CLIMATE CHANGE AND THE AQUACULTURE SECTOR OF SARAWAK

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CLIMATE CHANGE AND THE AQUACULTURE SECTOR OF SARAWAK

ABSTRACT

Aquaculture activities are an important contributor to the growth of the fisheries sector in Malaysia. However, climate changes provide major challenges in sustaining future outlook of the aquaculture sector. This study aims to investigate the impacts of climate change on Sarawak's aquaculture sector by assessing the biophysical and socio-economic vulnerability of aquaculture production, and identifying potential adaptation strategies to cope with climate change risks. Three principal essays address the study's three objectives. The first essay focused on the assessment of climate change impacts on the biophysical vulnerability of aquaculture production in Sarawak from a macro level perspective for pond and cage systems. Biophysical vulnerability factors (mean maximum temperature, mean minimum temperature, sunshine hours and the pond aquaculture farm size) were found to influence pond aquaculture production positively. The results showed that cage production is positively influenced by mean percentage relative humidity and negatively influenced by mean maximum temperature. The second essay focused on the farm level impact assessment of climate change impacts on the biophysical and socio-economic vulnerability of Sarawak's aquaculture sector based on evaluation of the physical value (production) and the financial value (income). The water quality, change in precipitation, drought, and hydrological events are biophysical factors that have effects on socio-economic vulnerability, whilst financial and physical factors were important in determining aquaculture productivity. In terms of farmers' income and livelihoods, the results further revealed that the aquaculture system and ethnicity (demographic factors), technology usage (physical asset), financial loans and off-farm income (financial assets), and farm size, dissolved oxygen depletion, and pandemic diseases (natural resources and environmental assets) were the significant factors influencing the socio-economic vulnerability of Sarawak's aquaculture sector.

The third essay identified the potential adaptation strategy to counter climate change risks in Sarawak, based on the comparison of three different farm management approaches with three different risk reduction strategies. The potential adaptation strategy for pond aquaculture in Sarawak is to implement a feed waste emission reduction with environmental restriction strategy; and for cage activities it was through a feed waste reduction implementation strategy. The study revealed that the marginal abatement costs of ponds are higher than for cage activities and if more stringent environmental regulation and restriction were to be imposed on farm production, the marginal abatement costs would increase. The results also suggested that effective resource allocation management in land used or space for aquaculture, fish feed management and working hours' (labor) in farm help would assist profit maximization for farms as well as reduce the climate change risks to aquaculture production. This study contributes towards an economic approach in the assessment of vulnerability to climate change risks and the potential adaptation option for Sarawak's aquaculture sector. The assessment provided empirical evidence that the existing climate change risks and hazards in the aquaculture sector might worsen and imperil the aquaculture sector's potential for future growth. The results of this study and recommendations made are important to improve current aquaculture management, policies, laws, and regulations in Malaysia to cope with climate change impacts.

Keywords: Aquaculture, climate change, biophysical vulnerability, socio-economic vulnerability, adaptation.

PERUBAHAN IKLIM DAN SEKTOR AKUAKULTUR DI SARAWAK

ABSTRAK

Aktiviti akuakultur merupakan penyumbang penting kepada perkembangan sektor perikanan di Malaysia. Walaubagaimanapun, insiden perubahan iklim memberikan cabaran besar kepada kelestarian sektor akuakultur pada masa depan. Kajian ini dijalankan bertujuan untuk mengkaji kesan perubahan iklim ke atas sektor akuakultur di Sarawak dengan menilai keterancaman biofizikal dan sosio-ekonomi pengeluaran akuakultur dan mengenalpasti strategi-strategi berpotensi untuk mengadaptasi dalam menghadapi risiko perubahan iklim. Tiga objektif kajian dikenalpasti dalam tiga prinsip esei. Esei pertama berfokus kepada penilaian impak perubahan iklim terhadap keterancaman biofizikal bagi pengeluaran akuakultur di Sarawak berdasarkan perspektif makro terhadap sistem akuakultur kolam dan sangkar. Faktor-faktor keterancaman biofizikal (min suhu maksimum, min suhu minimum, jumlah jam cahaya matahari, dan saiz ladang kolam) didapati mempunyai pengaruh positif terhadap pengeluaran akuakultur kolam. Keputusan juga menunjukkan pengeluaran sangkar dipengaruhi secara positif oleh min peratusan kelembapan relatif dan dipengaruhi secara negatif oleh min suhu maksimum. Manakala, esei kedua berfokus ke atas penilaian impak perubahan iklim ke atas keterancaman biofizikal dan sosioekonomi di peringkat ladang bagi sektor akuakultur di Sarawak berdasarkan penilaian nilai fizikal (pengeluaran) dan nilai kewangan (pendapatan). Daripada aspek pengeluaran, kualiti air, perubahan jumlah hujan, kemarau, dan aktiviti hidrologi merupakan faktor-faktor biofizikal yang memberi kesan terhadap keterancaman sosioekonomi, manakala, faktor kewangan dan fizikal penting dalam menentukan produktiviti akuakultur. Dari segi pendapatan dan penghidupan penternak, keputusan seterusnya menunjukkan bahawa sistem akuakultur dan etnik merupakan faktor demografi, penggunaan teknologi (aset fizikal), pinjaman kewangan dan pendapatan luar ladang (aset kewangan), dan saiz ladang, kekurangan oksigen terlarut, dan penyakit pandemik (aset sumber semulajadi dan alam sekitar) merupakan faktor-faktor signifikan yang mempengaruhi keterancaman sosioekonomi dalam sektor akuakultur di Sarawak. Esei ketiga mengenalpasti strategi adaptasi berpotensi dalam menangani risiko perubahan iklim di Sarawak berdasarkan perbandingan terhadap tiga pendekatan pengurusan ladang yang berbeza dan tiga strategi pengurangan risiko dalam ladang. Strategi adaptasi yang berpotensi untuk kolam adalah dengan melaksanakan pengurangan pelepasan makanan sisa dengan strategi sekatan alam sekitar dan untuk aktiviti sangkar ialah strategi pelaksanaan pengurangan sisa makanan. Kajian juga mendapati kos pengurangan marginal aktiviti kolam adalah lebih tinggi daripada aktiviti sangkar dan jika peraturan alam sekitar yang lebih ketat dan sekatan dikenakan untuk pengeluaran ladang, kos pengurangan marginal akan meningkat. Keputusan juga mencadangkan pengurusan peruntukan sumber yang effektif dalam penggunaan tanah atau kawasan untuk akuakultur, pengurusan makanan ikan dan waktu kerja buruh di ladang membantu dalam memaksimumkan keuntungan ladang sekaligus mengurangkan risiko perubahan iklim dalam pengeluaran akuakultur. Kajian ini menyumbang ke arah pendekatan ekonomi dalam penilaian keterancaman oleh risiko perubahan iklim dan pilihan adaptasi berpotensi dalam sektor akuakultur di Sarawak. Penilaian ini memberikan bukti empirikal bahawa risiko perubahan iklim dan bahaya yang sedia ada dalam sektor akuakultur mungkin menjadi lebih teruk dan bahaya kepada potensi pertumbuhan sektor akuakultur pada masa depan. Keputusan dan cadangan daripada kajian ini adalah penting kepada penambahbaikan pengurusan akuakultur, dasar, undang-undang, dan peraturan-peraturan semasa di Malaysia dalam menangani kesan perubahan iklim.

Kata kunci: Akuakultur, perubahan iklim, keterancaman biofizikal, keterancaman sosio-ekonomi, adaptasi.

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May Allah reward all of you with goodness.

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LIST OF SYMBOLS AND ABBREVIATIONS

ADB	:	Asian Development Bank
ADRC	:	Asian Disaster Reduction Center
AFSPAN	:	Aquaculture for Food Security, Poverty Alleviation and Nutrition
AIM	:	Amanah Ikhtiar Malaysia
AIZ	:	Aquaculture industrial zone
AOGCMs	:	Atmosphere-ocean general circulation models
ADF	:	Augmented Dickey Fuller
ACF	:	Autocorrelation function
AR	:	Autoregressive
ARCH	:	Autoregressive Conditional Heterokedasticity
BG	:	Breusch-Godfrey
BPG	:	Breusch Pagan Godfrey
CARE PECCN	:	CARE Poverty, Environment and Climate Change Network
CCP	:	Chance Constrained Programming
CGE	:	Computable General Equilibrium
CICS	:	Canadian Institute for Climate Studies

CONOPT	:	Large-scale nonlinear optimization solver
CS_0	:	Marginal cost of abatement
DD	:	Marginal damage
DFID	:	Department for International Development
DID	:	Department of Irrigation and Drainage
DOA	:	Department of Agricultural
DOF	:	Department of Fisheries
DOS	:	Department of Statistics
df	:	Degrees of freedom
EEA	:	European Environment Agency
EIA	:	Environmental impact assessment
ENSO	:	El-Niño Southern Oscillation
ER	:	Environmental regulation
EUT	:	Expected Utility Theory
FAO	:	Food and Agricultural Organization
FAR	:	Fourth assessment report
FCR	:	Food conversion ratio
GAMS	:	General Algebraic Modeling System

GARCH	:	Generalized Autoregressive Conditional Heterokedasticity
GCM	:	General Circulation Model
GDP	:	Gross Domestic Products
GHG	:	Greenhouse Gas
ha	:	Hectare
hrs/day	:	Hours per day
IAMs	:	Integrated Assessment Models
IPs	:	Institutions and processes
IPCC	:	Intergovernmental Panel on Climate Change
kg	:	Kilogram
km2	:	Kilometers square
KMO	:	Kaiser-Meyer-Olkin
LM	:	Langrange Multiplier
LP	:	Linear Programming
LR	:	Likelihood Ratio
m2	:	Square meters
m2/cage	:	Square meters per cage

MAC	:	Marginal Abatement Cost
MACC	:	Marginal Abatement Cost Curve
MAMPU	:	Malaysian Administrative Modernisation and Management Planning Unit
MEC	:	Marginal External Cost
MES	:	Minimum Efficient Scale
mm/day	:	Milimeter per day
MMD	:	Malaysian Meteorological Department
MOF	:	Ministry of Finance
MPC	:	Malaysia Productivity Corporation
MPC	:	Marginal Private Costs
MSC	:	Marginal Social Costs
NEP	:	National Environmental Policy
NKEA	:	National Key Economics Area
NPCCM	:	National Policy on Climate Change in Malaysia
NREB	:	Natural Resources and Environment Board
OECD	:	Organization for Economic Co-operation and Development
OLS	:	Ordinary Least Square

PCA	:	Principal Component Analysis
PLI	:	Poverty Line Income
PP	:	Phillips-Perron
RFF	:	Resources for the Future
RHS	:	Right hand side
RM	:	Malaysian Ringgit
R&D	:	Research and Development
SAR	:	Second Assessment Report
SCORE	:	Sarawak’s Corridor of Renewable Energy
SES	:	Social-Ecological System
SLA	:	Sustainable Livelihood Approach
SPSS	:	Statistical Packages for Social Sciences
STATA	:	Stata Statistical Software
TAR	:	Third Assessment Report
TOL	:	Temporary Occupational License
UNFCCC	:	United Nations Framework Convention on Climate Change
VIF	:	Variance Inflation Factor
WSSV	:	White Spot Syndrome Virus

WHO	:	World Health Organization
Yt/cage	:	Production per cage
3NAP	:	Third National Agriculture Policy
°C	:	Degree celcius
∀	:	Probability limit
τ_μ	:	Intercept
τ_τ	:	Trend and intercept (τ_τ)

CHAPTER 1: INTRODUCTION

1.1 Aquaculture Development and Growth in Malaysia

The development of the aquaculture sector, especially in the developing countries in the Asia Pacific region, has been pushed by the increase in world demand for fish protein for consumption and the over-exploitation of fish resources. China is the largest contributor to aquaculture production in Asia, producing 90% of the world's total production (Dey, Sheriff, & Bjornal, 2006; Edwards, 2000; Lungren, Staples, Funge-Smith, & Clausen, 2006). The world population is estimated to be seven to eight billion and 2.2 million metric tonnes of fish need to be produced to meet the demand for an annual per capita consumption of 29 kilogram (kg). In 1995, the aquaculture sector contributed 25% of the world's fish supply, a proportion that has increased gradually year-to-year. In 2006, aquaculture was identified as supplying 46% of the world's fish with an average annual growth of 7% (World Bank, 2010) growing to 87.5% (58.3 million tonnes of the world's food fish) in 2012 (Food and Agricultural Organization [FAO], 2014; World Bank, 2010). The growth of the aquaculture sector is dependent on market demand, competitiveness, accessibility (appropriate location), and environmental conditions (Canadian Institute for Climate Studies [CICS], 2000).

