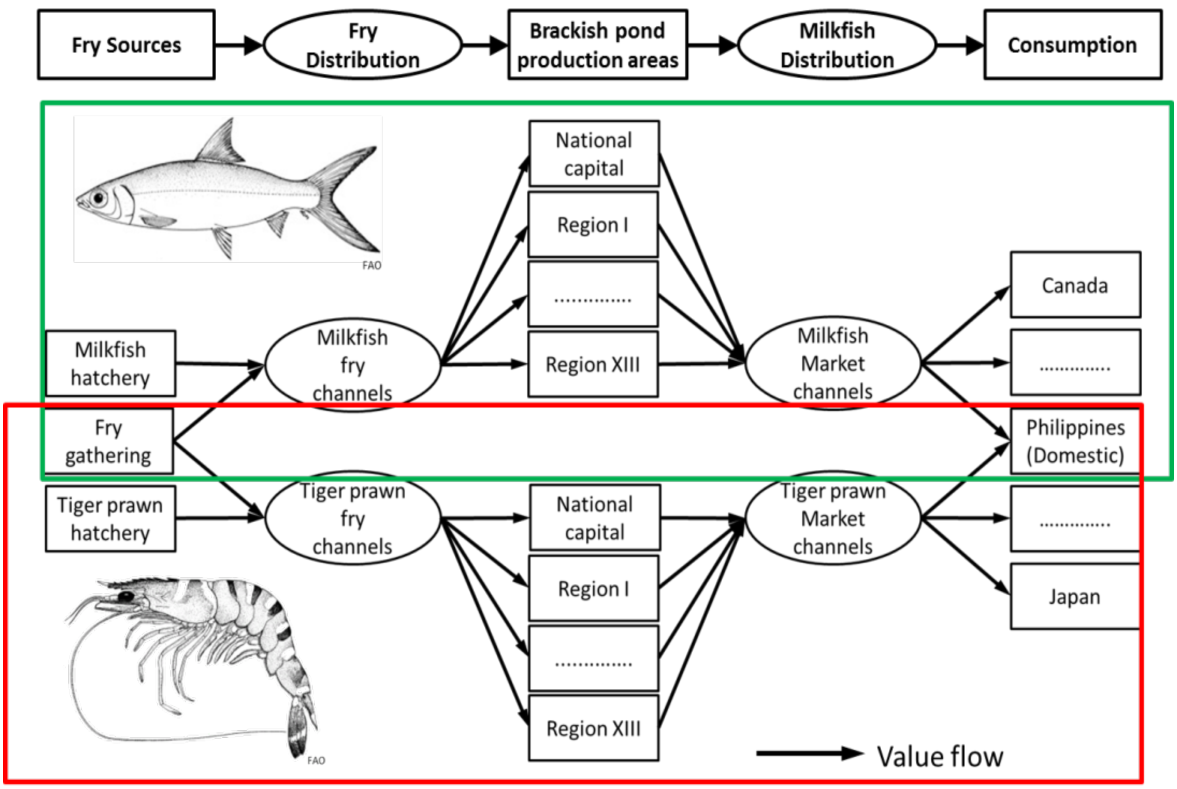


Figure 22. Brackish pond social-ecological resource network system for temporal analysis

The fry sources node is disaggregated to the fry gathering, milkfish hatchery and giant tiger prawn hatchery nodes. The brackish pond production areas are disaggregated according to the regional production areas in the country for the type of species cultured (milkfish and giant tiger prawn). The consumption node is disaggregated into the local and export maker of product destination. The connections between nodes are product flows for the milkfish and giant tiger prawn. The combination of the milkfish resource network and the giant tiger prawn resource network gives the overall structure of the brackish pond resource system.

4.4 Data sourcing and handling

In applying the calculus of the ecological information-based approach, the various information flows of the network systems needs to be identified. The information of interest in the identified networks is the product flow from the source to the final stage of consumption. In reconstructing the flows, various sources are used. One of the limitations of using the calculus is that all information flows should be of the same unit of measure. To overcome this limitation, the product flow is unified by considering the economic value of the material circulating in the systems. It is argued that by using monetary flow, the results for the levels of sustainability, resilience and efficiency, does not only include the social and ecological dimensions but the economic as well.

The identified connections of the economic resource system configuration are the economic flow of the cost of production cycling within the defined core components. The economic flows were constructed using volume and value of production that have been assembled using various data resources and empirical studies. The brackish pond production compartment is disaggregated according to the geographic regional divisions of the Philippine archipelago. There are 17 regional areas under the three main islands: 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) Northern Mindanao (Region X), 14) Davao Region (Region XI), 15) SOCCSKARGEN (Region XII), 16) Caraga (Region XIII), 17) Autonomous Region in Muslim Mindanao (ARMM). Out of the 16 regions, only CAR does not have brackish pond production being land locked and having no access to coastal areas. The market compartment is disaggregated into the local and export markets by country of destination of the products.

The network flow between the production areas to the market was constructed using data series (value and volume) of brackish water pond regional production and 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). Production data from the Bureau of Agricultural Statistics, Bureau of Fisheries and Aquatic Resources, FAO were also used to verify consistency of the data. The flows from the regional production areas to the market distribution channel nodes for milkfish and giant tiger prawn were converted to monetary value (1 USD = 56.04 PhP). The regional production for milkfish and giant tiger prawn from 1970 to 1978 was computed under the assumption that the rate of growth is the same for all regions. The resulting data set is provided in Appendix D.

Export of the milkfish product was obtained from the PCMARD and FAO – Fisheries and Aquaculture Information and Statistics Service (Appendix E). Milkfish exports comes in a variety of categorical forms: 1) whole or in pieces, not minced, prepared or preserved in airtight containers; 2) dried, salted, smoked or in brine; 3) frozen excluding livers and roes;

and 4) fresh or chilled. Data are pooled according to the country of destination to determine the export values of milkfish by country. Figure 23 shows the determined flow of export value for milkfish while Figure 24 is a representation of the export network for the milkfish product. The top importing countries from 1976 to 2001 are USA, Canada, Saudi Arabia, Japan and, more recently, Australia (Appendix F). Export of milkfish is mostly consumed by the Filipino communities in these countries (Tan et al. 1984). Deducting the export values from the total value of milkfish production gives the value flow to the domestic market. The same calculation is done to obtain the values for export and domestic market for the giant tiger prawn product based on the export of giant tiger prawn by metric tons (Appendix G). These regional production and market flows constitute the first half of the network structure.

There are no time series data for milkfish and giant tiger prawn 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 1978, 1979, 1985, 1986 and 1996 (Chong et al. 1984, Agbayani et al. 1989, Bombeo-Tuburan et al. 1989, and Israel 2000). The cost of milkfish-fry input for 2001 is based on the production cost statistics of the Philippines Bureau of Agricultural Statistics (BAS). The other values are taken as the average of in between years. The cost of inputs for tiger prawn fry is maximized at 20 % to capture optimum fluctuations in the cost of fry inputs in production.

The milkfish-fry source is disaggregated to two nodes. The first is the areas where wild caught milkfish-fry 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. To capture the transition of fry supply from wild fry gathering to hatchery systems an increment is established for the network model. The shift from wild caught milkfish fry to hatchery bred milkfish started 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 as nodes in the assemblage of the network to represent the function that facilitates the distribution of products. Here, we use these nodes 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. The following section is the results of the model in terms of the ecological information-based approach.

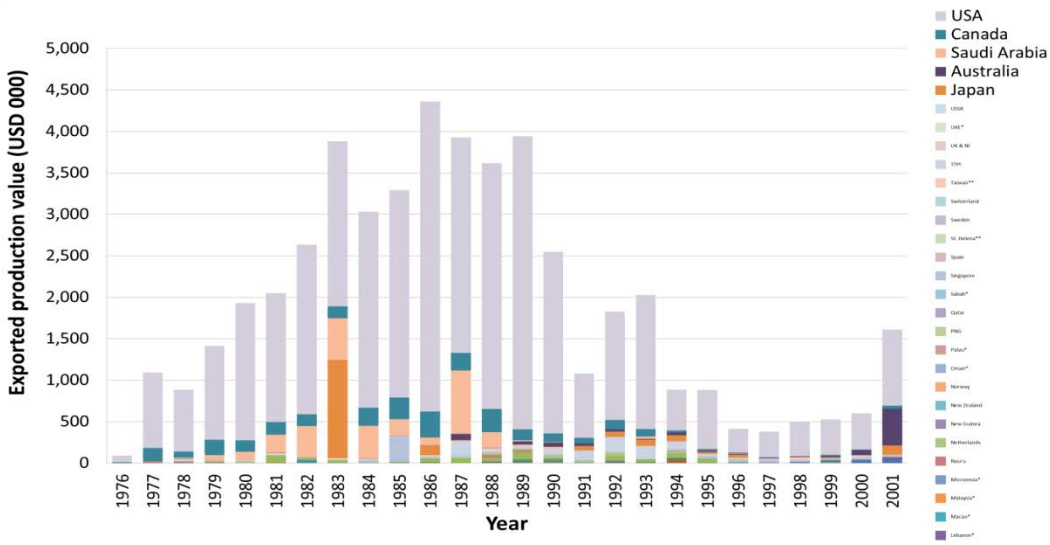


Figure 23. Milkfish export value by country of destination

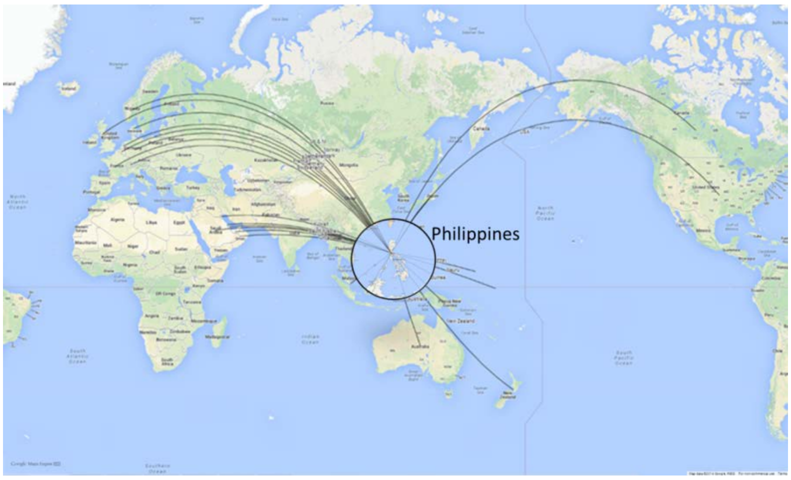


Figure 24. Global milkfish export markets

4.5 Temporal analysis

The economic flows of the milkfish economic resource network were based on production and export data as well as partially modelled from empirical studies. The figure below (Figure 25) is the analysis for the milkfish resource system composed of the milkfish the milkfish product system and resource sub-system. The resulting network robustness level is based on the 5%, 10% and 15% incremental shift per year from wild fry to hatchery supply starting 1997 and excluding the computed values from 1970 to 1978. The figure shows that from 1979 to 1990 the sustainability of the milkfish sector has been decreasing as the system undergoes growth and development. The lowest level of sustainability is reached in 1990s and although there is already an initial shift to increasing sustainability, the milkfish system has experienced a decline in production after 1991. This can also be observed in 1996 where there is a decrease in sustainability and a slight decrease in production output. The allotted increments do not change the general trend of increase and decrease of robustness from 1997 to 2001 and the assumptions remain valid in monitoring shifts in sustainability using the ecological information-based approach.