Aquaculture is defined simply by Edwards (2000, p.1) as "farming fish and other aquatic organisms". There are two main systems of aquaculture: Land-based systems in which fish are farmed in agricultural areas such as paddy fields and ponds; and water-based systems where water sources such as rivers, lakes, or the sea are stocked directly with fish (Edwards, 2000). Aquaculture activities are categorized as large, medium, or small scale, based on monthly and annual production yields.

Malaysia's aquaculture sector has been developing since the 1920s, starting with freshwater aquaculture, and then in the late 1930s, brackish water aquaculture. Brackish water aquaculture activities at that time were situated in mangrove areas and concentrated on shrimp farming using trapping ponds and also cockle culture in mud flats. Cage aquaculture started in Peninsular Malaysia in the 1970s (Tan, 1994) and the sector has significantly expanded over the last two decades. In 2003, pond aquaculture covered 14,200 hectares (ha), cockle culture on mud-flats 7,447 ha and cage and raft culture 1,376,300 square meters (m^2) (Hashim & Kathamuthu, 2005). Meanwhile, in East Malaysia (Sabah and Sarawak) the aquaculture sector only started to grow in the early 1990s. Currently, Malaysia's aquaculture comprises freshwater, brackish water, and marine aquaculture.

Aquaculture production, 196,874 tonnes valued at over RM 10 billion in 2003, contributes about 13% of the total fisheries production (Sulit et al., 2005). Brackish water aquaculture, with a total production of 144,189 tonnes and covering an area of 17,357 ha, represents almost 70% of aquaculture production in terms of both quantity and value (Anon, 2003). In Malaysia the total production and value of the aquaculture sector has kept on increasing year-to-year except for 2012 to 2013 (Table 1.1). In 2013, aquaculture production recorded a 13.9% decrease in quantity and a 5.47% decrease in value compared to 2012. The reasons for this were not stated but in Malaysia the decrease is usually due to factors such as management, market price, and current environmental problems such as haze, drought, floods, the El-Niño Southern Oscillation (ENSO) phenomenon, and tropical storms.

Table 1.1: Production and value of the aquaculture sector in Malaysia, 2012-2013 (Department of Fisheries [DOF], 2013)

Type of Aquaculture	2012		2013		Change	
	Quantity (tonnes)	Value (RM)	Quantity (tonnes)	Value (RM)	Quantity	Value
Freshwater	163,756.81	992,385,860	132,892.42	880,451,546	- 18.85	-11.28
Brackish water	139,129.51	1,566,776,160	127,881.42	1,538,831,510	- 8.08	-1.78
Total	302,886.32	2,559,162,020	260,773.84	2,419,283,056	- 13.90	-5.47

Dey et al. (2006) explained that the aquaculture industry expanded in Asia due to its high profitability with high expansion rates in China (4.69% per year), Malaysia (4.45% per year), and Thailand (4.01% per year). The aquaculture sector in Malaysia is still small compared to that of neighboring countries such as Thailand and Indonesia. However, Malaysia also supplies aquaculture products to other countries through exports. Malaysia's main exported aquaculture products are shrimps (*Penaeus monodon* and *P. merguiensis*), sea-perch (*Lates calcarifer*), grouper (*Epinephelus* spp.), crabs (*Scylla serrata*), cockles (*Anadara granosa*), and other freshwater species (Tan, 1998).

Two important drivers, the physical and financial drivers, have enhanced the competitiveness of Malaysia's aquaculture sector development. Starting in 2003, the Malaysian Government has announced and commenced many programs to enhance the potential of this sector. The government has made a huge allocation of physical and financial facilities to various aquaculture development projects, especially aquaculture industrial zone (AIZ) projects. The establishment of the AIZ has transformed the aquaculture sector into a more technological activity driven by high market contribution in order to increase national food production and resolve the shortfall in captured fish production and the exploitation of marine fish (Ministry of Finance [MOF], 2003, 2011).

The aquaculture sector has great potential to be developed and to play a significant role in overcoming the decrease in fish stocks due to over-exploitation by commercial fishery activities in coastal areas (CICS, 2000; Tan, 1998). Shariff, Yusoff, and Gopinath (1997) report that this sector has been greatly transformed through an increase in technological activities and high market contribution. Aquaculture has been identified as the strategic industry that shall fulfill the domestic demand for high value protein resources and the demand for fish products for export. This will help the government achieve its targets for food production growth (33.4% or 1.8 million metric tonnes for fisheries) and reach 103% self-sufficiency by 2010, the target stated in the Ninth Malaysia Plan Mid-term Review (Malaysia, 2008). The aquaculture sector benefits the nation at both the national and local levels by meeting the demand for fish and also endorses private sector technical and research capabilities for economic development (CICS, 2000).

The FAO of the United Nations has pointed out that aquaculture production will be an economically important way of increasing local fish production for food security while contributing less than 0.2% of gross domestic products [GDP] globally. Other authorities have made similar statements: Lungren et al. (2006) state that aquaculture contributed 0.283% of GDP in Malaysia in terms of production value in 2003; Sugiyama, Staples & Funge-Smith (2004) noted an increase in GDP to 0.367% in 2004; and Lymer, Funge-Smith, Clausen, and Miao (2008) noted a decrease to 0.3% in 2006. Thus, the Malaysian Government, in the Third National Agriculture Policy (3NAP) (1998-2010), targeted this sector for transformation into the major area of concentration to enhance the competitiveness of the country's agriculture sector.

The 3NAP plan envisions the steady growth of aquaculture production raising the current total 200,000 tonnes to 600,000 tonnes by 2010 (FAO, 2008). The government believes that aquaculture sector has the potential to make a major contribution to economic growth and will be able to supply both local and export demands for fisheries so, in 2009, they allocated RM373.5 million to maintain the aquaculture projects throughout Malaysia. The importance of aquaculture production in Malaysia's economic development continued to be highlighted in the National Agro-Food Policy (2011-2020) as the main area of concentration in accelerating the competitiveness of Malaysia's agriculture sector.

The aquaculture sector is recognized as one of the important drivers of economic activities under the Malaysia National Key Economics Area (NKEA). In terms of percentage share of GDP in the agriculture sector, the aquaculture sector consistently contributed significantly, from 4.5% in 2006 to 6.7% in 2010 (Department of Statistics [DOS], 2011). Meanwhile, the aquaculture sector's latest contribution to the Malaysian economy was a reported 5% added value to the Malaysian agriculture sub-sector (Malaysia Productivity Corporation [MPC], 2014).

In 1990, this sector employed 18,143 people who were occupied at various levels in operational activities including harvesting, processing, and marketing (Tan, 1998). Meanwhile, in 2013, 1,966 brackish water cages and 84 brackish water pond entrepreneurs were located in Malaysia. The total land used for the brackish water aquaculture projects was 2,861,068.89 m^2 for cages and 6,903.04 ha for ponds.

The socio-economic impacts of aquaculture are various. Aquaculture activities have assisted alleviate poverty especially in rural areas and benefit the poor by providing nutritious foods and opportunities for self-employment and to generate income (Edwards, 2000). Traditional aquaculture practices have helped reduce poverty and upgraded coastal communities' livelihoods, for example in China and Indonesia. Rural communities and farmers benefited through the development of aquaculture activities because of allocations for infrastructure that help improve the quality of life, such as electricity supplies, communications, and road access (Othman, 2006). Safa (2004) noted that the fishery sector in Malaysia is important because it meets the demand for fish as the main source of protein intake in daily life and helps rural development through job creation. Furthermore, farmers are able to generate income through various upstream and/or downstream activities that include harvesting, processing, and marketing (Edwards, 2000; Tan, 1994). More than 80,000 Malaysian fishermen live below the poverty line (Safa, 2004). They still practice traditional fishing techniques and are also involved in small scale aquaculture in rivers with open or free access (Othman, 2006). They meet their daily needs by consuming much of what they produce through aquaculture and some is sold in the market.

The aquaculture sector has developed rapidly over the past few years with large scale operators (using modern equipment and technologies) and rising investment (with high returns or profits) contributing to the industry. Ironically, however, most farmers still operate their small scale aquaculture farms in open access waters where no rental is charged, use traditional techniques, and consume most of what they produce, with what little excess there is being sold in the market. Farmers still lack the knowledge to operate high technology farming systems. Moreover, they are unable to access a supply of 'seeds' (fish fry) and do not receive any institutional support to develop their farming activities (Edwards, 2000).

1.2 Aquaculture Development and Growth in Malaysia

1.2.1 Malaysia's Climate

Malaysia (comprising Peninsular Malaysia and East Malaysia (Sabah and Sarawak)) is located in the equatorial region. Malaysia experiences four seasons: The southwest monsoon (mid May to September), the northeast monsoon (early November to March), and two shorter inter-monsoon periods. The northeast monsoon brings heavy rain to Peninsular Malaysia's east coast states, to Sabah, and to western Sarawak. Peninsular Malaysia's climate is directly affected by wind from the mainland while that of East Malaysia is under maritime influence (Malaysian Meteorological Department [MMD], 2009; World Health Organization [WHO], 2007). Peninsular Malaysia's east coast states are exposed to the maximum rainfall in November, December, and January while the dry season is during June and July. The rest of the peninsula, except for the southwest coastal area, receives maximum rainfall during October-November and April-May. The northwestern region has minimum rainfall during June and July and also in February. The southwest coastal area is exposed to maximum rainfall in October and November, minimum rainfall in February and the dry season from March to May and June to July.

The coastal areas of Sarawak and northeast Sabah experience maximum rainfall once only, in January. The minimum rainfall occurs in June or July for Sarawak's coastal areas and in April for Sabah's northeast coastal area. The northeast monsoon brings heavy rainfall from December to March. Sarawak's inland areas experience a balanced annual rainfall distribution and a dry season from June to August due to the southwesterly winds. Sabah's northwest coastal areas experience the primary maximum rainfall in October and then in June. The minimum rainfall occurs during February and August. The central parts of Sabah experience maximum rainfall in May and October and minimum rainfall in February and August. Southern Sabah has a balanced rainfall distribution, slightly drier from February to April.

The range in diurnal temperature in Malaysia's coastal areas is 5˚C to 10˚C while in the inland areas it ranges from 8˚C to 12˚C. The mean temperature in the lowlands ranges between 26˚C and 28˚C. The east coast states of Peninsular Malaysia experience clear temperature variation during the monsoon seasons. The highest average monthly temperature in most places is recorded during April and May and the lowest in December and January.

The mean monthly relative humidity in Malaysia (70% to 90%) differs according to location and month. Alor Setar has the widest range of mean monthly relative humidities (15%) and Bintulu (3%) the narrowest. Malaysia has, on average, six hours of sunshine per day (on average about seven hours per day in Alor Setar and Kota Bharu and five hours in Kuching). Alor Setar experiences the maximum hours of daily sunshine (8.7 hours) and Kuching the lowest (an average of 3.7 hours per day in January).

1.2.2 The Climate Change Scenario in Malaysia

Climate change is a major global environmental issue. Malaysia has experienced its effects in terms of increasingly volatile weather patterns and increasingly severe weather events as the years go by. Climate change is due both to natural factors (the long term interactions between the ocean and the atmosphere) and anthropogenic (human induced) factors. Climate change causes sea levels to rise and rainfall to increase (with increasing flood risks) as well as drought. The occurrence of the ENSO phenomenon in Malaysia causes a reduction in rainfall and significantly increases the regional temperatures during the dry season. Dry seasons have frequently occurred in Peninsular Malaysia and have become longer in East Malaysia since 1970.

Climate records for Malaysia show surface temperature maxima in 1972, 1982, and 1997. El-Niño events occurred in 1972, 1982, 1987, 1991, and 1997, with maximum annual temperatures recorded especially in western Peninsular Malaysia and Sabah. Over the past decade East Malaysia has recorded higher temperatures than Peninsular Malaysia with the highest temperature increase (3.8℃) recorded in Sarawak. Temperature increases in the eastern Sarawak region are forecasted to double, from 1.4˚C to 3.8˚C, over the period 2029 to 2050.

The Malaysian Meteorological Department's climate projections for the period 2001 to 2099 show future climate scenarios. The difference in surface temperatures, as projected by the Atmosphere-Ocean General Circulation Models (AOGCMs), is expected to increase and deviate over the next 50 years. Table 1.2 shows the annual mean temperature changes (˚C) during the 1990 to 1999 period. The simulation results indicate that the temperature in East Malaysia will increase by 1.0˚C to 3.5˚C and in Peninsular Malaysia by 1.1˚C to 3.6˚C. The projection also shows that rainfall will increase most significantly in western Sarawak. The northeast monsoon circulation from December to February will cause intense rainfall and flooding. The General Circulation Model (GCM) projection shows that in Peninsular Malaysia, Sabah, and Sarawak surface temperatures will remain consistent or be reduced by 0.4˚C to 0.5˚C in all months except March, April, and May over the period 2080 to 2089. The GCM simulation for all regions for 2028, 2048, 2061, and 2079 forecasts that the average surface temperature in Peninsular Malaysia will increase from 2.3℃ to 3.6℃ and increase from 2.4℃ to 3.7℃ in East Malaysia. By the end of the century, temperatures are predicted to be highest in eastern Sarawak (an increase of 3.8˚ C) and lowest in northeastern Peninsular Malaysia.

Table 1.2: Annual mean temperature changes (˚C) forecast over the 2020 – 2099 period (MMD, 2009)

Region	2020 - 2029	2050 – 2059	2090 – 2099
Northwest Peninsular Malaysia (PM)	1.3	1.9	3.1
Northeast PM	1.1	1.7	2.9
Central PM	1.5	2.0	3.2
Southern PM	1.4	1.9	3.2
Eastern Sabah	1.0	1.7	2.8
Western Sabah	1.2	1.9	3.0
Eastern Sarawak	1.4	2.0	3.8
Western Sarawak	1.2	2.0	3.4

Recent tremendous rainfall events in Peninsular and East Malaysia are due to weather pattern amplification by tropical storms in the South China Sea. El-Niño and La-Niña events influence rainfall patterns in Malaysia. The El-Niño events in 1963, 1970, 1997, and 2002 caused the driest years in Peninsular Malaysia and East Malaysia with a greater decrease in rainfall. La-Niña events bring wet years for Malaysia with the wettest years recorded in 1984, 1988, and 1999 in East Malaysia. The period 1961 to 2007 shows a trend of increasing rainfall for Sarawak. The maximum rainfall occurred in September, October, and November in western Sarawak and less in northern Sarawak in March, April, and May. Malaysia experienced heavy rainfall and floods during the 2006/2007 and 2007/2008 northeast monsoons. The temperature increases and changes in rainfall caused northern Peninsular Malaysia and also Sarawak and Sabah's coasts to become vulnerable (Baharuddin, 2007). Figure 1.1 shows projections for changes in annual rainfall from 2001 to 2099 relative to 1990 to 1999.

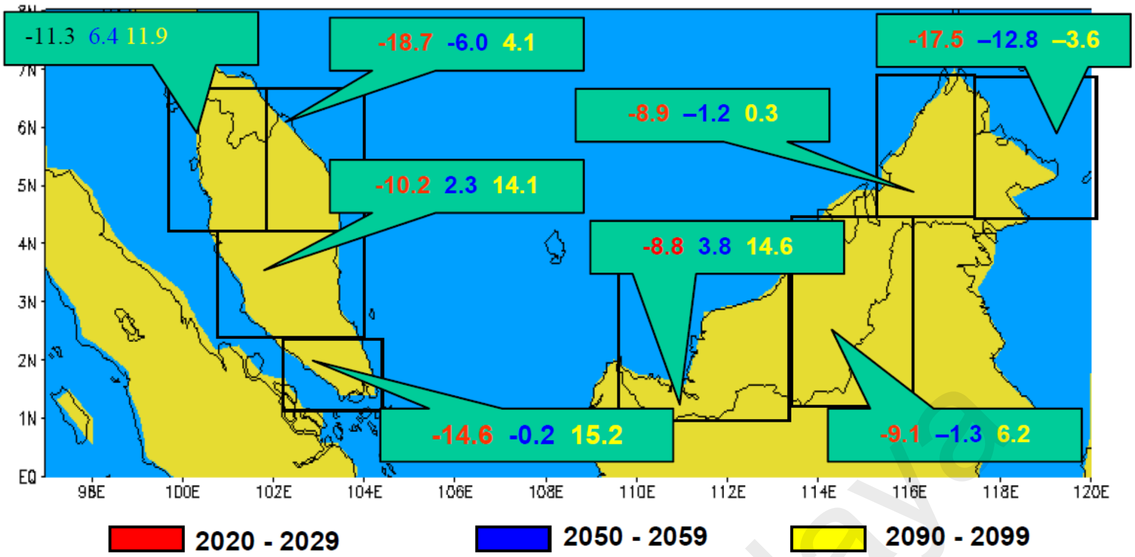

Figure 1.1: Annual mean rainfall anomaly projections (%) from 2001 to 2099 relative to 1990 to 1999.

Source: MMD (2009)

Simulations for seasonal temporal rainfall variation show the largest variation (-60% to 40%) in December, January, and February. The least variation (15% to 25%) occurs in September, October, and November. It is predicted that in 2028, 2048, 2061, and 2079 the El-Niño will affect Sabah, Sarawak, and Peninsular Malaysia and cause a reduction in rainfall in all regions. The average annual rainfall will be severely reduced in Sabah and Sarawak from 2079 to 2099 while Peninsular Malaysia will have higher rainfall from 2090 to 2099.

1.2.3 Climate Change Risks to the Growth of Aquaculture

The sustainable growth of aquaculture is mainly influenced by abiotic and biotic ecological factors that affect fish growth. Abiotic factors comprise the biosphere's nonliving elements (chemical factors such as pH, salinity, oxygen; location, geological factors such as minerals; and physical factors including temperature and light). Biotic factors are living elements that affect and interact with fish growth (such as other fish, predators, prey, algae, microorganisms, and other organisms) (Su, 1991). Climate change has modified the normal ecological patterns and cycles and this affects fish growth causing risks to the aquaculture sector. Handisyde, Ross, Badjeck, and Allison (2006) underline eight major drivers of climate change that cause negative impacts on world aquaculture systems and farm operations. These major drivers are alterations to sea surface temperature; modification of oceanographic factors; a rise in sea level; storm intensity and frequency; an increase in inland water temperatures; floods and precipitation; drought events; and water stress. These drivers affect fish production, causing sluggish growth rates and influencing the threat of diseases that can cause major mortalities. At the same time, climate change events increase aquaculture sector operational costs due to the rising cost of management, especially feeding and obtaining quality fries, competition for good natural resources for aquaculture activities, and the maintenance and restructuring of aquaculture infrastructure.

Several cases involving a nexus of production losses in the aquaculture sector in Malaysia have been reported (summarized in Table 1.3). Outbreaks of disease are the factor that contributes most to major losses in production in Malaysia. White Spot Disease or White Spot Syndrome Virus (WSSV) is among the common diseases that affect cultured species, especially farmed shrimp. The disease can break out within three to 10 days after the onset of signs and can cause mass mortality to all cultured species (Hashim & Kathamuthu, 2005). The production value of national aquaculture was reported to have decreased by 2.2% from January to June 2010 due to severe cases of *Streptococcus* infection causing tilapia fish to die (MOF, 2011).

Table 1.3: Climate change risk cases in the aquaculture sector in Malaysia

Climate change drivers	Year	Location / States
Water intrusion, water quality deterioration & White Spot Disease[1]	1992	Penang
Drought (El-Niño Southern Oscillation (ENSO))[2]	1997	Selangor, Sabah and Sarawak
Floods & water stratification[3]	2008	Sungai Semerak, Kelantan
Drought (El-Niño)[4]	2009	All states
Disease outbreaks (*Streptococcus*)[5]	2010	Peninsular Malaysia

Notes: [1]Hambal et al. (1994); [2]Sulong (2008); [3]Baharuddin (2007); [4]Farabi (2009); [5]MOF (2011)

Deterioration in water quality escalates disease eruptions and infectivity in aquaculture systems and this caused economic losses of RM 3,000 a day for one farmer of cultured groupers and seabass in Penang in 1992 (Hambal, Arshad, & Yahaya, 1994). In December 2008, producers culturing fish in brackish water cages at Sungai Semerak, Kelantan were reported to have borne losses of almost RM 1 million due to severe flood and water stratification effects causing fish deaths (Sulong, 2008). The ENSO was the major climatic threat to the agriculture sector in 1997/1997, especially in Selangor, Sarawak, and Sabah (Baharuddin, 2007) and has recently been classed as a threat to the agriculture sector (Farabi, 2009).

The in-depth impacts of climate change on the aquaculture sector can be assessed state by state as different states have different climatic and natural conditions that influence aquaculture production (Hamdan, Kari, & Othman, 2009). The effect of climate change on the aquaculture sector will be further discussed in chapter 3.

1.3 Problem Statement

Climate change is one of the major environmental issues that challenge the sustainable growth of the aquaculture sector (CICS, 2000; Hambal et al., 1994; Shariff et al., 1997). Climate change not only raises problems of environmental risks but also influences social problems. This is because environment, aquaculture, and socio-economics interact and depend on each other as explained by the concept of social-ecological systems. Climate change and the aquaculture sector have a give-and-take relationship whereby climate change may sometimes have a positive, but mostly a negative effect on aquaculture sector development while negative aquaculture practices cause an increase in environmental problems that indirectly contributes to climate change. This relationship directly affects a community's social and economic aspects especially in the case of communities that are both dependent on aquaculture resources and users of environmental resources. The socio-ecology concept will be used to identify the significance of climate change risks to aquaculture production in Malaysia and assess the entire exposure of the aquaculture system.

Climate change is a natural climatic event (production risk) that influences the quality and quantity of aquaculture production (Beach & Viator, 2008). Biophysical factors such as climatic change and extreme weather affect the sustainable growth of the aquaculture sector (Akegbejo-Samsons, 2009; Tisdell & Leung, 1999). Changes in water temperature, sea or pond water levels, water stratification, rainy seasons and dry seasons and changes in average annual precipitation, and evapotranspiration are common climatic events that harm aquaculture production (Akegbejo-Samsons, 2009). Climatic fluctuations will change the physiological, ecological, and operational aspects of aquaculture activities (Handisyde et al., 2006). Temperature and precipitation changes were the major causes of failure of aquaculture production in ponds. Such changes usually correspond with drought and flood seasons. These events have been implicated the water stratification that harms the culture of species, especially shrimp. Moreover, climate change also causes disease outbreaks (Handisyde et al., 2006; Siwar, Alam, Murad & Al-Amin, 2009) in fish and shrimp culture at all growth stages - effects that the aquaculture sector in Malaysia has experienced (Hambal et al., 1994; Hashim & Kathamuthu, 2005; MOF, 2011).

Extreme climate change impacts will slow the rate of development, destroying lives, and livelihoods. Attention to the environmental and social aspects of aquaculture production is important to ensure its sustainability and safety (Anon, 2003). Climate change effects increase the costs of managing the farm efficiently (Sulit et al., 2005). Aquaculture operations are usually conducted at low intensity in small-family owned environments in order to minimize production losses. However, small farmers are unable to survive in this sector due to rising production costs and lack of a support system to protect the cultured fish and shrimp from the impacts of production risks. Farmers' failure to produce and the concomitant decline in food production will lead to famine (Sen, 1981) and a poverty trap because of the permanent losses of human and physical capital (Heltberg, Siegel, & Jorgensen, 2009). Furthermore, the flood events recorded in Sarawak since 1946 (Table 1.4) show that the occurrence of mild climatic disasters caused significant socio-economic impacts on the community. Such events contributed to the major losses realized by aquaculture farmers running large-scale aquaculture production, especially in Kuching. Flood events caused landslides and damage and also claimed many lives. A study by Charles, Ting, Ahmad Bustami, and Futuhena (2009) supported the notion that rainfall patterns, temperature, and evaporation rates are trending upward in Sarawak and that such events may indicate the occurrence of climate change risks to activities involving hydrological systems.

Table 1.4: Number of flood events in Sarawak from 2004 to 2009 (Department of Irrigation and Drainage [DID] Sarawak, 2010)

Year	No. of cases	Months of occurrence	Location
2005	8	Jan., Feb., March, April, May, July & Oct.	Sri Aman, Sibu, Kapit, Kuching
2006	5	Feb., Sept. & Dec.	Kuching, Bau
2007	10	Jan., Nov. & Dec.	Kuching, Limbang, Lawas, Miri, Samarahan, Sibu
2008	9	Feb., March, Sept., Oct. & Nov.	Limbang, Baram, Marudi, Kuching, Sri Aman
2009	11	Jan.	Kuching, Samarahan, Serian, Betong, Sibu, Miri, Bintulu, Bau

Concern has risen over the consequences of environmental changes on the sustainability of aquaculture production. Nevertheless, few studies have focused on the impacts of climate change on the aquaculture sector, especially in Malaysia. Climate change assessment studies usually concentrate on discoveries in pure science such as those reported by Charles et al. (2009) with less focus on the area of social science in evaluating social responses and working out coping and adapting strategies. Moreover, in Malaysia fewer studies have been done that focus in depth on adaptation and mitigation options based on socio-economic assessments specific to the aquaculture sub-sector. Although there have been an increasing number of environmental issues in Malaysia since the industrial era in the 1970s, specific policy plans or strategy to address climate change was only created in 2009. Previous policy plans had included and addressed the sustainable management aspects of natural and energy resources but did not thoroughly cover aspects of climate change (Al-Amin & Filho, 2011). A recent study by Idris, Azman, D'Silva, Man, and Shaffril (2014) focused on identifying the climate threats to brackish water cage activities in selected states in Malaysia. The study revealed that climatic events consist of increases in temperature, heavy rainfall, floods and water currents that cause sediments, and wastes from nearby economic activities to pollute the aquaculture area, causing disease infections, fish deaths, and cage damage.