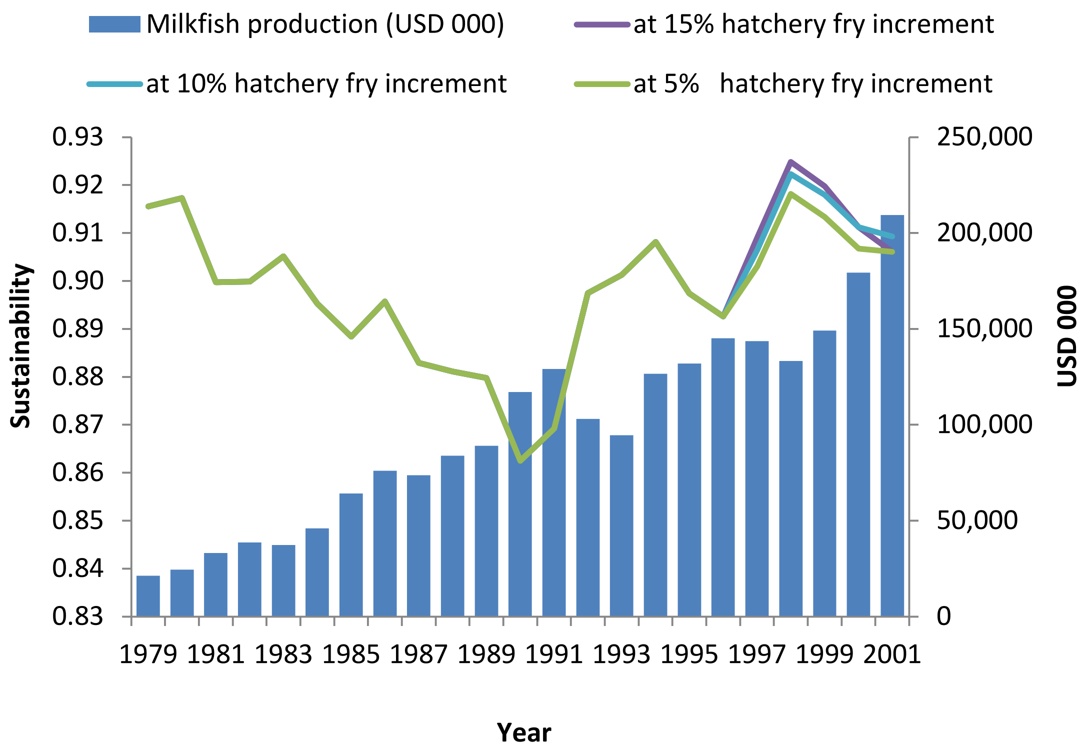


Figure 25. Sustainability of the milkfish resource system and shift in fry source

For the ensuing discussions of the rest of the paper, we use the 10% increment shift from wild to hatchery sourced milkfish-fry. Plotted against the milkfish production, 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. The milkfish industry operates in an environment open to natural disturbances and can be observed in the decrease in production. 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 a shift from milkfish to shrimp (Penaeus monodon) production due to market opportunities for the higher valued product for export (Rosario et al. 2005). In the same year, there was the largest volcanic eruption in Region III which also affected fishpond production (Stevenson 2005). The stated cases above are actual events of disturbances that could occur in the system and are very difficult to predict and one way of dealing with uncertain disturbances is to increase the resilience of the system over efficiency. Increasing sustainability through resilience offers more robustness to the given system especially in human managed environmental resource systems where efficiency is viewed most important in increasing outputs to meet demands for product consumption.

Having a diversity of production areas protects the entire system from isolated natural disasters and offers greater resilience. Volume and value of production is mostly used as an indicator of growth and development performance but does not include the inherent structural support for these material and monetary flow of the industry. The measure of robustness may be a useful systemic indicator that considers both the amount of flow (e.g. in terms of volume or value) as well as the inherent structure of the flow. We therefore recognize at this stage of the analysis that it may be equally important to draw research attention towards social-economic-ecological systems in order to link patches of SES at a wider scale of analysis which is evidently missing in SES studies (Young et al. 2006).

In the perspective of ecological system evolution, the development capacity (sustainability) of ecological network consists of two components: efficiency (ascendency), which maintains the structure through time, and reserve capacity (resilience) against perturbations (Ulanowicz et al. 2009). 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 reserve (Figure 26.). Such disturbances could be attributed to economic reasons (e.g. changes in prices and demand for the milkfish products) as well as natural (e.g. typhoon affecting production areas). In the early period of growth there is an even allocation of efficiency and resilience.

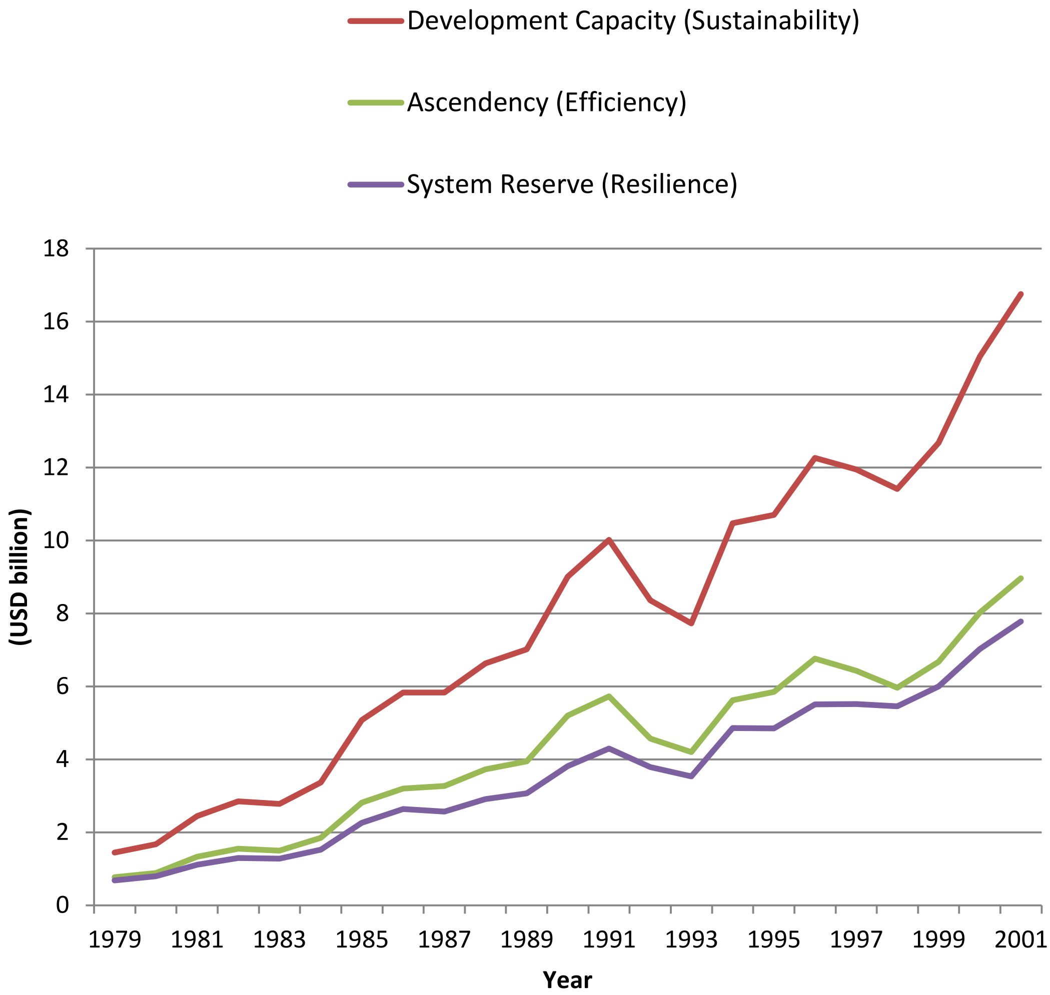


Figure 26. Milkfish systemic sustainability, efficiency and resilience.

As sustainability increase, efficiency of the system increases more than resilience. However a disturbance (sharp decline in sustainability) drives the system to reallocate efficiency and resilience to become more evenly distributed (e.g. in 1993 and 1998). The milkfish industry operates in an environment open to natural disturbances and can be observed in the decrease in production. It can be observed that there is a noticeable decrease in robustness (sustainability) prior to drop in production values. Having a diversity of production areas protects the entire system from isolated natural disasters and offers greater sustainability.

To summarize the results, development capacity of the system is the sum of efficiency and resilience. It has been observed in the results for the milkfish network 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, 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. The entire milkfish system (with the integrated milkfish fry and production components) is mapped against ecological and economic systems as has been previously done on the individual components. The succeeding section situates our results to those of ecological systems as well as economic systems measuring sustainability and efficiency. The purpose is to test the consistency of the results according to the arguments that has been stated.

To examine the implications of the results, it is necessary to establish a bench mark against other systems of varying 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, and Ulanowicz 2009). We take the example of 6 ecological systems which includes Modego estuary, Lake Findley, Maspalomas coastal lagoon, Crystal river creeks, Cone spring (Baird and Ulanowicz 1989, Kay et al. 1989). 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 recent study by Kharazzi 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, OECD-BRIC, OECD-BRIC FDI, and Iron and Steel.

We draw from these studies of essentially ecological and human built systems initially to put bearing on our results as was previously done in the previous section in analyzing the individual components of the milkfish fry and production systems. Figure 27 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 the 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.

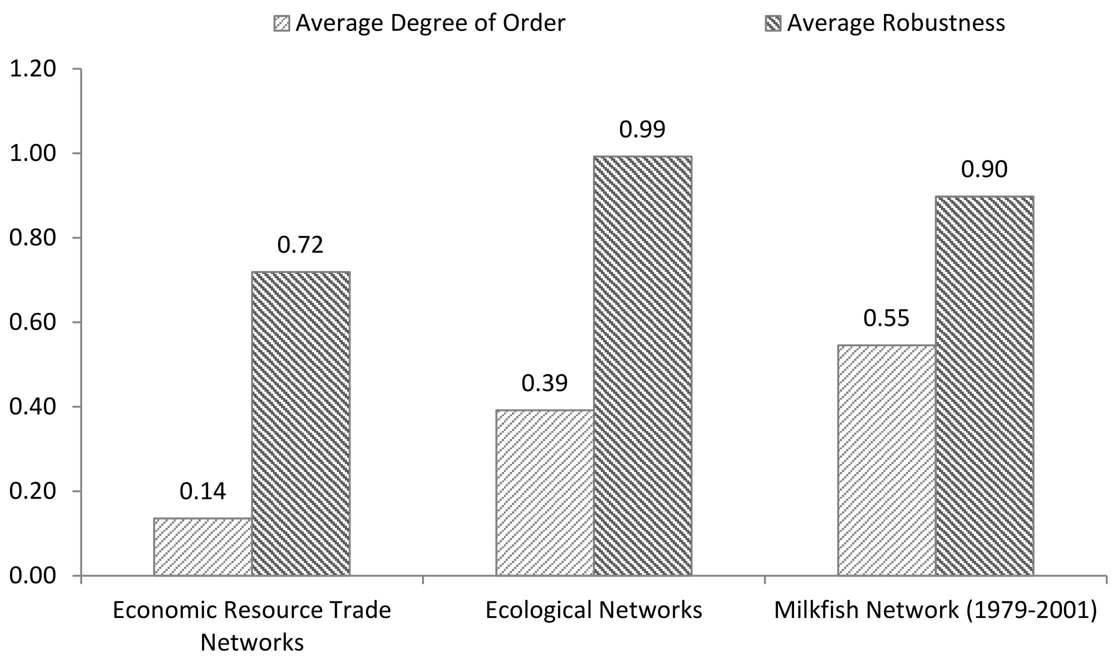


Figure 27. Average robustness and degree of order of network systems

To explicitly determine where along the optimal robustness the milkfish network lies, we graph the results together with the two other networks for benchmarking. Figure 28 summarize 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.