Khairulmaini (2007) and Khairulmaini and Fauza (2008) conducted conceptual studies of climate change and adaptation. Alam and Siwar (2009), Baharuddin (2007), Nasir and Makmom (2009), and Siwar et al. (2009) studied climate change impacts on the agriculture sector, especially on rice production. Meanwhile Hambal et al. (1994) and Ti, Rosli, and Rajamanikam (1985) studied the environmental issues of aquaculture development.

Assessment of the social dimension of aquaculture development is important for the improvement of policy and practices in coping with climate shocks (Adger & Kelly, 2000). Future studies on the environmental issues in aquaculture development in Malaysia need to concentrate on good management, technical improvement, and strategic planning (Hambal et al., 1994). FAO (2008a) indicated that studies that provide a good understanding of the vulnerability of fisheries and aquaculture to climate change causing constraints and limitations in prioritizing adaptive strategies were insufficient. Furthermore, research focusing on identifying the relationships between climate change's biophysical impacts and the vulnerability of poor fishing communities' livelihoods is lacking (Akegbejo-Samsons, 2009; Handisyde et al., 2006). Tol, Downing, Kuik, and Smith (2004) added that non-market damage, indirect effects, horizontal relationships, and socio-political implications are among the major issues that researchers have not yet covered or explored. The market's response to climate changes and the implications for prices, economic returns, and sector investment will have major impacts on sector performance, employment, food security as well as longer-term development impacts. Producers, consumers, or people dependent on aquaculture are vulnerable to the direct and indirect impacts of predicted climatic changes. The effects of climate change on aquaculture dependent livelihoods need to be assessed in order to identify and reduce the social problems and identify the best solutions to minimize the risks (Handisyde et al., 2006).

In identifying the problems of biophysical vulnerability and the effects of the climate change risks to farm management in the aquaculture sector, there is a need to prioritize actions or potential adaptations that can be made to reduce climate change risks through the synergy role of farmers and other stakeholders. Not many studies have focused on the effects of climate change on the aquaculture sector so the priority is to address aquaculture farmers' capabilities to cope with the risks and their adaptability. Furthermore, the need to formulate aquaculture adaptation plans may differ from farmer to farmer due to differences in aquaculture system practices and locations. An assessment of aquaculture farmers' limitations in implementing adaptations will help the government plan better strategies and better assistance consistent with the farmers' needs.

1.4 Research Questions

This study will address the following research questions:

1) How does climate change risk affect aquaculture production in Malaysia?
2) To what extend does climate change risk affect the aquaculture farmers' livelihoods (socio-economic aspects)?
3) What is the potential adaptation cost and what are the appropriate strategies for farmers in coping with the effects of risks to production due to climate change?

1.5 Objectives of the Study

This study attempts to identify the vulnerability of, and adaptation strategies for climate change impacts on Malaysia's aquaculture sector based on the economic approach. The specific objectives are:

1) To assess the impacts of climate change on the biophysical vulnerability of aquaculture production.
2) To examine the relationship between aquaculture farmers' livelihood assets and socio-economic vulnerability to climate change.
3) To estimate the potential adaptation costs and identify strategies to cope with climate change risks and the vulnerability of the aquaculture sector.

1.6 Scope of the Study

This study was conducted in 17 districts in six divisions in Sarawak. Information on freshwater and brackish water pond and cage aquaculture activities, the number of farmers and the species cultured were gathered from the Department of Agriculture, Sarawak. The overall number of freshwater and brackish water pond and cage farmers' population in Sarawak is shown in Table 1.5.

Table 1.5: Numbers of registered aquaculture farmers for pond and cage aquaculture in Sarawak by division and district (Department of Agricultural [DOA] Sarawak, 2010)

Division (Districts)	Pond system			Cage system		
	No. of pond operators	No. of ponds	Area (ha)	No. of cage operators	No. of cages	Area (m^2)
Kuching Division (Kuching, Siburan, Bau, Lundu)	241	898	208.19	69	1,902	17,118
Sri Aman Division (Batang Lupar, Lubok Antu, Pantu, Engkelili)	153	404	43.87	35	2,734	24,606
Sibu Division (Sibu, Kanowit, Selangau)	228	512	64.42	0	0	0
Miri Division (Miri, Marudi)	22	94	8.97	6	359	3,235
Limbang Division (Limbang, Lawas)	73	247	28.64	182	1,604	14,436
Sarikei Division (Sarikei, Maradong, Julau, Pakan)	76	365	45.94	6	150	1,350
Kapit Division (Kapit, Song, Belaga)	25	83	15.18	0	0	0
Bintulu Division (Bintulu, Tatau)	3	15	1.29	0	0	0
Samarahan Division (Samarahan, Asajaya, Simunjan, Serian)	152	418	65.74	1	12	108
Mukah Division (Mukah, Dalat, Daro, Matu)	16	43	9.28	8	114	1,026
Betong Division (Betong, Saratok)	72	253	24.95	3	114	1,026
Total	1,061	3,332	516.47	310	6,989	62,905

1.6.1 Study Area: Reasons for selection

Sarawak (Figure 1.2) with a total area of 124,500 kilometers square (km^2), is Malaysia's largest state. Sarawak has 11 divisions: Kuching, Samarahan, Sri Aman, Betong, Sarikei, Sibu, Mukah, Kapit, Bintulu, Miri, and Limbang. Different divisions have different climate patterns and environmental features. Sarawak has great prospects for aquaculture development as a total area of 1,539 km^2 in the state is suitable for brackish water aquaculture activities. Sarawak has 21 river basins which connect to the South China Sea and several river areas that are suitable for brackish water aquaculture due to the effects of seawater streams (Kusuadi, 2005).

Figure 1.2: Map of Sarawak, Malaysia

The great potential of aquaculture sector development in Sarawak has stimulated both federal and local governments to develop intensive aquaculture activities by introducing the AIZ. From 1990 to 2010, the total land use for aquaculture pond systems increased from 210.78 ha to 516.47 ha. The numbers of cages in cage aquaculture increased from 100 units (1,000 m^2) in 1992 to 6,989 units (62,905 m^2) in 2009 (DOF, 1990, 1992; DOA, 2010). Sarawak (together with Sabah, Perak, Johor, and Kedah) is among the five states that are major shrimp farm areas in Malaysia and contribute 10% of the total area. The aquaculture industry is one of the major focus sectors or industries (others being the aluminum, glass, marine engineering, metal-based, petroleum-based, timber-based, livestock, palm oil, and tourism industries) listed in Sarawak's Corridor of Renewable Energy (SCORE) industrial plan, to be developed from 2008 to 2030 (Malaysia, 2008). The aquaculture industry has been highlighted as a sub-sector with great potential to be developed and to play a role as a major contributor to agriculture sector development in the future.

Legislation is another reason for Sarawak being selected as the study site. Aquaculture projects in Sarawak are controlled by state institutions (the chief of which is the Inland Fisheries Unit, DOA) and not a federal institution (DOF) as in Peninsular Malaysia and Sabah. All the farmers are registered under the Inland Fisheries Division, DOA Sarawak. The other institutions that monitor the impacts of aquaculture on Sarawak's environment are the Natural Resources and Environment Board [NREB], Sarawak and the Sarawak Rivers Board. The roles of these institutions are given in Table 1.6.

Table 1.6: Institutions with roles in aquaculture development in Sarawak (Phillips et al., 2009)

Institution	Legislation	Provisions / Responsibilities
Natural Resource and Environment Board, Sarawak	Natural resources and Environment Ordinance 1993	- Prescribed activities (Environmental Impact Assessment [EIA])
	Natural Resources and Environment (Prescribed Activities) Order 1994	- Monitoring and enforcement post-EIA
		- Prohibition, restriction and control of pollution
	Natural Resources and Environment (Prescribed Activities) (Amendment) Order 1997	- Monitoring of river pollution and water quality
Inland Fisheries Division, Department of Agriculture Sarawak	State Fisheries Ordinance 2003	- Aquaculture licensing - Enforcement and monitoring of aquaculture premises based on conditions imposed on the permit or license
Sarawak Rivers Board	Sarawak Rivers Ordinance 1993	- Monitoring of river pollution and water quality

Moreover, Sarawak has its own state laws relating to aquaculture practices due to constitutional safeguards that give the state a degree of autonomy to regulate its own resources. Activities that impact the environment need to produce an EIA as stipulated in the Natural Resources and Environment Ordinance 1993 (amended in 1997). The various prescribed activities related to aquaculture in the EIA orders for Peninsular Malaysia, Sarawak, and Sabah are shown in Table 1.7.

Table 1.7: Prescribed activities related to aquaculture development in EIA orders in Malaysia (Phillips et al., 2009)

State	Legislation	Prescribed activities that require an EIA report
All states in Peninsular Malaysia	Environmental Impact Assessment Order of 1987 (Prescribed Activities)	- Aquaculture projects which involve an area of more than 50 ha
Sarawak	Natural Resources and Environment (Prescribed Activities) (Amendment) Order 1997	- Conversion of mangrove swamps into industrial, commercial or a housing estate exceeding 10 ha area - Creation of lakes, ponds, or reservoirs for the rearing of fish or prawn exceeding 50 ha in area, which may pollute inland water or affect sources of water supply - Fish culture and other forms of fishing on a commercial scale which involve setting up of fishing appliances and equipment in the rivers or water courses, which may endanger marine or aquatic life, plants in inland waters or cause erosion of riverbanks.
Sabah	Environment Protection Enactment (prescribed activities) (EIA) Order 2005	- Conversion of wetland forests into fisheries or aquaculture development covering an area of 50 ha or more - Creation of lakes or ponds in fisheries or aquaculture development covering an area of 50 ha or more

Thus, the regulation of Sarawak's aquaculture practice differs from that in other states in Malaysia. This is important in identification of the effectiveness of the institution's role through regulation and control of the sustainable aquaculture practices.

1.7 Significance of the Study

1.7.1 Aquaculture Sector Development

This study will contribute valuable information for the future development of Malaysia's sustainable aquaculture growth strategy. Downing, Patwardhan, Klein, and Mukhala (2005) note that the findings from vulnerability assessments contribute to setting development priorities and monitoring progress. The vulnerability study provides more detail and targets for strategic development plans. It will also raise awareness in the government, related agencies, and producers of the environmental problems connected with the aquaculture sector and hence encourage identification of solutions for the issues. Operational information related to aquaculture practice and management will be covered in order to address the strengths and weaknesses of the aquaculture sector and threats to it, in line with Malaysia's climate change problems. The findings can be adopted as a guideline for strategic planning to sustain competitive development in the future. It is anticipated that the government and related agencies will be able to reduce the impacts of climate change on the aquaculture sector and develop relevant and robust strategies to enhance the competitiveness of Malaysia's aquaculture sector. The study will focus on Sarawak so the findings can contribute to the efficient planning of an environmentally friendly and eco-efficient aquaculture sector as one of the major industries under the SCORE.

1.7.2 Aquaculture Producers' Welfare

The results of this study can be used to help assess and identify the socio-economic status of aquaculture producers, especially the smaller ones or those with limited resources, who are most vulnerable to climate change risks. This would allow the government to plan specific incentives or social resilience schemes to minimize the producers' burdens and cushion the risks they will need to adapt to. This study will also provide useful information for the assessment of previous schemes and whether they are still relevant to the present situation.

1.7.3 Enhance Information about Potential Adaptations to Climate Change

This study will contribute additional information about climate change impact assessment in Malaysia, specifically to the economic (aquaculture production) sub-sector. Current predictions of climate change impacts will help in the future projection of climate change risks. The study will provide findings on the biophysical, social, and economic vulnerability of the aquaculture sector to climate change and also identify the adaptive capacity of the producers to confront the risks facing their owned assets. This study is expected to guide short term and long term planning and action in adapting to and mitigating the present and future climate change hazards, especially in the aquaculture sector.