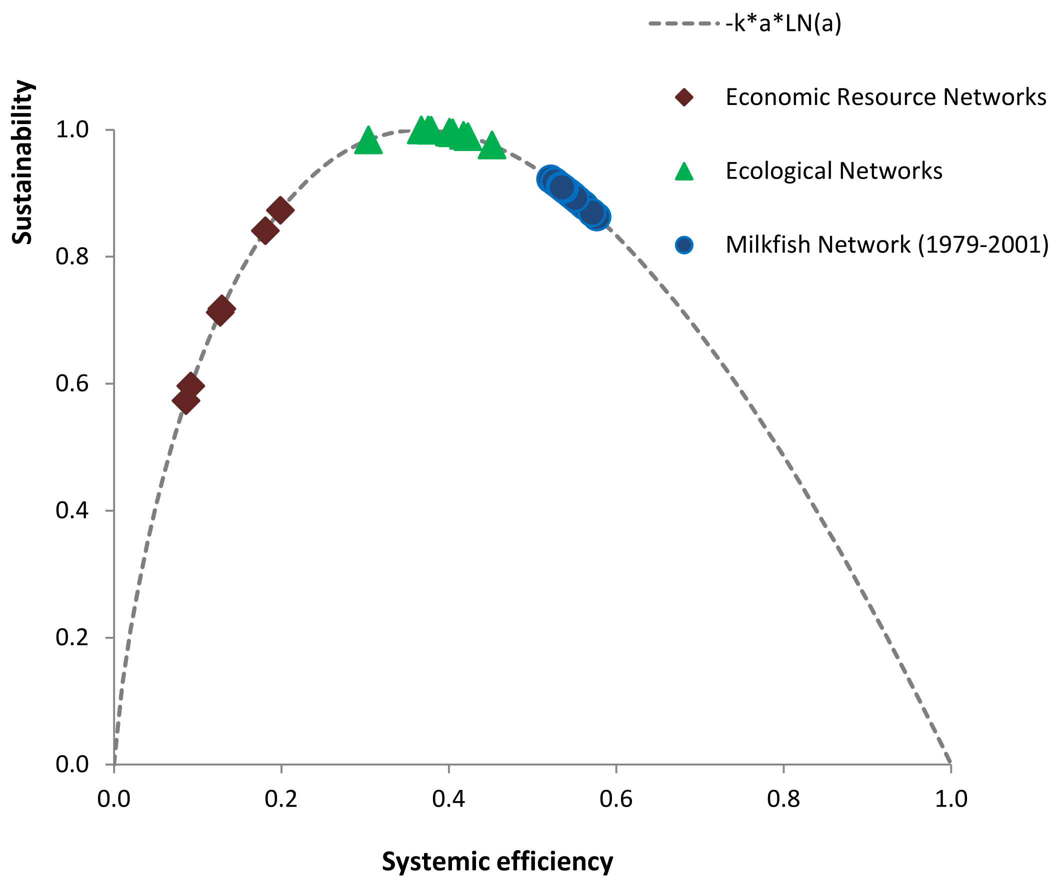


Figure 28. Window of Vitality for economic, ecological and milkfish systems

Although we have indicated the limitation of applying the network approach to networks that have minimal distinction of functions, we must also consider the scale of analysis. The scope of the economic networks 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 this resource network 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 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 dire 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. Finally, we observe the yearly changes in efficiency against the production trend of the milkfish sector where we draw our lesson on how to manage robustness of the sector in consideration to distribution of flows in the following section.

The network allows us to reveal how the distribution of flows affect resilience, efficiency and over all sustainability of the system. Milkfish is essentially a local market product with very low export volume. It has also been shown that the shift from wild to hatchery milkfish-fry source has minimal impact on influencing the robustness of the system. The very nature of the network allows us to focus on the distribution of the flow according to the regional areas to assess the relationship of efficiency (degree of order) and production. It could be observed that production of milkfish is focused on two main regions (Region VI and III) which may be the reason for the high measure of resilience of the system (Figure 29). High levels of efficiency are matched with higher rate of increase in production from 1979 to 1991. At the peak of efficiency corresponds to the lowest level of robustness and resilience. The system in this case became vulnerable to disturbance and production dropped dramatically after 1991 due to the previously mentioned perturbations. The graph also shows that a more even distribution of volume of production contributes to increase in resilience. This is most notable in 1998, 1992 and 1980 where the difference in production between region VI and III is relatively smaller to other years as well as higher production in other regions.

To increase the resilience of the system one can either increase the production of the low producing areas which might not be feasible due to limitations of natural, human and economic resources. The other way to increase resilience in this case is to reduce the levels of production of high producing regions. One possible approach of doing so is to diversify production to other cultured species. Although the total output of milkfish would decrease, this could be compensated by production of other species. Thus, it may be necessary to manage the system by reduction for the milkfish sector but maintaining production levels for the overall aquaculture production if there is a shift to other species of production. This may have implication to policies in diverting growth and development to other sector of brackish-water pond production such as tilapia, mudcrab, white shrimp and other potential species. It would also be possible to culture mixed species such as tilapia and shrimp in one culture system.

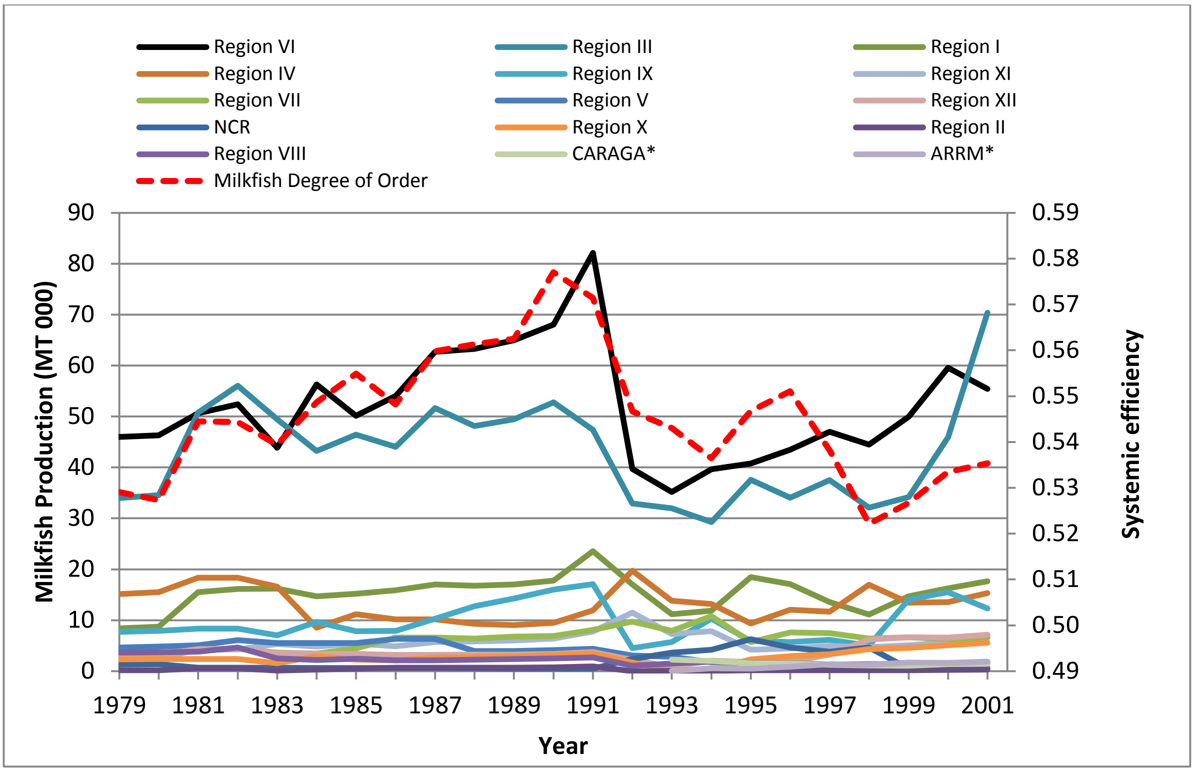


Figure 29. Milkfish network systemic efficiency and regional production

Having established the potential applicability of the ecological information-based approach in measuring sustainability of social-ecological resource systems in terms of efficiency and resilience, the dissertation moves forward by providing a qualitative interpretation in the variation of resilience by using the "adaptive cycle" narrative for the milkfish and giant tiger prawn social-ecological resource system as well as the over-arching system which is the brackish pond social-ecological resource system. Proceeding with the milkfish social-ecological resource system, Figure 30 shows the trend in the change of the level of resilience as the system goes through growth, development and experiences disturbances from 1970 to 2001. The first observable trait is that there is a decreasing trend in resilience prior to drastic decrease of production due to disturbance particularly in 1982 and 1991. These disturbances have been previously described. The decrease in resilience made the system vulnerable to such disturbances.

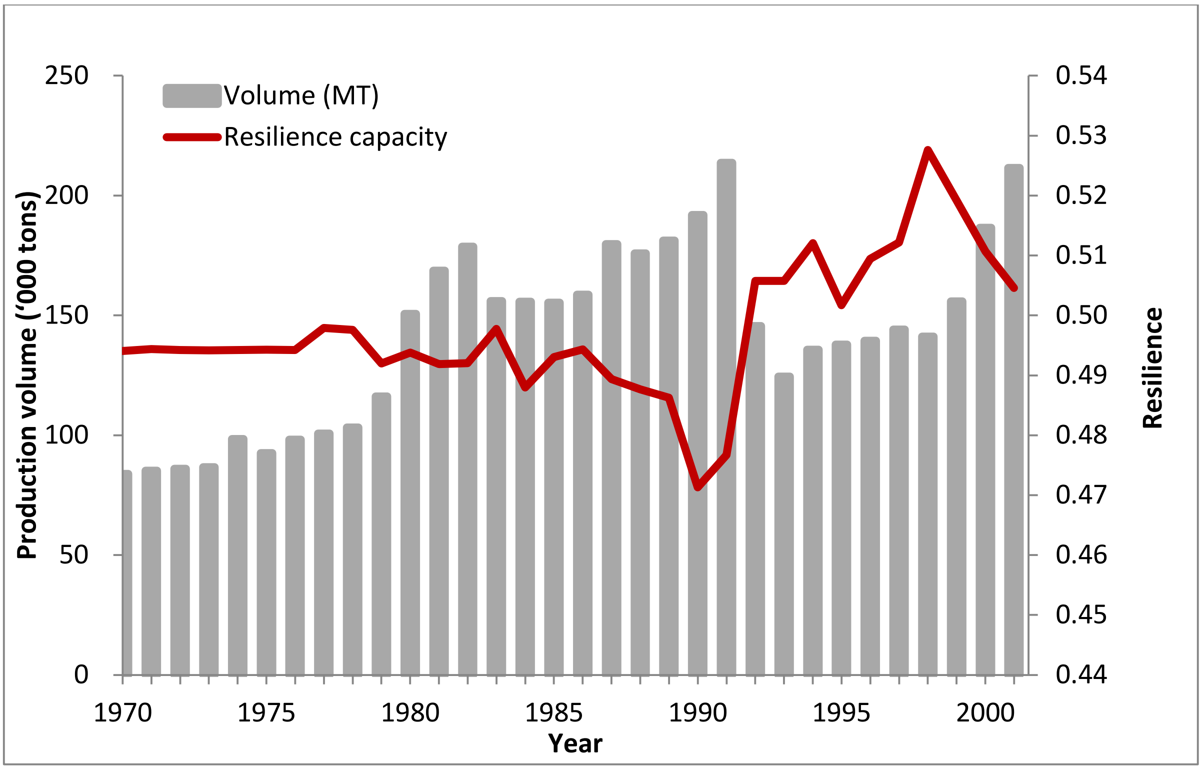


Figure 30. Resilience of the Milkfish social-ecological resource system

In terms of the Adaptive Cycle, systems tha approaches the phase of conservation have eroding resilience which makes the system vulnerable to external disturbance. This approach to the conservation phase is matched with increasing capital in the system. From 1970 to 1990, the systemic resilience is decreasing while production (which represent capital accummulation) is still increasing. This indicates that the milkfish social-ecological system is approaching the phase of conservation. So far, both the quantitative and qualitative measure of resilience remain consistent in explaining the systemic behavior of the milkfish social-ecological system. From 1990 to 1993, the decrease in production is matched with increasing resilience, this is indicative of a system that is going through the renewal and the growth phase which indicated by decreasing capital and increasing resilience. The slow increase of production post 1993 whith general increase in resilience shows the transistion of moving fully into the growth phase. The decrease in resilience and increase in production from 1998 is again a sign that the system is already moving towards the conservation phase. The given narrative and quantitative measure of resilience do indicate that the milkfish social-ecological resource system have similar behaviour to ecological system in following a pattern of systemic progression.

Figure 31 provides the quantitative analysis of the giant tiger prawn social-ecological network. From 1970 to 1983, there is a general decreasing trend in resilience with very low levels of production. During this time frame, the giant tiger prawn industry is in its early stages of establishement. In terms of the Adaptive Cycle, it represents the stage or reorganization where capital is being drawn for growth and development. From 1983 to 1991, there is increasing resilience and production which is indicative of the reorganization to the growth phase in the narrative of the Adaptive Cycle. After 1991 there is already the decrease in resilience which indicates that the system is already approaching the conservation stage after which a quick decline in production ensued after 1994. The system has reached the release phase as production quickly declines and releasing capital available for utilization for aquaculture production.

The fit of the Adaptive Cycle with the quantitative measure aids to explain the cycle of the giant tiger prawn social-ecological system. It has further potential to determine if the systems are reaching the limits of resilience such that it makes the system vulnerable to disturbances. In the case of the giant tiger prawn industry, the outbreak of disease has been the unforseen disturbance that has hit the industry which contributed to its decline. Another disturbance also comes from the economic dimension. Since the giant tiger prawn is an export product heavily dependent on only a few major markets, any decline in the demand in one of the major markets would cause drastic decline in production such as the case of the industry. This is where the importance of increasing redundancy in increasing sustainability of a system. By increasing network pathways, vulnerability of the system decreases by having alternative routes for the product flow. On the other hand, efficiency is also necessary for healthy growth and development of an industry. The appropiate allocation of both is thus necessary in maintaining sustainability.

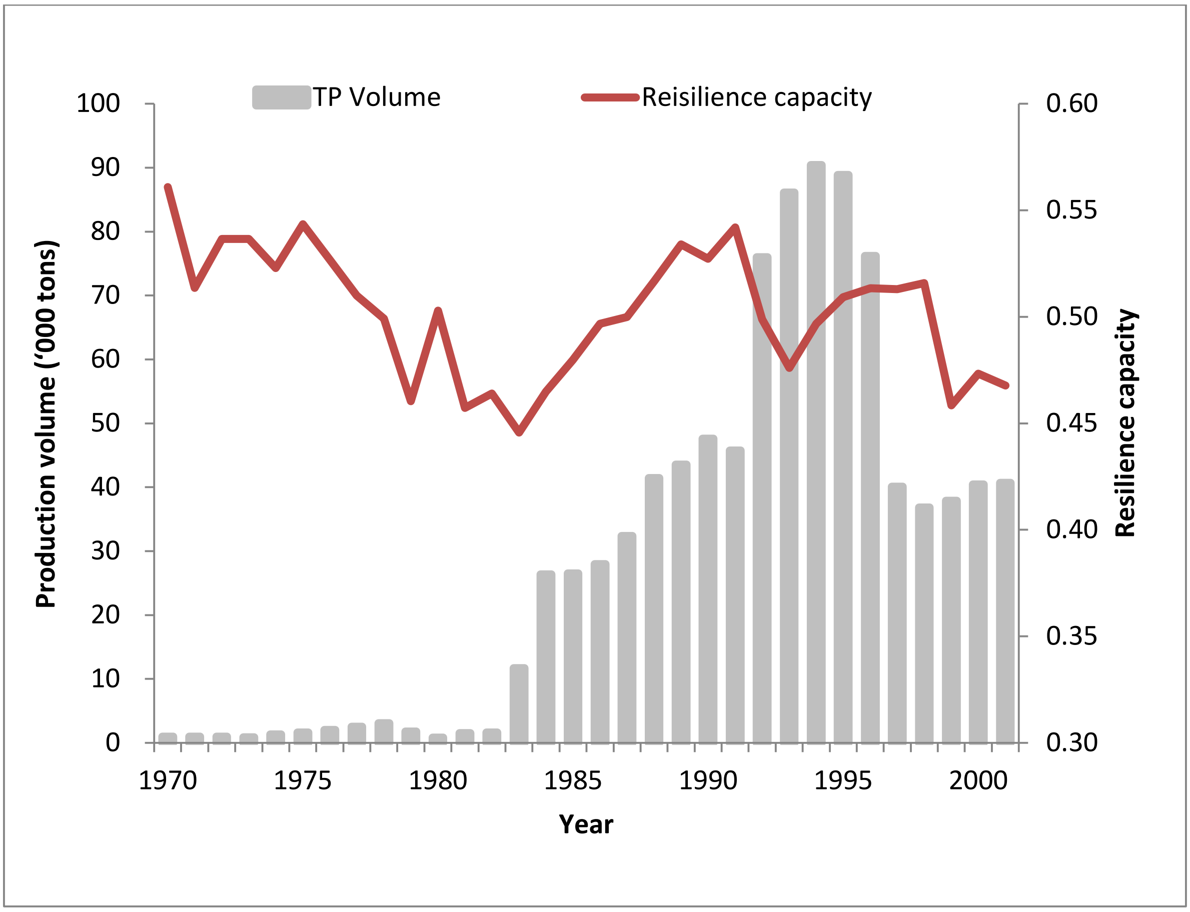


Figure 31. Resilience of the giant tiger prawn social-ecological resource system

Finally, the ecological information-based approach and the Adaptive Cycle narrative are applied to the entire brackish water social-ecological system which is the composition of both the milkfish and giant tiger prawn sub-systems (Figure 1). From 1970 to 1983, there is the general decline in resilience accompanied by continuous growth in production. Once again, this phase is the transition from the growth phase to the conservation phase. From 1983 to

1991, there is the shift to increasing in resilience matched with increasing production, which is a sign of reorganization to growth. During this time is the introduction of giant tiger prawn intensive production into the brackish water pond production. The system has transformed from a milkfish production system to one that includes the giant tiger prawn industry. However, from 1991 to 1996, the increase in resilience is matched with decrease in production which is the reorganization to the growth phase. Instead of going through a full cycle towards the conservation phase, the system has moved from growth to reorganization. 1991 to 1996 also represents the rapid growth in the prawn production.

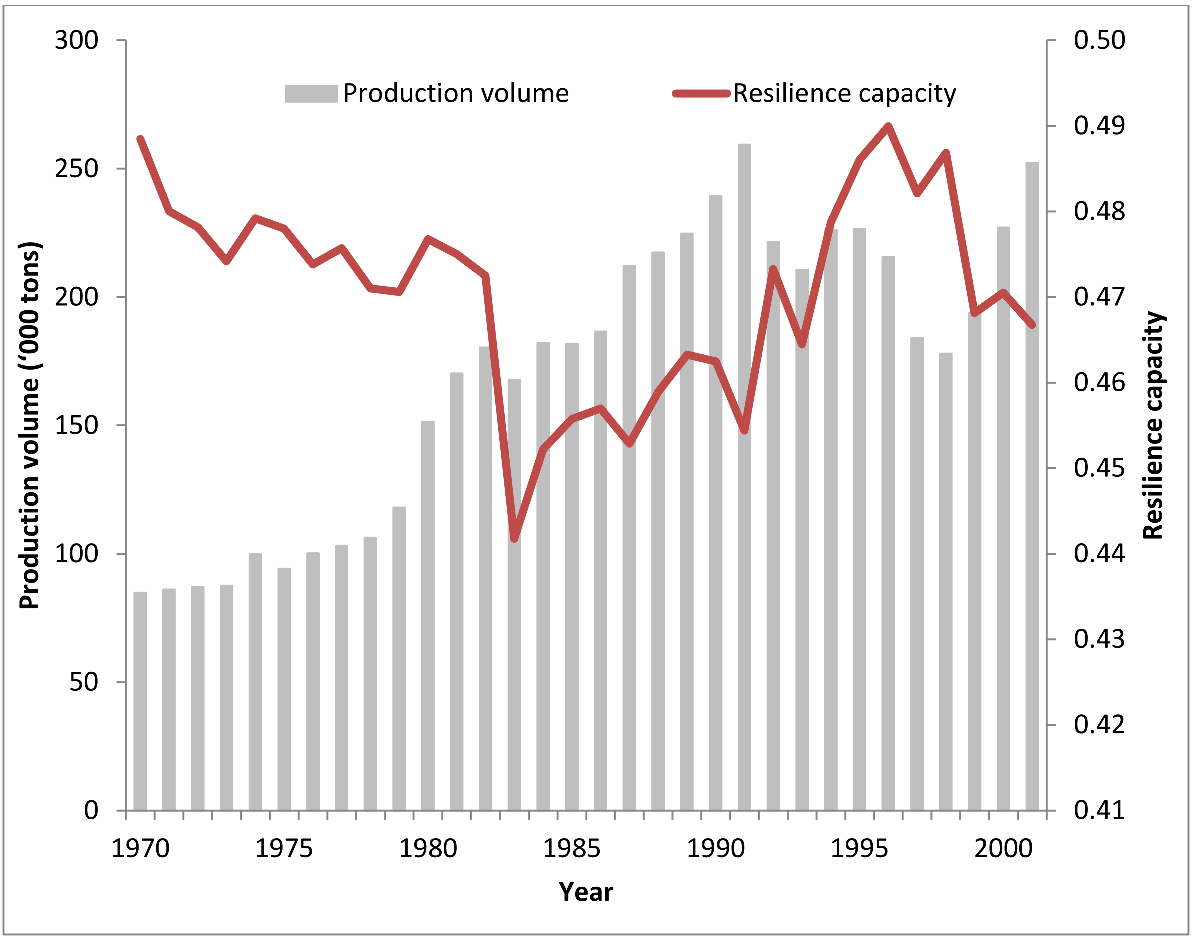


Figure 32. Resilience of the brackish water pond social-ecological resource system

Complementary qualitative and quantitative concepts of ecological sustainability and resilience embodied by the Adaptive Cycle and the Window of Vitality have been applied to understand systemic limits and transformations of social-ecological resource systems expressed as network configuration of flows. The Brackish water pond social-ecological resource systems and its corresponding sub-systems (milkfish and giant tiger prawn) have similar general traits to ecological systems in terms of network structural limits as well as reconfiguration that maintains systemic efficiency and resilience that determines sustainability of the system.