1.7.4 Recommendation for the Enhancement of Climate Change Policy in Malaysia

The first National Policy on Climate Change in Malaysia (NPCCM) was launched by the Ministry of Natural Resources and Environment Malaysia in 2010 as the government's initiative to ensure climate-resilient development to fulfill the national aspirations for sustainability. In the past Malaysia had not developed any specific policy to address global warming or climate change risks in any economic sector although it affects productivity. The National Environmental Policy (NEP) was the only policy that all agencies used to minimize environmental degradation and limit natural resource exploitation (Khairulmaini, 2007). Under the NEP, the government commenced several environmental programs that focused on river water quality improvement, air quality improvement, toxic and hazardous waste management, endangered species and wild flora and fauna protection and flood management to improve sustainability, and the quality of life (Malaysia, 2008). Under the apprentice NPCCM policy, the government plans several key actions to focus on the improvement of policies, plans, programs and projects (KA25-ST6) in agriculture and food security, natural resources and environment, infrastructure, land use, human settlement and livelihood, disaster risk reduction, and other economic elements. Furthermore, the government plans to establish and implement a research and development program on climate change that concentrates on those sectors (KA 28-ST7) and establishes and strengthens the national data repository on climate change information (KA29-ST7). Thus, the results of environmental and socio-economic impacts assessment from the current and earlier studies can be used to identify the appropriateness of, and improve, several key policy actions on climate change in Malaysia. Moreover, the findings can be used as a major reference which related institutions, public and private agencies, industries, and also communities can use to confront climate change challenges. Last but not least, this study will provide a viewpoint on the relevant adaptation strategies that farmers (especially aquaculture farmers) could apply in coping with climate change hazards.

1.8 Organization of the Chapters

This report comprises six chapters. Chapters three, four, and five are written in essay format and contain the three principle essays that address the study objectives. The chapters are organized as follows:

Chapter 1 Background to the study (including the current performance of Malaysia's aquaculture sector and climate change scenarios that may affect aquaculture production), problem statement, research questions, objectives of the study, scope of the study, significance of the study and lastly, how the report is organized.

Chapter 2 Detailed discussion of several theoretical aspects that are relevant to, and support the research objectives. This chapter emphasizes the conceptual framework.

Chapter 3 The first principle essay focusing on biophysical vulnerability assessment in the aquaculture sector. The chapter includes background to the issues; the objective; a review of the literature on the biophysical vulnerability theory and empirical aspects; methodology; findings and discussion; and conclusions.

Chapter 4 The second principal essay which concentrates on the impacts on the social and economic aspects of producers' livelihoods. The chapter also includes the objective; review of literature on the theory and on empirical work on socio-economic vulnerability to climate change; method and procedure including study site, questionnaire design and empirical techniques; findings and discussion; and conclusions.

Chapter 5 The third principal essay focusing on assessing the potential adaptation strategies based on the aquaculture farm model assessment. Includes an overview of adaptation to climate change; a review of the literature on adaptation and cost of adaptation assessment in selecting the appropriate strategies to cope with climate change risks; the methodology including data description and the empirical techniques; results and discussion; and conclusions.

Chapter 6 A conclusion of the combined research findings of three principle essays from the study. This chapter highlights the contribution of the study in methodology, its theoretical and policy implications as well as the study's limitations. Recommendations are made that suggest potential future research directions in the area.

CHAPTER 2: VULNERABILITY OF THE AQUACULTURE SECTOR AND ITS ADAPTATION TO CLIMATE CHANGE RISKS: THEORETICAL AND CONCEPTUAL FRAMEWORK

2.1 Introduction

This chapter provides the theoretical linkages between the impacts of climate change on biophysical and socio-economic vulnerability and potential adaptations that can reduce or help people cope with the climate change risks. The chapter starts with a progression from the theories of environmental economics to that of the economics of climate change. This helps us understand the fundamentals of the study research field. The following section discusses the theoretical framework for this study. This framework includes the theory of production, the theory of firms, the theory of entitlement, externalities, and market failure, the expected utility theory and risk, the theory of vulnerability, the theory of resilience, adaptation theory and the sustainable livelihood approach model. The third section concentrates on the study's conceptual framework and elaborates on the combination of theory, model and literature gaps that contribute to the study objectives.

Climate change studies fall into two main areas: Those based on scientific theories and those based on social science theories. This study focuses on discovering the impacts of climate change from the economics perspective. As such the theoretical framework will link several classical and modern theory postulations. Discussions will concentrate on the foundational aspects of aquaculture production which stress environmental quality (climate change effects) as production factors.

Subsequently, the discussion will further link the foundation theories of aquaculture production with the climate change theories, i.e. vulnerability theory and adaptation theory. Scientific postulations, especially concerning biophysical vulnerability and adaptation assessment, will be put forward to support the study. Climate change risks are uncertain yet may be a reason for market failure, so the expected utility theory (EUT) will then be set out to improve the understanding of how the individual or firm reacts to the existence of climate change risks and exposure. The theoretical framework will be supported by the resilience theory, entitlement theory, and Sustainable Livelihood Approach (SLA) to bridge the relationships between vulnerability and adaptation of socio-ecological factors under a risk and uncertainty environment and to arrive at a clear knowledge and understanding of the study area and explain the study's important variables.

2.2 Progression of the Environmental Economics and the Economics of Climate Change Theories

The economics of climate change theory came about as an extension theory to tackle one of the wider environmental economics issues. As such, the growth of environmental economics will be described first. Environmental economics started to grow as a major economic sub-discipline in the 1960s. The establishment of the United States' Resources for the Future (RFF) in the 1950s, the organization that developed and applied economics to environmental issues, initiated the field. The field was then developed by combining welfare economics and economic growth theories from the latest political economic standpoint in selecting the policy instruments and sustainable development philosophy (Pearce, 2002). According to Sandmo (2015) concerns regarding the physical environment as the major constraint on economic development began with Thomas Robert Malthus' (1798) as cited in Sandmo (2015) Theory of

Population that pointed out that population increase constrained the returns from agriculture so the population will increase as the agricultural output expands. Malthus' model was reflected in households' awareness and response to the effects of the physical and man-made environment on human productivity and standard of living. David Ricardo (1817) as cited in Sandmo (2015) expanded Malthus' Theory of Population from a different standpoint, i.e. the link between the physical environment and standard of living. Ricardo suggested that when population size and labor increase the demand for agricultural output will increase, as will rental income. Ricardo's theory on resource scarcity and economic growth argued that land productivity depended on land fertility. The producer determined the price of agricultural products based on the amount by which the cost of production was exceeded on the least fertile land. Pearce (2002) pointed out that Ricardo had expanded the notion of absolute limits in Malthus' theory by developing the different notion of scarcity arising from rising marginal costs of resource extraction and use.

Economic theories relating to environmental aspects were further developed during the marginalist revolution in the 1870s. William Stanley Jevons, Carl Merger, and Leon Walras (1870) improved the classical economists' economic theories in two ways. Firstly, they developed the theory of utility maximization from their generalization of the theory of price formation which clarifies the role of demand and secondly, they studied in depth the allocation of resources in the public interest by scrutinizing the basis of Adam Smith's argument. Walras (1874-1877) through the general equilibrium theory, focused on the general equilibrium of a competitive market economy and emphasized social utility maximization which, like the Vilfredo Pareto (1909) as cited in Sandmo (2015) works on the concept of optimality. However, Walras, Jevons, and Merger failed to connect the competitive equilibrium model with the optimal policy in explaining market failure. Later, Pareto proved the conditions for optimum allocation of resources and was able to characterize the competitive equilibrium in the absence of externalities.

At the same time, Alfred Marshall's partial equilibrium theory in 1890 introduced the concept of externalities, including external economies and diseconomies. Marshall explained that in competitive competition the long run supply curve for individual firms had to slope upward. Downward sloping curves were due to positive cost externalities or represented lower costs for orders due to increased output by one firm. Marshall argued that the externalities could be external diseconomies which showed that the competitive equilibrium would no longer be socially efficient or no longer maximize the social surplus. Marshallian ideas are significant in explaining the issues in the fisheries sector - an example of a common property resource. The individual firms in the fishing industry may experience a constant return to scale due to over-exploitation of fish stocks. The increase in unit cost of fishing due to fishing activities which move the private marginal cost of fishing to be less than the social cost, result in individual firms having an incentive to push the aggregate resource use beyond the social optimum.

Arthur C. Pigou developed Marshall's theory of externalities further in the 1920s. Pigou (1920) extended the theory of externalities in consumption. In this era the focus was on the issue of environmental damage due to pollution (Pearce, 2002). Pigou also analyzed the choice of policies, such as taxes to improve the efficiency of resource allocation. Pigou studied market failure that explained the private and social marginal net products. The negative external effects will affect the social marginal net product less than the private marginal net product. At the same time, the social marginal benefit is less than the marginal benefit of the social marginal cost, which is higher than the private marginal cost. Furthermore, Pigou noted that taxes and subsidies could assist in improving the allocation of resources but did not only use policy options to address environmental problems. Pigou contributed to the development of modern benefit cost analysis methods by using afforestation as an instrument for global climate policy through his examples on positive environmental externalities where, in the case of afforestation, the beneficial effects on climate often occur beyond the borders of the estates owned by the person responsible for the forests.

Dupuit (1844, 1853) as cited in Pearce (2002), developed the concept of costs and benefits identified by human preferences and willingness to pay and his idea had been further developed in the 19^{th} century and contributed to the establishment of welfare economics by Hicks (1939, 1943), Kaldor (1939), and others in the 1930s and 1940s. This introduced cost benefit analysis in the water sector in the United States. The Kaldor-Hicks compensation criterion was developed - this infers that when compensation exists neither gainers nor losers are worse off and shows the Pareto criterion for an improvement in overall well-being. In the early 20^{th} century Gray (1914) and later Hotelling (1931) established the concept of optimal use of natural resources. Later optimal use theorems were applied in natural resource economics, which mainly concerned the rates of exhaustible resource depletion and indication of optimal harvest rates for renewable resources (Pearce, 2002).

Fisheries activities were going to be of interest to economists explaining common property resources. Gordon (1954) noted Marshall's interest in fisheries - in his model Gordon noted that free access to one or more fishing stocks and the marginal costs of fishing efforts are assumed to be constant. Fishing efforts are optimal when the value of marginal productivity equals the unit cost. Thus, equilibrium occurs when the value of the average productivity equals the unit cost when access to the common property resource is free. If the average productivity is greater than marginal productivity, it reflects that the level of fishing effort will be too high (Sandmo, 2015).

Harold Hotelling (1931), in studies on the economics of exhaustible resources, emphasized that the world's diminishing reserves of natural resources caused demands for the regulation of their exploitation. Monopolies control some of the resources so the output was restricted below the social optimum. Hotelling's theory emphasized that under perfect competition the net price of a natural resource must grow at the rate of interest. The equilibrium of this relationship was compared with the social welfare maximization results which showed that the welfare function took the form of time additive discounted utility.

In the mid-twentieth century Lange (1942), Samuelson (1947), Little (1950), and Graaf (1957) extended Pareto's work and contributed towards modern environmental economics. Previous theories had widely noted that externalities were a source of market failure. However, in this era, externalities were considered insignificant and not the major factor in welfare theory. Welfare economics in this era focused on the marginal conditions required for an optimum but gave less attention to the marginal conditions that emerge from utility and profit maximization in a competitive equilibrium. The starting point for analysis of market failure was developed from the comparison of these two sets of marginal conditions. Bator (1958) indicated that the externalities and prices are actually being treated explicitly, which illustrates market failure. All the costs and benefits in socially optimal allocation of resources were captured by linked externalities to the failure of the competitive price system. Bator had differentiated categories of externalities, including the public goods type of externalities, which related to the work of Samuelson (1954).

Samuelson introduced the theory of public goods in 1954. This presented the framework of welfare economics, based on the work of Mill (1848, 1972) as cited in Sandmo (2015) and Pigou (1920). Environmental benefit cost analyses were important practical applications of the fundamental ideas in the theory of public goods. In the efficient provision of public goods, the optimality formula shows the sum of marginal benefits equal to the marginal costs. However, Samuelson's work failed to point out the conceptual difference between individual and total consumption and that the individual agent has no – or least extremely weak - incentive to provide goods whose costs he bears. Although the private incentive to consume or produce the good is positive in the case of private goods with externalities, the individual has no incentive to bear the positive or negative additional costs and benefits which arise for other people in the community. Thus, there were propensities for an amount of produced goods with negative externalities exceeding the social optimum, whilst goods with positive external effects were not provided. In the market failure model in the environmental study, public goods externalities were contributed by private goods production or consumption. This had been supported by Samuelson's proposition where the sum of marginal rates of substitution measures the benefits from public goods provision and benefits from aptly leveled Pigouvian taxes that reduce harmful externalities.

Boulding's essay entitled 'Spaceship Earth' published in 1966 was the foundation for ecological economics. Ecological economics focused on the physical limits. The human capital formations influence on technological change was vague and effective to escape from the limits. Furthermore, Boulding postulates that externalities were respected as minor and manageable deviations from the optimum. Externalities existed distant from the emissions sources and were accumulating through time as well. Boulding referenced the first law of thermodynamics that posits that any use of resources sectors must recur in equal weight as disposed waste as matter and energy can neither be created nor destroyed. The expansion of economic activities will expand physical resource extraction and cause physical waste to be emitted to the environment. Thus, as Ayres and Kneese (1969) showed in the first materials balance, externalities can be prevalent if the waste is prevalent to economic systems and if environmental systems are restricted and have limits to receive waste.