The Window of Vitality and its mathematical foundation (ecological information-based approach) has provided a glimpse of possible limits that could determine the persistence or vulnerability of social-ecological systems expressed as a network of resource flow. It has been demonstrated that sustainability of the overall system may depend upon replacement of inefficient components such as the fry gathering system that was replaced by the milkfish fry hatchery production sector. This is the outcome of human efforts, as self-organizing system, in securing source of milkfish fry to maintain the overall sector. It has also been shown that a system that goes through growth and development behaves in a way that increases ascendency that erodes resilience very much like the ecological systems.On the other hand, the Adaptive Cycle provides a framework to determine the qualitative stages of growth, conservation, release and reorganization that has been observed in the case study and its components at various scales. These complementary concepts has the potential to be applied to other resource systems to determine limits and monitor progression of the system that is undergoing runaway growth from having too much efficiency and not enough resilience such as the case of the giant tiger prawn resource system.

5. RESEARCH CONCLUSION AND DISCUSSION

5.1 Conclusion

Sustainability is an important debate in managing integrated human and nature systems that remains elusive to quantify and is open to various interpretations. Resilience on the other hand has emerged to add dimension to sustainability. However, resilience has also become a boundary object for various fields that can be adopted and applied in various contexts. This has put the concept of resilience in a predicament of having multiple meanings that could hinder accumulation of knowledge to advance development. An objective measure could provide a foundation for the qualitative characteristics of resilience and facilitate a common ground of understanding. It is therefore essential to provide an approach that would put into context the concept of sustainability and resilience of integrated human-nature systems to advance our scientific understanding of systemic complexity, dynamics and limits.

The Window of Vitality is general concept that captures the relationship of sustainability and resilience in a single framework. The concept also highlights another dimension of sustainability which is efficiency. In this concept, sustainability is a systemic trait that pertains to robustness. For a system to remain sustainable, it must possess just enough efficiency to ensure persistence over time as well as just enough resilience to withstand perturbations. The main two components essential in determining robustness are the amount of information (e.g. matter or energy) in the system and the structure containing the information. These two components of information and structure can be quantified using network, graph and information theories. The information theory as applied to ecological systems is an effective indicator not only for growth but as well as development in terms of structural integrity against known and unknown perturbations.

The Adaptive Cycle is another concept that captures the four phase system succession of growth, conservation, collapse and renewal. This concept has three generic qualitative variables which are the levels of capital, connectivity and resilience of a system. In this concept, resilience is the systemic capacity to absorb shocks and maintain function, which is very similar to robustness. These variables have varying combinations dependent on the phase of the system. The theoretical integration of Window of Vitality and Adaptive Cycle, allows a qualitative description to be provided to the quantitative measure of sustainability, resilience and efficiency.

The concepts are operationalized by applying on the Philippine brackish pond aquaculture network systems to measure sustainability, resilience and efficiency. The milkfish fry and production networks occupy a narrow range between resilience and efficiency that optimize sustainability. For the given resource system, the distribution of networks appear to lean towards higher efficiency than resilience. This could be due to the economic interest of increasing productivity which requires higher levels of efficiency over resilience. This is also evident in the decline of the highly resilient milkfish fry gathering ancillary industry that was replaced by the more efficient and cost effective hatchery systems. High resiliency renders a system uncompetitive and stagnates being unable to accumulate capital resource. This may be the case in systems that operate within the economic domain where efficiency is of greater importance for faster growth and development than resilience even though it does not fully optimize sustainability. This observation of bias towards efficiency is very much different from ecological systems that optimize sustainability (Ulanowicz 2009). It would be interesting to determine if systems from different domains (economic, ecological or social networks) have particular preference for resiliency or efficiency. An example is that of global economic trade networks (Kharazzi et al. 2013) that occupy levels of higher resilience.

Furthermore, the three milkfish production networks at the main island scale have increasing resilience according to the level of growth and development. Resource networks that are more advanced and has higher production has higher levels of resilience. This would suggest the increase in the amount of cycled material in a network requires a more resilient structure. Such is the case for ecological systems that are in the initial stages of reorganization where there is capital accumulation and increase in resilience proceeding towards the growth phase. In human managed resource systems, growth and development has been conventionally measured by production output. In maintaining sustainability, it would be equally important to identify the structure facilitating the circulation of the product and increase in output should be matched with structural changes in the network to maintain both efficiency and resilience. This management of network structure should also consider if the system is embedded in the economic domain which may require maintaining a minimum level of efficiency.

Application of the ecological information-based approach on temporal analysis of the milkfish and giant tiger prawn revealed various combination of production and resilience trends that is interpreted by the taking the Adaptive Cycle standpoint. There appears a pattern of decrease of resilience prior to sharp declines in production outputs. Decrease in resilience leaves both systems susceptible to production disruptions. Moreover, the phase cycles of the networks systems is determined by the relationship of the change in trend of production output and resilience. Both qualitative and quantitative approach is needed in monitoring sustainability of social-ecological resource systems as well as tracks various stages of development in terms succession phases. Such applicability of complementing concepts is useful in comparing policy interventions that has direct implication on resource flow structures.

The main learning in this dissertation is that social-ecological network systems have similar traits to environmental systems. Many are familiar with the concept of efficiency, but in attaining systemic sustainability, resilience should also be considered. The approach conducted in this research can assist policy makers and practitioners in making informed decisions in maintaining sustainability by deciding over the trade-off between efficiency and resilience.

5.2 Research implications

Having established the applicability of measuring sustainability (robustness) in terms of resilience and efficiency trade-offs, this could provide a common language in understanding resilience being applied in various fields of studies and application. Conventional indicator for development has been increase in production output or economic growth. In attaining this perceived development, emphasis has already been given towards maximizing efficiency which in past experiences has turned systems unstable and vulnerable to economic shocks. The emerging concept of resilience with a quantitative approach can provide an objective and quantitative measure where efficiency can me assessed against. As an example, the milkfish fry system has a network structure that is highly inefficient. One on the policies that contributed to the defined network structure of flows of fry is the establishment of property right under the commissionaire system. The commissionaire has the sole right to purchase fry from the gatherers and becomes the main hub of distribution. Commissionaires pay a lower price to gatherers compared to other dealer in the system due to the cost of maintaining the right over the property. The policy has affected the network to become more complex, redundant and inefficient. Thus, such measure of efficiency and resilience would be quite useful for policy makers to assess policy implications to the persistence of the network system of interest.

In combination with the Adaptive Cycle, the quantitative measure of resilience can provide a warning sign if a resource system is already at the conservation stage and is vulnerable to perturbations. Thus, managing transformation of systems may perhaps become more manageable if such combined quantitative and qualitative approach is employed in assessing interventions. A managed cycle of growth and development and transformation may perhaps be more relevant than having runaway growth that suffers drastic fluctuation in production such as the milkfish and giant tiger prawn social-ecological resource system.

5.3 Limitations of the study

Although the applicability of ecological information-based approach in measuring social-ecological resource network system sustainability has been established in this research, one limitation is the availability of data and information for the temporal analysis of network configurations. This has set the limit of retrospective analysis in a much shorter period than intended. Another constraint is that the social-ecological unit of study has not been expressed into individual human and ecological components. Even though the analysis of using hybrid systems is accepted in social-ecological resource system analysis, more explicit interaction between social and ecological interrelationships may reveal other systemic traits relevant in producing knowledge on social-ecological resource system dynamics. Even though insights on how large scale systems are dependent on the renewal (or unsustainability) of lower sub-systems, temporal dynamics could not be obtained due to the reasons already stated above.

Research on the dynamics of social and ecological systems is still essentially an emerging field and only a hand full of empirical research on the use of network theories have been conducted which makes it difficult to set a standard for the approach. It is also recognized here that the potential of individual elements or nodes cannot be captured by the approach. For example, the potential capacity of milkfish fry gatherers to supply the optimum amount of milkfish fry cannot be integrated into the ecological information approach. This would be the same case where the potential of fish grow-out farmers to increase production or to shift to another type of production in not incorporated in the current study. This is the same issue in studying ecological systems where standing stock of a species is not included in the computation of sustainability, efficiency and resilience. The biggest limitation of the study is that, currently, the main purpose of the research is focused on the conceptualization of a framework that combines both quantitative and qualitative approaches to understand resilience of complex system and not at this point to contribute to the case being studied but to the science of sustainability.

5.4 Recommendation for further research

There are two avenues in the future expansion of this research. The first is the practical application of the theoretical combination of the Adaptive Cycle and the Window of Vitality on current sustainability issues of actual SES and the second is the further conceptual development using other cases vis a vis the brackish water pond production system.

Since the applicability of quantifying systemic persistence has been operationalized on the brackish water pond social-ecological resource system retrospectively, it would be invaluable to apply the approach to other more contemporary case studies of social and ecological resilience. This is to determine if there exists a general trait across case studies in having specific range of resilience and efficiency that optimizes sustainability. Application to current case studies would have even more relevance to policy implementation and decision making processes in managing natural resource systems. It is also important to consider a more detailed analysis of explicit interaction of human and nature elements considering various types of information flows or relationships, which has been the limitation of this current study. Likewise, it would be also be appropriate to extend research to the current situation of the brackish pond system by including other culture species. Having a measure for sustainability, scenario settings could also be made in terms of production and distribution of aquaculture products that involves that the stakeholders of the industry.

Conceptual development in analysing social-ecological networks is still wanting. The Adaptive Cycle can be applied as nested systems that have cross-scale dynamics and interactions. Having a quantitative measure of the temporal dynamics can open avenues for further research in understanding system dynamics not only within the context of SES but also to different studies in the social, ecological and economic domains. This could help researchers understand how to sustain larger systems by managing sub-systems with a quantitative gauge in case studies which are riddled with uncertainties.

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APPENDIX

Appendix A

Table 13. Global capture fisheries and aquaculture volume production in metric tons

Year	Aquaculture volume (t)	Capture volume (t)
1950	584,507	17,549,941
1951	718,270	19,744,808
1952	837,304	21,734,335
1953	973,292	22,111,263
1954	1,092,629	23,757,865
1955	1,236,648	25,034,607
1956	1,238,560	26,592,518
1957	1,636,418	26,861,470
1958	1,603,343	27,411,832
1959	1,849,318	29,599,207
1960	1,974,549	31,689,535
1961	1,885,793	35,340,199
1962	1,960,424	38,372,097
1963	2,189,986	38,975,108
1964	2,341,347	43,071,638
1965	2,543,563	43,500,907
1966	2,725,216	47,201,352
1967	2,843,414	50,213,531
1968	3,020,173	53,193,454
1969	3,169,136	51,240,479
1970	3,447,217	56,317,531

Year	Aquaculture volume (t)	Capture Volume (t)
1971	3,849,172	56,439,090
1972	4,184,103	51,605,435
1973	4,399,542	51,287,532
1974	4,832,624	54,135,588
1975	5,086,240	52,762,975
1976	5,277,885	56,079,150
1977	6,144,819	55,570,643
1978	6,453,379	57,904,819
1979	6,555,900	58,431,099
1980	7,189,320	58,460,973
1981	7,633,236	60,670,693
1982	8,004,319	62,184,560
1983	8,863,887	62,170,644
1984	9,921,027	67,238,902
1985	11,061,058	68,934,999
1986	12,347,408	73,838,295
1987	13,622,680	74,520,669
1988	15,531,105	88,586,800
1989	16,482,942	89,207,163
1990	16,840,105	85,494,040
1991	18,305,024	84,461,778

Year	Aquaculture volume (t)	Capture Volume (t)
1992	21,211,484	86,270,922
1993	24,470,880	87,562,875
1994	27,798,554	93,188,803
1995	31,232,311	93,390,603
1996	33,842,616	94,965,307
1997	34,296,332	94,288,470
1998	36,460,929	86,653,408
1999	39,603,307	92,572,784
2000	41,724,624	94,506,483
2001	44,329,772	91,746,639
2002	47,384,864	92,053,559
2003	50,319,462	89,313,800
2004	54,588,261	93,889,515
2005	57,835,398	93,638,671
2006	61,401,680	91,265,788
2007	64,956,991	91,864,883
2008	68,853,308	91,326,917
2009	73,095,241	91,195,743
2010	78,110,453	90,091,113
2011	83,044,109	94,782,430
2012	90,432,105	92,420,695

Source: FAO, Fisheries and Aquaculture (http://www.fao.org/fishery/topic/16140/en)

Appendix B

Table 14. Southeast Asia milkfish production in metric tons

Year	Indonesia volume (t)	Philippines volume (t)	Taiwan volume (t)
1950	18,800	22,154	15,259
1951	19,000	25,812	13,990
1952	21,300	27,003	15,317
1953	24,900	29,121	19,124
1954	23,400	30,480	22,157
1955	26,500	34,569	26,187
1956	30,400	33,478	24,097
1957	33,000	34,290	26,683
1958	27,300	50,133	28,806
1959	36,400	50,538	25,343
1960	35,600	52,304	25,756
1961	39,600	52,918	31,114
1962	41,300	53,449	25,439
1963	38,800	53,978	25,607
1964	42,200	54,532	29,986
1965	41,300	54,982	26,938
1966	49,500	55,379	28,443
1967	51,700	55,603	23,046
1968	44,900	84,139	19,689
1969	44,100	82,279	18,975
1970	43,000	83,921	27,725
1971	43,000	85,186	30,388
1972	43,900	86,062	24,852
1973	38,439	86,652	31,437
1974	41,650	98,480	28,730
1975	44,692	92,621	33,164
1976	44,027	98,102	26,651
1977	48,641	100,708	26,261
1978	48,287	103,253	29,858
1979	46,187	116,230	31,879
1980	52,922	150,631	18,883
1981	61,041	206,507	21,929
1982	73,330	219,967	23,416
1983	81,506	233,515	27,964
1984	84,365	155,709	23,344
1985	93,508	155,344	25,599
1986	103,588	158,621	21,949
1987	105,947	179,791	19,476
1988	118,001	175,935	23,161
1989	119,339	181,197	12,601
1990	132,432	191,878	75,244
1991	141,024	213,674	27,106
1992	147,032	145,554	15,580
1993	164,448	124,510	16,844
1994	153,093	135,682	26,188
1995	151,256	137,796	28,058
1996	162,127	139,372	27,806
1997	142,709	144,076	30,653
1998	158,666	141,131	28,359
1999	209,758	155,833	22,649
2000	217,208	186,599	16,267
2001	209,525	211,594	21,892
2002	222,317	203,517	28,424
2003	226,114	202,973	32,971
2004	241,418	208,975	25,053
2005	254,018	219,906	23,386
2006	212,883	220,602	29,375
2007	263,139	229,111	27,515
2008	277,002	226,032	27,944
2009	328,189	225,320	26,433
2010	421,757	219,444	20,380
2011	467,044	226,371	24,091
2012	482,803	232,515	42,296

Source: Source: FAO, Fisheries and Aquaculture (http://www.fao.org/fishery/topic/16140/en)

Appendix C

Table 15. Interregional Tras of milkfish fry in thousands

Regions	Ilocos	Cagayan Valley	Central Luzon	Rizal and Bulacan	South Tagalog	Mindoro	Palawan	Bicol	Wester n Visayas	Central Visayas	Eastern Visayas	Western Mindanao	Northern Mindanao	Southern Mindanao	Central Mindanao
Ilocos (Region I)			1363	26648											
Cagayan Valley (Region II)	1722		438												
Central Luzon (Region III)	5000											215			59
Rizal and Bulacan (Region IV-A and III)			42027		1187			509							
South Tagalog (Region IV)				6924		497			400						
Mindoro (Region IV-B)				14975											
Palawan (Region IV-B)				12545					11935						
Bicol (Region V)	246			1584	14946	133			5000						
Western Visayas (Region VI)				89562						304	275				
Central Visayas (Region VII)				29836				768	18888		990	7	732	115	
Eastern Visayas (Region VIII)				342						6098					
Western Mindanao (Region IX)				43441					1664	790			3146		45
Northern Mindanao (Region X)				1935											
Southern Mindanao (Region XI)			7082	302486	861				10600				1595		
Central Mindanao (Region XII)				117440					888						

Source: Smith 1981

Appendix D

Table 16.Milkfish Production Value by region (USD 000)

Region	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
NCR	170	172	174	175	199	187	198	204	209	214	253	132	145	161	183
I	1,044	1,060	1,071	1,078	1,225	1,152	1,221	1,253	1,285	1,354	1,588	3,047	3,483	3,879	4,337
II	26	26	27	27	31	29	31	31	32	28	32	103	118	28	90
III	3,459	3,511	3,547	3,571	4,059	3,817	4,043	4,150	4,256	5,458	6,293	9,962	12,102	11,834	12,772
IV	1,945	1,974	1,994	2,008	2,282	2,146	2,273	2,334	2,393	2,433	2,820	3,605	3,966	3,971	2,532
(IV-A)															
(IV-B)															
V	561	570	576	579	659	619	656	673	691	743	877	997	1,316	1,323	1,625
VI	5,429	5,511	5,568	5,606	6,371	5,992	6,347	6,515	6,681	7,385	8,424	9,935	11,309	10,494	16,637
VII	418	424	428	431	490	461	488	501	514	539	632	802	942	873	1,017
VIII	457	464	468	472	536	504	534	548	562	582	676	749	1,005	601	655
IX	992	1,007	1,017	1,024	1,164	1,095	1,159	1,190	1,221	1,240	1,440	1,639	1,803	1,678	2,861
X	287	291	294	296	337	317	336	345	353	369	431	468	515	375	871
XI	287	291	294	296	337	317	336	345	353	371	431	837	920	1,279	1,433
XII	418	424	428	431	490	461	488	501	514	523	602	843	956	833	998
CARAGA															
ARMM															

Source: PCMARD/PCAARRD

Appendix D (continued)

Table 16.Milkfish Production Value by region (USD 000)

Region	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
NCR	256	302	254	265	247	385	392	2,190	3,307	4,326	6,135	4,945	3,459	5,854	504	500	631
I	6,275	7,629	6,975	7,987	8,349	6,481	11,814	12,845	10,599	14,632	21,345	19,637	16,615	12,803	17,728	19,960	20,967
II	203	316	288	330	334	377	509	17	84	99	187	207	226	212	280	293	369
III	19,168	21,137	21,145	22,951	24,306	40,058	35,708	25,433	26,901	32,413	38,191	39,985	41,585	33,085	37,517	51,087	78,179
IV	4,615	4,875	4,164	4,442	4,452	7,246	8,710	15,651	12,488	15,321	10,583						
(IV-A)												11,585	10,345	18,738	12,231	12,427	14,493
(IV-B)												3,356	2,944	2,999	2,528	2,701	2,939
V	2,280	3,048	2,603	1,894	1,946	2,417	2,500	2,215	2,359	1,506	1,546	1,549	1,426	1,246	1,419	1,374	1,671
VI	20,700	25,925	25,687	30,191	31,912	41,269	48,461	25,933	22,656	29,630	33,298	39,497	40,104	31,777	41,837	52,034	49,214
VII	1,833	3,150	2,689	3,047	3,326	2,772	2,697	5,844	4,468	7,632	4,770	6,492	6,128	4,996	5,462	5,488	6,224
VIII	1,003	1,019	874	1,079	1,154	1,793	1,826	823	1,175	1,819	1,653	1,644	1,536	1,481	1,668	1,823	2,250
IX	3,248	3,802	4,218	6,080	7,002	6,298	7,190	2,378	3,089	8,509	4,554	4,138	4,689	3,610	10,004	11,955	9,419
X	939	1,010	1,089	1,328	1,430	1,772	1,884	1,018	111	170	1,883	3,330	3,648	3,698	3,813	4,445	4,917
XI	2,220	2,362	2,345	2,783	2,953	4,005	4,886	7,449	5,290	7,022	3,832	4,236	4,637	4,085	4,587	5,161	6,622
XII	1,404	1,538	1,298	1,541	1,603	2,302	2,454	1,264	461	1,502	2,091	2,089	3,768	6,109	6,675	6,759	7,614
CARAGA									45	453	1,369	1,476	1,215	1,172	1,145	1,519	1,657
ARMM									1,589	1,653	476	889	1,386	1,351	1,796	1,850	2,270

Source: PCMARD/PCAARRD

Appendix D (continued)

Table 17.Giant Tiger prawn Production value (USD 000)

Region	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
NCR	0.30	0.31	0.31	0.28	0.42	1	1	1	1	0.42	1	0.27	0.31	0.00	0.00
I	2	2	2	2	3	3	4	5	6	3	3	6	7	122	469
II	0.05	0.05	0.05	0.04	0.06	0.08	0.10	0.12	0.15	0.06	0.07	0.20	0.22	0.00	0.00
III	8	8	8	7	11	14	17	21	26	11	13	20	25	184	3,774
IV	4	4	4	3	5	6	7	9	11	5	6	7	8	134	1,952
IV-A															
IV-B															
V	1	1	1	1	2	2	2	3	3	2	2	2	3	21	59
VI	11	11	11	10	15	18	23	28	35	15	17	20	23	2,318	1,505
VII	1	1	1	1	1	1	2	2	3	1	1	2	2	2	7
VIII	1	1	1	1	1	1	2	2	3	1	1	2	2	75	103
IX	2	2	2	2	3	3	4	5	6	3	3	3	4	2	8
X	1	1	1	0.50	1	1	1	1	2	1	1	1	1	16	33
XI	1	1	1	0.50	1	1	1	1	2	1	1	2	2	0.00	2
XII	1	1	1	1	1	1	2	2	2	1	1	2	2	109	97
CARAGA															
ARMM															

Source: PCMARD/PCAARRD

Appendix D (continued)

Table 17.Giant Tiger prawn Production value (USD 000)