Ronald Coase (1960) indicated two potential solutions for externality: Pigou's work on the implementation of a tax on the polluter (creator of the externality); and the polluter's victims paying the polluter not to pollute. Coase provided equivalent solutions for environmental quality which opened up a substantial potential for free market environmentalism. However, the second solution for externality was criticized as unfair, especially when the polluter is a low-income agent and the victims are high-income agents.

Pearce (2002) explained that welfare economics is the foundation in understanding optima in economic systems. In welfare economics, externalities may lie beyond the optimum and tend to be inescapable, dominant, and widely spread, which results in inefficient economic systems. Thus, the limitations pointed out in Malthusian theory can be solved through technological change. Peters, Ackerman, and Bernow (1999) noted that economics, which can be used to assess the impacts of policy actions in production, consumption and incomes of the whole body of nations, plays an important role in the development of climate change policy. Economics differs from sciences, especially in the rationality of decision making which science is unable to explain in the absence of optimization. Economics is capable of valuing the consequences of different policy choices, assessing policy costs and evaluating the benefits of policy actions through monetary valuation.

2.3 Theoretical Framework

2.3.1 Theory of Production

Winter (2005) considers that the theory of production focuses mainly on the distribution problems and notes the division of the social product in the classic factors of production: land, labor, and capital. Production theory development during economics' classical era and emphasized the economies of marginal productivity while in the neoclassical era until today concerns about production possibilities' part in fixing the relative prices and efficient allocation of resources was growing. Work by von Neumann, Leontief, Koopsmans, Kantorovich, Dantzig, and others from 1936 to 1951 extended the production theory and production function through new approaches including linear analysis, linear programming, input-output analysis, nonlinear programming, and game theory. The objective of production theory using such methods was to try to answer how much output would rise as input increases, given that all other inputs held constant.

Mcconnell and Bockstael (2005) consider that in theory changes in human welfare due to the effects of environmental changes can be gauged through models of households' and firms' decisions. The use of such models to identify linkages between production, the state of the environment and the state of the market, is preferable when faced with limited knowledge of the interactions between human activities and ecosystems and also data scarcity. The households and firms decision theory's main goal is to measure the compensation in income and people's welfare from three different points of view: That of firms' owners, factors of production owners and consumers.

Two concerns exist concerning the environmental aspects of production: The environment as a factor of production and the environment as the consumption of good. From the point of view of climate change, the environment's influences are assessed in terms of whether they are positive or negative on inputs or outputs of production. Environmental factors affect output by altering input productivity, changing the produced output, and decreasing input supplies. Several studies have been conducted on the negative consequences of environment to production. These include assessment of the economic cost effects of air pollution on agriculture and forestry; production and consumption effects due to the potential loss of spawning habitats in wetlands and mangrove swamps; and land degradation and soil erosion and water pollution effects on the decline of commercial fisheries (Mcconnell & Bockstael, 2005).

The empirical models of cost and production of neoclassical production functions are unable to provide a better understanding of input substitution possibilities for improvement of the environment. Thus, the environmental factors need to be included along with other factors of production (Van den Bergh, 1999). Considine and Larson (2004) state that the environmental factors in production activities were included by the firm in response to market failure due to inefficient allocation of environmental resources. Therefore, to assess the impacts of climate change on aquaculture production it would be useful to explain the production function of aquaculture activities, presented as:

$$\mathrm{Y}(t) = f(K, L, E) \tag{2.1}$$

where, $Y(t)$ is the production output of aquaculture in time, t, and Y is a function of capital, K, labour, L, and environmental quality, E. By adapting Vincent's (2008) explanation of production, the output produced by a farm and the input used for production are priced. The farm's supply of output or the input demand did not affect the prices - there was only a simple static setting and the dynamic issues were ignored. Then it was assumed that the change in the firm's profit was equivalent to the welfare impact on the farmer, which changes the owner's income. In production, the farmer controls the input price. However, environmental quality is beyond the farmer's control as the environment is a public good. Thus, the main purpose of understanding the production theory before expanding to other theories was to answer the following question: "if the climate change impacts (environmental quality) change, how does the profit of aquaculture production change?"

The Cobb-Douglas production function explains the technical relationship that relates physical quantities of outputs to physical quantities of inputs. The function is represented as:

$$q = ax^{b}E^{r} \tag{2.2}$$

where q is output, x is variable input, E is environmental quality (climate change biophysical risk) and α, β and γ are parameters. If the variables q, x and E are assumed to be positive the interaction of two inputs in multiplicative ways shows that if either $x = 0$ or $E = 0$, then $q = 0$, and if q, x and E are positive, production has diminishing returns although inputs of production increase where $0 < \beta < 1$ or $0 < \gamma$<1.

Given two different climate change levels and production increasing with decreasing climate change risks ($0 < \gamma$), the production function with the lower level of climate change impacts (E_1) is greater than that with the higher level of climate change impacts (E_0). The influence of climate change risks on aquaculture production to a farm's profits can be explained by the input demand function, which shows the optimal value of x that maximizes the farm's profit for a given level of E (known as the profit maximizing level of x). Let profit = π, derived by $p = pq - wx$ where p is price of output and w is price of variable input, and substitute the production of q,

$$\pi = p\left(ax^{\beta}E^{\gamma}\right) - wx \tag{2.3}$$

$$\frac{\partial \pi}{\partial x} = p\left(\alpha\beta x^{\beta-1}E^{\gamma}\right) - w = 0 \tag{2.4}$$

$$w = p\alpha\beta x^{\beta-1}E^{\gamma} \tag{2.5}$$

This expression is known as the marginal value product of the inputs, which indicates the farm's marginal willingness to pay for the input, also known as the inverse input demand function. Thus, the farm uses x up until its marginal value product (demand) equals its price, w supply. Profit maximization also occurs if the marginal product of input is equivalent to the ratio of input to output price. The increase of x beyond the optimal point will cause the revenue to be less than the cost of the inputs, x.

The cost function includes the prices of inputs, quantities of fixed inputs including environmental inputs, $C = wx$, and the quantity of x, $x = \left(\frac{q}{\alpha E^{\gamma}}\right)^{\frac{1}{\beta}}$. Thus, the cost function is given by $C^{*} = w\left(\frac{q}{\alpha E^{\gamma}}\right)^{\frac{1}{\beta}}$. This cost function $C^{*}(q, w, E)$ posits three important characteristics:

1) If the output is increasing or positive, the production costs increase when output increases,

2) If the price of inputs increases or is positive, production costs increase if the variable inputs' price increases,

3) If the climate change risks increase or cause negative effects on environmental quality, the production cost will reduce with the decrease of climate change risk.

The cost function change with respect to input price is known as Hotelling's lemma, given by:

$$\frac{\partial C^{*}}{\partial w} = \left(\frac{q}{\alpha E^{\gamma}}\right)^{\frac{1}{\beta}} = x \qquad (2.6)$$

Hottelling's lemma is commonly used in the theory of firms.

Vincent (2008) verified that profit is a useful measure to indicate the impact of climate change (environmental change) on farms. The input demand function can be used to calculate the change in consumer surplus between different levels of climate change impacts where the environmental change is equivalent to the change in profit. Furthermore, the marginal cost function can be used to calculate the change in producer surplus between different levels of an indicated climate change impact where the change is equivalent to the change in profit. Then the estimation of the profit function can indicate the change in profits under different levels of climate change impacts.

Stern (2006) stated that environmental quality is a natural asset needed for aquaculture production. The link between economics, climate change, and environment in input-output relationships showed that with increasing negative impacts of climate change, E decreases and reduces and effects reduction on the output as production depends on all the factors of production. The existence of extreme climate change will, directly or indirectly, reduce the capital and labor productivity. However, climate change may have the positive impact of increasing the environmental quality in certain areas. This adaptation to climate change can help reduce the decrease in E and the opportunity cost of adaptation may represent a gain (investment) or loss from adding to K.

Smith in 1776 considers that market price cannot be considered as a theoretical or empirical value, but only given some notion in economic activities. Therefore, he did not conduct a systematic economic analysis on the market price. Smith noted that when any output supplied decreases short of the effectual demand, the market price will increase above the natural price and vice versa. The deviation of market price will affect the producer by reallocating his land, capital, and labor and the quantity of output brought to the market is a necessity to the effectual demand (Kurz & Salvadori, 1997).

Peters et al. (1999) found that the rationality of choice in climate change policy is technological change. The success of climate change policy depended on the speed and direction of technological change. The technology must, at the same time, ensure increasing returns to scale in production and verify that every optimal resource allocation can be reached. Winter (2005) agrees that the complex structure of the production function system iscomplemented by a variety of formal actions due to technological change.

Variation of profit happens as producers have an invariant set of technical alternative choices and with technological change, new products will be produced as new methods of production become accessible. Ricardo (1772 – 1823) focuses on the determination of profit as Smith did not provide an explanation of this aspect in his argument. Ricardo was concerned about the decisions of profit-seeking capital owners and financial capitalists. However, his perspective is more that of a 'monies man' or banker and focuses on the floating capital in which the deviation of profit decreases rapidly. Ricardo was concerned about the problem of income distribution and noted that profit is created by surplus produce (Kurz & Salvadori, 1997).

2.3.2 The Theory of the Firm

The theory of the firm is an extension of the classical theory of production. This theory in economics research was believed to have surfaced in the 1970s (Foss, 1997). Based on Coase's (1937) foundations and the work of Herbert Simon in 1940 and 1950, this theory was developed to expand the assessment of the profit-seeking private sector firm in order to understand the firm's behavior in a market economy. It concentrated mainly on explaining problems due to the existence of asymmetric information and morally hazardous behavior.

Foss (1997) also compared the different understandings of specialization from the points of view of the classical and the modern concept of the firm. Classically specialization is explained as one product of the firm whereas modern thought sees specialization from the perspective of activities and capabilities. The diversified firm was believed to have specialized capabilities. Furthermore, the firm's capabilities are known as organizational capital. The classical viewpoint focuses on individual skills while the modern viewpoint focuses on organizational skills in completing activities either individually or in a team.

The firm's objective is profit maximization, given a set of inputs and outputs of production. There is also an assumption that the sector is in equilibrium in terms of market demand and supply, having grown due to expansion of production in supply (Nelson & Winter, 1974). Sporleder (1992) mentioned that in the early stages of production the producer has to deal with a diversity of risks including price, quantity, quality, and delivery aspects (including storage and inventory). Intrinsic risks occur in all production processes and influence the firm's decisions in managing risk and controlling exposure.

The firm's growth and size were found to be two independent factors but the firm size is connected with its age. The younger firm is growing more rapidly than the older firm. With increasing age, the firm's operation increased in efficiency. Meanwhile, in terms of farm size itself, the smallest value of the cost parameter is more efficient and also has less space for further growth as the information distribution has lower bounds. The firm will diversify its operations when the product market does not function efficiently or when inputs are specific and inseparable (Rizov & Mathijs, 2003).

Foss (1997) noted that knowledge is the major factor determining the firm's economic organization. Linking the division of labor stated in Smith's in 1776, classical theory of production, the productivity of labor was based on knowledge which is important in the division of labor and time saving. A critique by Cannan in 1929 revealed that classical economics had completely ignored the role of knowledge in economic growth and productivity. However, Langlois in 1986 argued that Cannan's view disregards the benefits of the divisions of labor towards the development of the role of science and technology in the economy, skills, and other types of knowledge. Thus, the division of labor was initiated based on scale economies in knowledge accumulation. Furthermore, advancements in knowledge and experience will increase the next divisions and subdivisions and also expand the knowledge. Foss (1997) mentioned that allowing the technology in a firm may depend on the production cost. Furthermore, local knowledge, learning, and technological changes due to the division of labor will cause costs of communication or various agency costs.

Rizov and Mathijs (2003) added that individual farms started small and at sub-optimal scales of production. The farm extended depending on good performance. The successful farm will remain and expand, but the unsuccessful one may remain small and, if operating at a sub-optimal scale of production, may exit from production. Farmers involved in production have to be ready with three conditions; 1) maintain output and farm size; 2) extend production; and 3) contract or exit production.

The existence of farm activities depends on the farm size and growth-inducing activities. Thus, to remain in production, the average cost of producing a minimum efficient scale (MES) of output must be at a minimum. A decrease in MES means a high likelihood that a farm will survive in production and the larger the farm size, the less it will need to grow in order to use the potential scale economies. However, a high MES will force the farm to exit the sector if it cannot expand and attain the MES level of operation. Furthermore, farms preferred to operate at a sub-optimal scale if the fundamental market and technology aspects provide opportunities to generate farm growth.