Region	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
NCR	0.00	0.00	0.00	41	32	31	34	309	366	26	62	80	70	11	1	1	0.00
I	691	1,048	1,146	2,290	2,150	1,850	1,906	427	712	243	762	616	353	221	179	193	268
II	1	2	4	8	11	10	16	7	7	21	55	84	115	112	69	75	81
III	4,179	6,153	4,033	6,819	6,885	10,898	9,360	9,873	7,506	22,443	22,047	21,786	20,540	19,682	18,809	19,516	23,424
IV	2,218	2,833	2,891	4,889	4,588	4,610	3,927	466	1,256	2,403	1,786						
IV-A												742	1,164	1,312	822	557	665
IV-B												505	566	742	1,093	1,002	1,020
V	72	165	165	511	729	761	740	1,183	855	768	704	541	359	322	407	448	557
VI	1,449	2,815	7,060	10,649	8,964	11,978	10,389	23,580	34,010	28,103	23,529	16,075	2,757	1,528	945	1,386	1,742
VII	11	75	77	168	212	221	226	2,391	2,750	1,614	3,609	4,657	2,539	2,882	2,106	2,487	1,772
VIII	125	158	159	245	257	376	343	327	321	147	338	290	201	182	185	182	225
IX	15	24	32	129	210	1,070	1,040	1,811	2,241	5,129	4,754	4,667	3,666	4,126	6,495	8,006	9,113
X	26	34	37	70	89	164	184	1,400	1,682	914	1,307	6,754	6,643	6,390	6,203	6,295	6,835
XI	7	10	152	348	344	538	632	1,998	1,006	4,011	4,452	729	100	27	46	35	70
XII	106	165	165	377	390	609	633	740	3,032	2,015	4,444	5,422	504	465	322	399	463
CARAGA										72	22	1,377	1,031	1,100	869	1,246	1,962
ARMM										1,116	1,118	59	173	180	208	254	339

Source: PCMARD/PCAARRD

Appendix E

Table 18. Milkfish export (whole/in pieces, not minced, prepared/preserved in airtight containers) by country of destination in kilograms

Year	Total (SUM)	APS	Australia	Austria	Belgium*	Bosnia*	Brunei*	Bahrain	Canada	Czechoslovakia	Denmark	Germany	Greece*	Hongkong	Indonesia
1970	6,758														
1971	9,300														
1972	6,828														
1973	9,085								123						
1974	3,948														
1975	11,252								1,172						
1976	6,065								287						
1977	5,278														
1978	14,584		304						36					2,500	
1979	23,964								817					1,633	
1980	16,393								1,832					218	
1981	47,520		544					300	3,176						
1982	59,291							281	1,992					439	
1983	70,993		38						7,001			34		50	
1984	44,601		11	96					3,021						29
1985	50,730								1,735					38	
1986	41,014		29						3,280			125			
1987	78,095	150	689	48				335	1,689						
1988	94,342	240	233					48	1,662		238				
1989	45,780		3,549						565		91				
1990	63,194		808	96				709	634		124	71		57	
1991*	45,519		3,884	48					699		10	426		181	
1992	51,634		2,066						181	3,463		805		533	
1993	67,297		927				192		680				166		
1994	72,437		4,215	384	9,072		720		3,646				144	12	
1995	140,636		3,372						2,742					380	
1996	45,971		3,565						1,238					1,044	
1997	26,069		2,189								48			343	
1998	34,697		957	29					253			22		727	
1999	42,922		3,728				65		286				350	1,015	
2000	91,326		11,908			190			747					1,729	
2001	194,020		2,398						4,020		16			1,123	

Source: PCMARD/PCAARRD

Appendix E (continued)

Table 18. Milkfish export (whole/in pieces, not minced, prepared/preserved in airtight containers) by country of destination in kilograms

Year	Iraq	Italy*	Japan	Jordan	Korea*	Kuwait	Lebanon*	Macau*	Malaysia*	Micronesia*	Netherlands	New Zealand	Norway	Oman
1970														
1971														
1972														
1973														
1974														
1975														
1976														
1977														
1978														
1979			200											
1980														
1981	671					8,828								
1982	2,262					2,566								
1983						1,685								
1984				953										
1985														
1986						864							86	
1987						2,891						89	191	68
1988						240							39	
1989											264	113		
1990												78		
1991*			36			533					340		74	
1992						710					960	102	192	
1993			1,835			796					454		84	
1994		768	1,895								1,665	42	96	
1995			1,760								980			
1996			2,456								3,629			
1997			697				24						96	
1998			911						32			54		
1999		362	979			129								
2000			660					63				1,358		
2001			432		29				12	609				

Source: PCMARD/PCAARRD

Appendix E (continued)

Table 18. Milkfish export (whole/in pieces, not minced, prepared/preserved in airtight containers) by country of destination in kilograms

Year	Palau*	PNG	Qatar	Saudi Arabia	Singapore	Spain	Sweden	Switzerland	Taiwan*	TTPI	UK	UAE*	USA
1970													2,818
1971													5,358
1972													2,884
1973													5,016
1974													
1975													6,130
1976													1,826
1977													1,324
1978				3,820									3,968
1979				11,761									5,595
1980				3,173									7,210
1981		530	544	3,588									25,377
1982				10,448	180								37,159
1983				9,670						30	2,358		46,161
1984				7,716							671		28,136
1985				11,629				19					33,339
1986				4,286	9			96			187		28,080
1987				23,950				98			470		43,453
1988				30,547		238	19				1,027		55,835
1989										413	544		36,263
1990							691			48	463		55,435
1991*							425	10		794	43		38,016
1992		54						215		7	358	44	37,960
1993				7,911	468			262		41	149	1,752	47,594
1994				150	3,643			250			1,086		40,661
1995				227	3,876					56	503		122,750
1996	29			567	5,194			50		435			23,772
1997					6,589			305					11,784
1998					5,021			373		750			21,572
1999					4,480			15		409			27,106
2000	25				4,627				53	155			65,811
2001	600		125		4,242			153		544		120	175,595

Source: PCMARD/PCAARRD

Appendix E (continued)

Table 19. Milkfish (dried, salted, smoked or in brine) export, by country of destination in kilograms

Year	Total	APS	Australia	Bahrain	Belgium*	Brunei	Canada	China*	France*	Denmark	Germany	Hongkong	Japan	Kuwait	Nauru
1970	8,969														
1971	41,494						1,092								
1972	23,478												215		
1973	18,725											408			
1974	36,557						2,969								
1975	31,491						4,543								
1976	28,795						3,761								
1977	29,708						5,419			18					
1978	26,927		1,342				1,340					22			
1979	9,461						1,125						250		
1980	23,122						656								
1981	35,746			54			1,203							8,522	
1982	33,646			189			2,453				2,500	54		1,435	
1983	13,920						1,971					55			
1984	14,428						3,282								
1985	17,634						695								
1986	16,573						379							680	
1987	30,813						689								33
1988	11,408	112	278				326							1,225	
1989	6,761		181				157			18					
1990	3,327		168			14									
1991*	12,617		279						88				54		
1992	8,181		307				272						287	3,629	
1993	5,945		210										394		
1994	4,337		1,195										27		
1995	2,687		200				250				114		600	399	
1996	8,567		468		1,021	27						50	4,148		
1997	1,633											99	181		
1998	11,414		450									716	998		
1999	16,219		40			182	1,854					450	2,307		
2000	32,643		195				65	22				884	500		
2001	28,888		396				2,460					682	17,278		

Source: PCMARD/PCAARRD

Appendix E (continued)

Table 19. Milkfish (dried, salted, smoked or in brine) export, by country of destination in kilograms

Year	Netherlands	New Guinea	New Zealand	Norway	Oman*	Palau*	Qatar	Sabah*	Saudi Arabia	Singapore	Switzerland	TTPI	UAE*	UK & NI	USA
1970															8,969
1971															40,402
1972	2,483														20,780
1973															18,317
1974															33,588
1975												18			26,930
1976												67			24,967
1977												280			23,991
1978															24,223
1979										90					7,996
1980									9,048						13,418
1981							272		12,276		25				13,394
1982		422							12,213			23			14,357
1983		136							6,313			25		227	5,193
1984									4,038						7,108
1985									9,535	40					7,364
1986										43					15,471
1987			54						680	2,794				72	26,491
1988	136			87					816					95	8,333
1989												18			6,387
1990															3,145
1991*												363			11,833
1992											427	12			3,247
1993											18	75			5,248
1994											62				3,053
1995											31	227		263	603
1996								120	1,134		22				1,577
1997										250	99				1,004
1998										535	44	227			8,444
1999						350				60	45				10,931
2000										364				8,661	21,952
2001					325		57				15	374	248		7,053

Source: PCMARD/PCAARRD

Appendix E (continued)

Table 20. Milkfish (frozen excluding livers and roes) export, by country of destination (in net kilograms)

Year	Total (SUM)	APS	Australia	Bahrain	BPI	Belgium*	Brunei	Canada	China	Denmark	Germany	Greece*	Hongkong	Iraq	Israel	Japan	Kuwait
1977	557,524				475			80,740		254						50	
1978	499,480		90					44,209		227						120	
1979	595,492							80,380								650	
1980	759,664							54,194								500	
1981	734,886							56,945	3,222				60				8,159
1982	984,712							52,131	24		8,260		1,755	20			932
1983	2,539,010		500					81,080			2,850		583			827,038	17,200
1984	1,577,183		100				6	108,829					45			3,266	2,400
1985	1,524,246	1,670	1,000	400				124,645									4,316
1986	1,812,270		495	5,580				129,385								49,399	11,581
1987	1,691,335		32,914					95,389								3,330	21,498
1988	1,513,619		1,694	2,000				125,523		2,449	3,912						18,174
1989	1,289,351		8,863	7,500				44,947		689	6,844						31,165
1990	807,167		15,791	7,000			80	36,167			6,600					1,700	2,000
1991*	271,925		5,115					24,239								20,687	
1992	518,214		7,415	2,000				37,496				1,800				21,025	14,775
1993	564,756		1,833	3,000		998		30,556					193			23,081	10,775
1994	139,243		3,275	2,500				2,885								21,515	17,848
1995	67,560		600					2,213				700	115			3,810	15,200
1996	68,568		754					1,270					91			8,014	
1997	41,170							1,144					51				
1998	88,332							1,270					357			400	
1999	89,100		319	8,550				2,867					25			1,330	
2000	50,126							1,996					5,447				
2001	347,055		173,560					6,484					15,677		10,800	24,933	

Source: PCMARD/PCAARRD

Appendix E (continued)

Table 20. Milkfish (frozen excluding livers and roes) export, by country of destination (in net kilograms)

Year	Macau	Nauru	Netherlands	New Guinea	New Zealand	Norway	Oman	Palau	Saudi Arabia	Singapore	Switzerland	Taiwan *	TTPI	UK	USA	USSR
1977		12,015											110		461,903	
1978		6,738	4,536							650				15,000	425,932	
1979		3,365	8,959						4,000	235				4,082	491,842	
1980			8,784						20,847	170				10,190	662,999	
1981			2,494						68,253	173				9,582	584,017	
1982			5,670						124,479	50			216	2,268	786,925	
1983		150		96					314,371				2,656	10,058	1,280,445	
1984		497							195,030	15,054			7,612	1,361	1,240,999	
1985		976		1,740					69,774	145,682			3,525	1,452	1,167,081	
1986		2,510	7,348						36,210	410			8,792	3,085	1,555,489	
1987		500	5,770		109				323,165		13,050		67,177	8,818	1,117,628	
1988		15,214	14,289			100			43,467		500		11,287	8,699	1,264,323	
1989		7,832	5,739						3,800				3,692	10,953	1,155,338	
1990		3,635	14,914						2,000		500		18,192	11,672	684,848	78
1991			8,500								2,540		26,745	1,506	182,593	
1992			12,375					77		2,880			50,025		366,354	
1993								83			369		31,323		460,552	
1994			6,000						576	248	603		14,728		67,071	
1995										1,945	501		1,369		39,112	
1996			3,279							800	122		2,490		49,752	
1997											115		960		36,903	
1998	95										341	11,000	140		72,731	
1999	105										80				73,825	
2000					812					369					39,502	
2001							780						908	400	111,512	

Source: PCMARD/PCAARRD

Appendix E (continued)

Table 21. Milkfish (fresh/chilled) export by country of destination in kilograms

Year	Total	Australia	Bahrain	Brunei	Egypt	Hongkong	Japan	Korea	Palau	Singapore	St. Helena	Switzerland	Taiwan	TTPI	UK	USA
1991	85,356	700	1,000	110			486		383					18,676	91	63,910
1992	65,409						92		166			963		16,626		47,562
1993	84,840					100	1,474					561		26,657	272	55,776
1994	79,400					4,800	651		4,000	50		50		19,804		50,045
1995	48,142	110				567						36		9,147		38,282
1996	55,325					908			261					6,540		47,616
1997	70,383					1,181			1,743			130	150	2,958		64,221
1998	76,102	160				4,200			297			11	800	505		70,129
1999	61,321					3,790	300	600						301		56,330
2000	41,803	8,958				8,706					15		15	55		24,054
2001	26,682	10,500		70	500	422							18	75		15,097

Source: **PCMARD/PCAARRD**

Appendix F

Table 22. Total milkfish export by country in kilograms

Year	Total (SUM)	APS	Australia	Austria	Bahrain	Belgium	Bosnia	BPI	Brunei	Canada	Czechoslovakia	China	Egypt
1970	17697												
1971	52765									1092			
1972	32278												
1973	29783									123			
1974	42479									2969			
1975	44718									5715			
1976	36836									4048			
1977	586579							475		86159			
1978	540991		1736							45585			
1979	628917									82322			
1980	799179									56682			
1981	818152		544		354					61324		3222	
1982	1077649				470					56576		24	
1983	2623923		538							90052			
1984	1636212		111	96					6	115132			
1985	1592610	1670	1000		400					127075			
1986	1869857		524		5580					133044			
1987	1800243	150	33603	48	335					97767			
1988	1619369	352	2205		2048					127511			
1989	1341892		12593		7500					45669			
1990	873688		16767	96	7709				94	36801			
1991	415417		9978	48	1000				110	24938			
1992	643438		9788		2000					37949	3463		
1993	722838		2970		3000	998			192	31236			
1994	295417		8685	384	2500	9072			720	6531			
1995	259025		4282							5205			
1996	178431		4787			1021			27	2508			
1997	139255		2189							1144			
1998	210545		1567	29						1523			
1999	209562		4087		8550				247	5007			
2000	215898		21061				190			2808		22	
2001	596645		186854						70	12964			500

Source: PCMARD/PCAARRD

Appendix F (continued)

Table 22. Total milkfish export by country in kilograms

Year	France	Denmark	Germany	Greece	Hongkong	Indonesia	Iraq	Italy	Israel	Japan	Jordan	Korea	Kuwait
1970													
1971													
1972										215			
1973					408								
1974													
1975													
1976													
1977		272								50			
1978		227			2522					120			
1979					1633					1100			
1980					218					500			
1981					60		671						25509
1982			10760		2248		2282						4933
1983			2884		688					827038			18885
1984					45	29				3266	953		2400
1985					38								4316
1986			125							49399			13125
1987										3330			24389
1988		2687	3912										19639
1989		798	6844										31165
1990		124	6671		57					1700			2000
1991	88	10	426		181					21263			533
1992			805	1800	533					21404			19114
1993				166	293					26784			11571
1994				144	4812			768		24088			17848
1995			114	700	1062					6170			15599
1996					2093					14618			
1997		48			1674					878			
1998			22		6000					2309			
1999				350	5280			362		4916		600	129
2000					16766					1160			
2001		16			17904				10800	42643		29	

Source: PCMARD/PCAARRD

Appendix F (continued)

Table 22. Total milkfish export by country in kilograms

Year	Lebanon	Macau	Malaysia	Micronesia	Nauru	Netherlands	New Guinea	New Zealand	Norway	Oman	Palau	PNG	Qatar
1970													
1971													
1972						2483							
1973													
1974													
1975													
1976													
1977					12015								
1978					6738	4536							
1979					3365	8959							
1980						8784							
1981						2494						530	816
1982						5670	422						
1983					150		232						
1984					497								
1985					976		1740						
1986					2510	7348			86				
1987					533	5770		252	191	68			
1988					15214	14425			226				
1989					7832	6003		113					
1990					3635	14914		78					
1991						8840			74		383		
1992						13335		102	192		243	54	
1993						454			84		83		
1994						7665		42	96		4000		
1995						980							
1996						6908					290		
1997	24								96		1743		
1998		95	32					54			297		
1999		105									350		
2000		63						2170			25		
2001			12	609						1105	600		182

Source: PCMARD/PCAARRD

Appendix F (continued)

Table 22. Total milkfish export by country in kilograms

Year	Sabah	Saudi Arabia	Singapore	St. Helena	Spain	Sweden	Switzerland	Taiwan	TTPI	UAE	UK & NI	USA	USSR
1970												11787	
1971												45760	
1972												23664	
1973												23333	
1974												33588	
1975									18			33060	
1976									67			26793	
1977									390			487218	
1978		3820	650								15000	454123	
1979		15761	325								4082	505433	
1980		33068	170								10190	683627	
1981		84117	173				25				9582	622788	
1982		147140	230						239		2268	838441	
1983		330354							2711		12643	1331799	
1984		206784	15054						7612		2032	1276243	
1985		90938	145722				19		3525		1452	1207784	
1986		40496	462				96		8792		3272	1599040	
1987		347795	2794				13148		67177		9360	1187572	
1988		74830			238	19	500		11287		9821	1328491	
1989		3800							4123		11497	1197988	
1990		2000				691	500		18240		12135	743428	78
1991						425	2550		46578		1640	296352	
1992			2880				1605		66670	44	358	455123	
1993		7911	468				1210		58096	1752	421	569170	
1994		726	3941				965		34532		1086	160830	
1995		227	5821				568		10799		766	200747	
1996	120	1701	5994				194		9465			122717	
1997			6839				649	150	3918			113912	
1998			5556				769	11800	1622			172876	
1999			4540				140		710			168192	
2000			5360	15				68	210		8661	151319	
2001			4242				168	18	1901	368	400	309257	

Source: PCMARD/PCAARRD

Appendix G

Table 23. Total Giant tiger prawn export by country in metric tons

Year	Total	Arabian Peninsula States	Australia	Austria	Bahrain	Belgium	Canada	China	Cyprus	Denmark	France	French Indian Ocean Areas	Germany	Greece
1970	4521						120				7			
1971	5466						77				3			
1972	5956						141				4			
1973	7013						87						2	
1974	5726						66			0.02				
1975	5622						15				2			
1976	6421		31				39			0.20				
1977	6503		3				27			0.27				
1978	7156		46				3							
1979	7787		12				4	0.01						
1980	6529		69				1							
1981	6678		3				1							
1982	7902		75				2	5					1	
1983	8709		37		0.04		3	25					3	
1984	10393	0.24	123				5	3						
1985	12075	12	109				40	2						
1986	15183	13	81				28	21			10		37	
1987	18909		159				70	0.25	5		26		19	
1988	27512	0.01	191			91	77			1	65		30	
1989	30030		219	1		53	210	5		0.03	80			
1990	28126		206	0.21	1		284	2	0.25		182		10	13
1991	33589		213				214				292	3	29	0.46
1992	26987		146			9	207				91		20	3
1993	26192		95	2	0.07		182	0.19					7	5
1994	25664		46	3	0.34		106	137			3		0.10	
1995	21814		23	0.20			166				3			
1996	17044		0.05				132						24	
1997	14267		5	2			114	9					0.02	
1998	14512					35	104	21			49		50	
1999	5696													
2000	6679													
2001	6852													

Source: PCMARD/PCAARRD

Appendix G (continued)

Table 23. Total Giant tiger prawn export by country in metric tons

Year	Guam	Hawaii	Hongkong	Israel	Italy	Japan	Korea	Malaysia	Marshal Islands	Nauru	Netherlands	New Zealand	Norway	Palau
1970	6					396								
1971	23	1	26		2	1260								
1972	34	12	28			1509								
1973	58	0.22	36			2445					1			
1974	24	2	17			1336								
1975	57	5	1			1109								
1976	60	26	17			2021								
1977	54	32				2285								
1978	47	20	1			2992						2	2	
1979	49	13	1			3603								
1980	57	9	2			2307								
1981	54	0.50	2			2632						1		
1982		0.16	12			3683		0.02						
1983	76	1	25			3870					10			
1984	72	2	50			4525								
1985	150	26	56			5917		14		0.37	9			
1986	101	235	35		7	8686					23			
1987	122	234	58		19	12124						0.03		
1988	193	186	34		8	19068				0.05	8		0.10	
1989	285	296	117		4	18832					6			
1990	434	241	50	0.13	41	18702	41		2					
1991	310	261	184		19	21910	119							0.29
1992	202	206	318		12	17342	270							2
1993	188		138			18469	301							0.39
1994	239	48	363	10		16920	1082			0.30				5
1995	194	96	229		8	13486	1455							
1996	158	49	179			9611	1593				18			
1997	194	12	314	1		7205	1059				4			6
1998	138	16	429			7571	125				15			2
1999							324							
2000							686							
2001							1206							

Source: PCMARD/PCAARRD

Appendix G (continued)

Table 23. Total Giant tiger prawn export by country in metric tons

Year	Portugal	Puerto Rico	Qatar	Saudi Arabia	Singapore	Spain	Sweden	Switzerland	Taiwan	Thailand	TTPI	UK	US	USSR	Wake Island
1970												1	52		
1971													133		
1972								2				0.13	283		
1973													438		
1974													334		
1975						1						52	431		
1976											0.10	6	269		
1977					0.20						0.04		148		0.02
1978					0.16								86		
1979					4								143		
1980				29	1	18						12	64		
1981				4	3						0.17		17		
1982					2						1		157		
1983				22	10		0.06				3	0.09	655		
1984				0.24	12		0.40				1	0.07	1631		
1985					4						1	5	1759		
1986					16					8	1	54	1854		
1987					12						4	9	2074		
1988					9		7	1	4		10	10	3544		
1989		7		14		12	26				46	70	5770		
1990					12	26	18			13	40	30	3797	1	
1991	24	31			2	177	17		4		128	11	5660		
1992	82	21	0.24		50	40	25	0.10	46		110		3800		
1993		16			30		25	10	150		134	0.05	2453		
1994		22			65		37	3	148		119	0.07	2319		
1995		25			6		72	0.10	100		127	15	1817		
1996					18		21	1	68		128		1052		
1997		4			2			6	135	0.11	221	28	952		
1998					0	74	0.10	9	17	20	183	75	1581		
1999													1374		
2000													1993		
2001													1644		

Source: PCMARD/PCAARRD