Decanio, Howarth, Sanstad, Schneider, and Thompson (2000) put forward several criticisms of the neoclassical theory regarding the firm unitary objective assumption, which is profit maximization, while in reality there might be more. Furthermore, the firm was concerned mainly to manage the factor of production but also on other aspects of the firm's activities. The use of technology arises in a firm due to the firm's procedures and decisions, rather, than has been assumed, from exogenous factors or the firm's independent activity. Furthermore, the assumption that firms always make optimal decisions is not really true as environmental improvement was too complex a task to allow full optimization.

2.3.3 The Theory of Entitlement

Production theory puts forward three factors: environmental, economic, and social, that are important in enhancing aquaculture production. These three factors are also the important assets or capital owned by the producers and used to increase their welfare through livelihood strategies. The vulnerability of aquaculture producers can be assessed in two ways: through entitlement evaluation (Eakin & Luers, 2006) or through identification of their capacity to use and convert their assets or capital endowments to cope with climate change risks, and thereby achieve increments of production and/or positive adaptation. This assessment can be applied by using the asset based approach developed from the entitlement theory (Sen, 1981, 1984).

The entitlement theory in origin exclusively revealed the famine problem and covered the alliance of economic and institutional factors. It encompassed the potential resources available as the ownership of individuals from production, assets or mutual arrangements. This theory revealed that climate change caused asset inequalities where the poor (highly vulnerable) people lost a greater share of assets in disasters and recovered at a slower rate than the non-poor (less vulnerable) people. Weaknesses in risk management capacity will cause people to become highly vulnerable.

The entitlements-based approach of vulnerability focuses on the social area of institutions, well-being and on class, social status and gender as important variables. Entitlement theory has linkages with economics and institutional factors. This theory encompasses the actual or potential resources available to individuals based on their own production, assets or reciprocal arrangements. It verifies the welfare or income that the community is able to control, i.e. the bunch of goods options by the rights and prospects that they own (Sen, 1984). Individual rights and access to produce, trade or allocate determine food security. People with less power or entitlement will be more vulnerable among their community (Liverman, 2001). Moreover, entitlement theory particularly explains that individuals, groups or communities are able to find a way to deal with, or adjust to, stress through their entitled ownership. Thus, the application of this theory has gone beyond income and measures of wellbeing.

Leach and Mearns (1991) extended this theory to the field of environmental entitlement. Here the theory focuses on evaluating the interaction between ecological and social dynamics to manipulate environmental management activities. Leach, Mearns, and Scoones (1999, p. 233) defined environmental entitlements as the *"alternative sets of utilities derived from environmental goods and services over which social actors have legitimate effective command and which are instrumental in achieving well-being".* In contrast to its original application to famine problems, the theory could be used to cover scarcity problems due to environmental depletion and degradation. This theory can be applied to identify solutions to environmental problems through diverse institutions as intermediate agents between different social actors and different components of local ecologies (Leach et al., 1999).

Past studies have revealed that climate change causes asset inequalities whereby poor people lose a greater share of assets in a disaster and recover at a slower rate than the non-poor. People who have assets and livelihoods that are exposed and sensitive to climatic risks and those who have weak risk management capacity are the most vulnerable to climate change. The asset-based approach, based on Sen’s (1981) entitlement theory, was developed and is able to explain and link risks, human exposure and sensitivity, adaptation and household vulnerability outcomes. This approach also works with the livelihood approach and justifies that household well-being is multi-dimensional and is directly linked to command over assets and livelihood strategies (Heltberg et al., 2009). The asset-based approach states that livelihoods own several assets: productive assets (human, natural, physical, and financial); social and political assets; and location assets. The producers use their assets to cope with risks and the results help them to maximize productivity. Producers who have limited assets in terms of quantity and quality are more vulnerable to risks due to the low return and high variance of returns in their production. The asset-based approach represents social differentiation where discrimination always existed in accessing the market and community assets (Heltberg et al., 2009).

2.3.4 Externalities and Market Failure

Climate change impacts are an example of externalities that contribute to market failure in the global economic sector, including aquaculture production (Stern, 2007). Schmelev (2012) explained the development of the externalities theory. Arthur Pigou, who had introduced the environmental tax in economics, pioneered work on externalities (Pigou, 1920). This theory in environmental economics was developed by several later economists such as Ayres and Kneese (1969), Baumol (1972), Baumol and Oates (1971), Coase (1960), Hotelling (1931), Kneese (1971) as cited in shmelev

(2012), Leontief (1970), Myrdal (1973) as cited in shmelev (2012), and Tietenberg (1973).

The social and private costs must be distinguished in a consideration of externalities. The marginal social costs (MSC) curve diverges from the marginal private costs (MPC) curve, whose value is given by the marginal external cost (MEC) (Shmelev, 2012). Decision makers usually take into account the private cost of their actions but ignore the external costs that society will suffer. Thus, decision makers set prices equal to only to the private marginal costs. However, the externalities can be reduced to the level where the social cost is equivalent to the marginal social benefit and this will reduce the production externalities to a tolerable level - an optimal amount known as Pareto-relevant.

Van den Bergh (2009) explained that externalities were due to the decision of an economic agent involving a direct or physical influence on a utility or another agent's production that happens outside the market and remains uncompensated. Kverndokk and Rose (2009) suggested that the existence of externalities means that there was inefficiency in terms of full social cost of actions and this occurred because market prices had failed to allocate the value of resources. Meanwhile, Shmelev (2012) indicated that externalities happen when the decision of economic agents, whether in production or consumption, affect the utility or profit of another, i.e. when climate change externalities may positively or negatively affect aquaculture farmers. Negative externalities impose harm on others without compensation while positive externalities raise the value of private property. For instance, in aquaculture production, positive externalities of climate change happen when the changing climate or biophysical vulnerability increase the growth of aquaculture production due to 'good' changes in environmental quality which lessen operation costs, or the changing weather enables the growth of new fish species. Meanwhile, negative externalities were the common externalities that related to climate change impacts as changes in climate and biophysical factors affects risks to, and losses of aquaculture production. In the context of climate change, the existence of externalities indicates that individuals are not fully in control of their factors of production or utility levels. The discussion of externality is usually supported by the partial and general equilibrium theories which concentrate on incomplete sets of markets or complete sets of interrelated markets (Van den Bergh, 2009).

2.3.5 Expected Utility Theory and Risk

Climate change causes global environmental risks that raise severe issues in the economy at every scale, from small to global. Catastrophic climate change causes a rise in several different types of risks in the environment; influences the environment on public good consumption in an optimal environmental quality for socio-economic activities; has implications on the policy instruments to environment and pushes the need to evaluate allocations for risk reduction in society (Siebert & Nixdorf, 2008). Marra, Pannel, and Ghadim (2003) point out that the idea of uncertainty was absorbed into environmental and resource economics studies from the field of finance, which focused on the future value of investments and identified sunk costs for investment gap options. The factors that influence the success of development of policies to address the human dimension of climate change were determined by experience, the diversity in options of adapting the potential future climate and knowledge on potential agents of societal change.

Risk is the effects of a decision that are not completely defined by forecasting or actual results (*ex ante*) (Siebert & Nixdorf, 2008). Meanwhile, Slovic, Finucane, Peters, and MacGregor (2004) defined risk according to a specific perspective in which risk analysis provides reason, cause, and scientific debate to allow for hazard management. According to Tol (2009), in understanding climate change risks, some studies applied utility-equivalent effects which include a social planner and global welfare functions. The estimation of the social costs of climate change risks depended on different postulations on the overall welfare function. Gerst, Howarth, and Borsuk (2013) explain that three critical issues are important for the rational choice of climate policy in decision theory. These include: 1) how the costs and benefits of policy outcomes are weighted by society over time; 2) the unexpected outcome of risks including low probability and high cost outcomes; and 3) society's collective attitude towards downside risks. The focus of studies on climate change were imbalanced, with greater concentration on cost benefit studies than on society's risk attitude's role and relationships to risk exposure.

The term 'utility' was introduced in risk studies in decision theory and appeared early in financial risk evaluations by Gabriel Cramer (1728), Daniel Bernoulli (1738) in Bernoulli (1954), and Jeremy Bentham (1823). Bentham (1823) as cited in Fishburn (1989) gives an early definition of utility: any object of property that creates positive effects such as benefits, advantages, pleasure, good or happy or averting the occurrence of harm, pain, evil or unhappiness (Fishburn, 1989). Irving Fisher (1918) and other economists in the 19th century subsequently applied the term utility in consumer economics. Hicks and Allen (1934) developed the utility concept to measure utility, including ordinal, and cardinal utility. If utility is purely in the ordinal position and without constraint, it is ordinal. Alt (1936) and Frisch (1926) as cited in Fishburn

(1989), and Lange (1934) then axiomatized cardinal utility based on Pareto's approach that was similar to their preference differences. Many economists accepted their idea of the relationship between cardinal utility and similar preference differences although the results were restricted by the popularity of ordinal utility.

Several economists have developed the utility concept. The most remarkable work was that of Neumann and Morgenstern in 1950 whose new idea of expected utility is given in the written piece on the theory of games and economic behavior. The expected utility theory was also called a probability-weighted utility theory where the weighted average for each alternative utility value is assigned under different states of nature in which the weights are determined by the probabilities of these states (Hansson, 2005). The expected utility was presented by:

$$u(p) = \sum p(x)u(x), \tag{2.7}$$

for every finite $p \in P$, where $u(p)$ is the expected utility form, if P includes every finite-support distribution on X and u is defined on X by:

$$u(x) = u(p) \text{when } p(x) = 1. \tag{2.8}$$

Farber (2003) explained that uncertainty can be measured by variance. The expected value is the chance of an event times its value. The coincidence of large events is not adequate to enhance the rapid increment of magnitude of the event although it may decrease rapidly. The uncertain environmental damage means either that the expected risk value might be infinite or might be finite but variance might be infinite. The incidence of "fat tails" in the bell shaped normal probability curve shows that the events that occurred were much more likely to be extreme. Thus, the most likely outcome may be much less serious than the expected value of damage and the variance which shows the degree of risk measurement may be larger than the expected value.

Von Neumann and Morgenstern's EUT had been developed further, with additional axioms added for other probability distributions types, by Arrow (1958) as cited in Fishburn (1989), Blackwell and Girshick (1954), Fishburn (1970, 1982), and Jensen (1967). The later development of von Neumann and Morgernstern's version of the theory focused on the expansion of the representational theory of measurement. According to Buchholz and Schymura (2012) the expected utility theory is still relevant in environmental economics as the standard theoretical tool for cost-benefit analysis of risk which indicates whether or not the uncertain environmental events consequences provide economic benefit.

The EUT was long applied in individual decisions under risk and ethical selection in the society. Lempert, Nakicenovic, Sarewitz, and Schlesinger (2004) added that the probability-based estimates in expected utility are a powerful risk management tool. Hansson (2005) noted that the application of utility in welfare economics postulates that the increasing functions of wealth influence an individual's utility and was different due to the individual's preference. However, in risk analysis the ruling approach was used through the objective utility where the expectation value (the probability of risk with its rigorousness) obtained to relate to risk.

The advantage of using expected utility in risk analysis is in terms of inter-subjective validity, where if the application has been correctly determined for one person, it will also have been correctly determined for all persons. The expected utility is identified as a safe method to maximize the outcome in the long run due to its maximizing objective.

The expected utility is appropriate for risk analysis (Marra et al., 2003) and apposite in comparing single possibilities with the same decision. In generalized expected utility the utilities were influenced by attitudes towards risk and certainty.

The probability-based methods have some limitations in application to climate change problem (Lempert et al., 2004). Weitzman (2011) indicated the application of the expected utility theory in climate change in developing the dismal theorem with the assumption that the people are willing to pay, although at high prices, to prevent the risks. The dismal theorem exists due to the interface between the probability distribution of harm, known as a positive character, and the stated von Neumann-Morgenstern utility function that has normative characteristics. However, expected utility analysis has limitations as it is unable to give logical results under any possible condition but only when constrained by weight in estimation (Buchholz & Schymura, 2012).

Farmers' attitudes to risk and uncertainty were crucial in coping with the potential threats and impacts of climate change, as they can result in effective adaptation (Tompkins & Adger, 2005). The assessment of risk attitudes can help in planning and strengthening countries' capacity building to manage the environment sustainably, provide adaptation options at the local level and engage private agencies with climate change risk reduction. Perceptions towards risk also benefit a country in making a decision on whether to adopt the technology to maximize the benefits in future climate change. Siebert and Nixdorf (2008) noted three types of attitudes towards risk. Individuals' risk preference attitudes vary from risk adverse to risk neutral to risk lover. Therefore, an identified variable may show different levels of risks among the farmers in their probability distribution or a given variable's variance. Thus, the private risk or the objective function and limitation sets of the individual agent was useful to specify the risk. There were also other types of risk: independent risk (where risk is not associated with persons; dependent risks (opposite to independent risk and associated with persons); social risk (about the random variable of the public good); and pure social risk (that involves all agents in a similar approach). Furthermore, there was dissimilarity between private risk and social risk, where private risk can be shifted with the consent of another agent and does not affect the agreed agent.

Leiserowitz (2006) emphasized that the perception of risk was determined by experiential factors that include affect, imagery, and values. Meanwhile, the public's response to climate change was influenced by psychological and socio-cultural aspects. Leiserowitz explained that the rational choice, for instance of the expected utility model, is a combination of economic and psychological theory and was based on the desirability and likelihood of potential outcomes to measure the decision. Furthermore, social values and world views also influence risk perception and behavior. The perception and behavior towards risk depends on the individual's self-interest, of which four types are recognized: Hierarchies, individualists, egalitarians, and fatalists. The hierarchies and individualists focus more on instruments or technology which can give social control and more individual effectiveness. Egalitarians persons on the other hand focus on inequality in risk costs and benefits distribution, accept social deviance and diversity and doubt technology. No details were given about fatalists in the study and there were criticisms regarding these individual types which lack support from other studies.

Siebert and Nixdorf (2008) added that types of risk depended on the environmental conditions where the risk can exist due to accumulation, interaction, and spatial transport of emissions in lieu of the environment's assimilative capacity from consumption and production activities. The severity of risk was uncertainty and the magnitude of effects hard to define, making the production and cost abatement technologies impossible to define *ex ante*. In managing the risk the policy maker will focus on the objective of identifying the individual preferences with respect to climate change shifts and the individuals were not involved in the other individual preference changes.

In environmental allocation, the environment is a public good consumption whilst the residuals repository in environment is a private good. Thus, all environmental risks of the public good were social risks if the risk is impossible to shift and the risk reduction approach is inappropriate. Furthermore, the problem of free riders is an issue in the public good of the environment and in social risk when there is an evaluation of the probability distribution or variance of study variables related to the public good. The risk attitude assessment found that the combination of individual risk attitudes developed society's risk attitudes. Furthermore, an indication of perceptions on the uncertainty in individual risk attitudes can contribute to the combination of risk attitudes and policy making. The optimal allocation of risk was guided by the *ex post* and not *ex ante* perception. Given that U is the quality of the environment, S is climate change impact and $\tilde{\theta}$ is the state of nature, the damage function due to risk is:

$$U = G(S, \tilde{\theta}) \text{ or } U = \tilde{\theta} G(S), \theta \leq 1, \text{ (multiplicative risk)} \tag{2.9}$$

If the variable of constraints in the maximization model is random, the policy maker maximizes the expected utility subject to constraints for the target variables. If the social welfare, W, depends on a private good, Q, and on an environmental quality, U, the welfare function is given by:

$$W = W(Q, U) \tag{2.10}$$

If Γ denotes a utility function indicating society's risk attitudes then the expected utility of a social welfare is:

$$E\Gamma[W(Q,U)] \tag{2.11}$$

Thus, if a country is risk averse, $\Gamma' > 0$ and $\Gamma'' < 0$ and a linear combination of possible outcomes will be selected. The environmental risk can be interpreted intuitively based on Figure 2.1 which shows the marginal damage [DD] function and the marginal cost of abatement (CS_0) function.

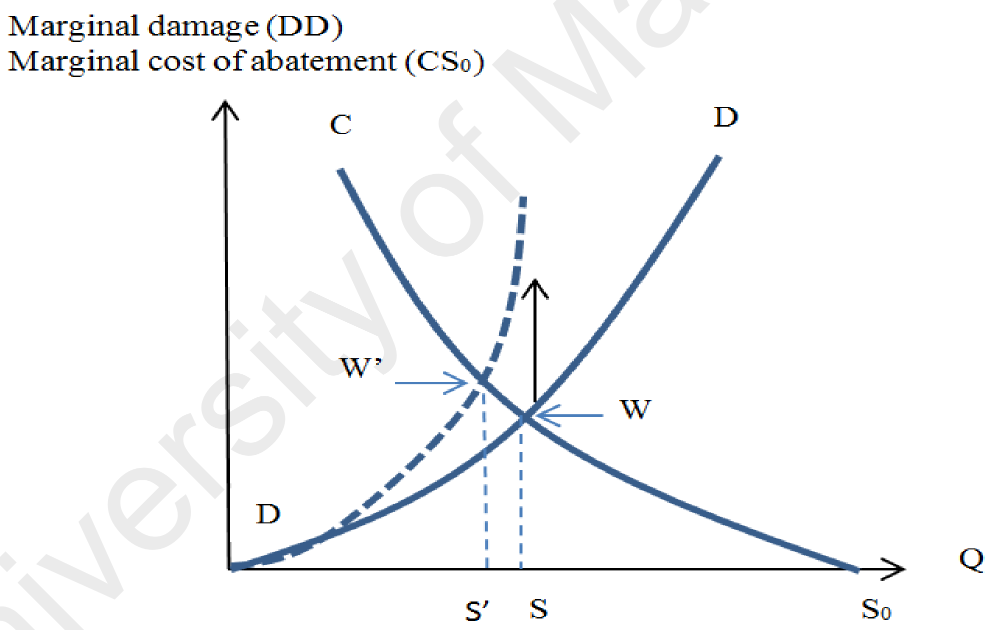

Figure 2.1: Optimal environmental quality and increased risk

If the variance of climate change risk is greater, the marginal damage function will shift upward with the increase in level of climate change risk. The optimal environmental quality is to abate S_0S' and not S_0S. Siebert and Nixdorf (2008) mentioned that the penalty charged was one of the preventive environmental policies that can be applied to improve the scarcity of environmental quality. The best environmental quality is known as an insurance or risk premium for the risk of environment degradation. Furthermore, the discounted rate of disutility is another aspect that can be applied to improve environmental quality. However, higher discount rates in certainty results in lower environmental quality.

Environmental risks were irreversibility, which means uncertain negative effects on the environment can be remedied in future. Pure irreversibility causes a lower discount rate in which opportunity cost for the future was given more weight. The willingness to pay for keeping the environment good by a risk adverse agent known as a risk premium against the irreversible loss of options and the willingness to pay exceeds the consumer’s surplus. Gerst et al. (2013) explained that in decision theory, if there is satisfactory risk aversion, the rational policy choice will be low probability with high impact outcomes. However, other researchers have questioned this policy choice from the point of view of the magnitudes of its impacts and probabilities of outcomes and also the exact degree of risk aversion.

Siebert and Nixdorf (2008) reported that the climate change risk to the environment was a public good and cannot be transferred, a risk known as a social risk. Risk reduction through a risk management approach was the best option, compared to allocating for environmental risk. Thus, information on the risk through risk assessment research is important if effective risk reduction is to be implemented and the uncertainty reduced. Therefore, environmental risk modeling in risk reduction studies needs to include the aspects of irreversibility and the applicable cost to restore and rearrange the damages into the future, which change over time. Furthermore, the cost attributes of reducing the social risk to decentralized units of economy is one risk reduction strategy and if the cost allocation is effective it will give an incentive in reducing the social risk.

2.3.6 Theory of Vulnerability

The Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR) in 1995 defined vulnerability as, "the extent to which climate change may damage or harm a system. It depends not only on a systems' sensitivity but also on its ability to adapt to new climatic conditions. Both magnitude and the rate of climate change are important in determining the sensitivity, adaptability, and vulnerability of a system" (IPCC, 1995, p. 28). Kelly and Adger (2000) defined vulnerability through the ability or inability of individuals and social groupings to respond to, in the sense of cope with, recover from or adapt to, any external stress placed on their livelihoods and wellbeing. The nature of stress and exposure should be the priority in starting this approach and then this develops the context for the study. Social vulnerability is used to explain the process of the starting point approach to present the human dimension in the impact of climate change study.

Liverman (2001), in her study of environmental change, has verified Timmerman's (1981) definition of vulnerability as the level where a system responds unfavorably to the level to which a system may react adversely to the incidence of a risky event and connected to resilience as the system's capacity assessment to understand and recuperate from the risk. A vulnerability has a strong connection with the concepts of resilience, marginality, susceptibility, adaptability, fragility, and risk. The study also found that biophysical conditions help in defining vulnerability.

Burton et al. (2002) extended the definition of vulnerability according to human dimensions as the capacity to anticipate, cope with, resist, and recover from the impact of natural hazards. The vulnerability should be related to specific hazards or a set of hazards, so vulnerability and exposure have always been considered together. The diversification of research on climate change impact studies should include the economic, social, political, and environmental aspects in identifying vulnerability.

Badjeck, Allison, Halls, and Dulvy (2010) clarify that vulnerability is an exogenous turbulence that impacts risk and reduces producers' production and income. In this context, vulnerability (of a producers' livelihood) is a function of the risk to which people may be exposed, the sensitivity of their livelihood system to those risks and their ability to adapt, cope with, or recover from the impact of an external shock (climate change) to their livelihood system (Allison & Horemans, 2006). In other studies the component of exposure, E, is not alone but includes sensitivity as the response of the individual to climate change risk. The combination of exposure and sensitivity is known as potential impact (FAO, 2008a). The vulnerability model is generally articulated as:

$$V_{ist} = f(E_{ist}, A_{ist}) \quad (2.12)$$

where

V_{ist} = vulnerability of community *i* to stimulus *s* in time *t*

E_{ist} = exposure of *i* to *s* in *t*

A_{ist} = adaptive capacity of *i* to deal with *s* in time *t*

The relationship between the elements of this model explain that vulnerability, V, is positively related to a function of exposure, E, which means that the greater the exposure to climatic risks, the greater the vulnerability. However, vulnerability, V, shows an inverse relationship to a function of adaptive capacity, A, where the greater the adaptive capacity, the less the vulnerability (Smit & Pilisofa, 2001). However, Guzman (2003) in his definition of vulnerability used the term resilience or the capacity to cope with hazard as the change in adaptive capacity. The vulnerability theory and its concept can apply to the livelihood and resources that the aquaculture producers own. The information about people's experience and their response to past and current stresses is very useful in identifying the environmental and social factors that contribute to the vulnerability assessment potential (Andrachuk, 2008).

2.3.6.1 Biophysical vulnerability

The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) in 2001 defined biophysical vulnerability as: a function of hazard, exposure, and sensitivity. The term biophysical refers to the physical components of hazards and their first order physical impacts on the affected system that act to reduce the damage from impacts. Brooks (2003) defined biophysical vulnerability as a function of the regularity and the rigorousness of hazards that cause harm, an interaction known as the outcome risks, while Blaikie, Cannon, Davis, and Wisner (1994) noted that hazards or exposure measurement in the system interacts with social vulnerability. In the context of the fishery community, vulnerability is a function of the risks to which people may be exposed; the sensitivity of their livelihood system to those risks and their ability to adapt, cope with, or recover from the impacts of an external shock (climate change) to their livelihood system (Allison & Horemans, 2006).

Vulnerability is an integral part of the causal chain of risk and altering it is an effective risk-management strategy. Biophysical assessment explains the situation of environmental risk or physical environment change and how it harms aquaculture production and producer welfare. Climatic fluctuations affect the physical yield of aquaculture species and increase the farmer's production risks. However, Daw, Adger, Brown, and Badjeck (2009) put forward a contradictory idea concerning biophysical vulnerability effects, whereby, in the long run, there is a positive result from the negative impacts, that is, from the increase and recruitment of fisheries ecosystem resilience to future changes. The sensitivity of the aquaculture sector can be measured by the number of farmers or fishers, poverty, the proportion of aquaculture export value to fish export value, employment sector size, total production, and daily consumption of fish products (WorldFish, 2007a). The physical impacts of climate change differ from one place to another and the effect varies in respect of humans and the environment (World Bank, 2010).

2.3.6.2 Socio-economic vulnerability

The socio-economic study of vulnerability conducted by Susman, O'Keefe, and Wisner (1984) viewed vulnerability from the perspective that the experience of risk differs according to individual social status. The poor are highly vulnerable to disaster and willing to degrade the environment under development conditions of social marginalization. However, a later study by Adger (1998) identified social vulnerability as a group or individual exposure to pressure that their livelihoods are disturbed and obliged them to alter their physical environment through adaptation due to the impacts of climate change and extremes.

Brugere and De Young (2015) stated that there are two schools of thought in assessing vulnerability from the socio-economic perspective. The risk or hazards school of thought on vulnerability identifies the outcome constraints of vulnerability whereas the resilience school of thought focuses closely on dimensions of both political economy and ecology. Meanwhile, Kelly and Adger (1999) emphasized that social vulnerability fell into two categories: the individual category that focuses on resources and income sources, and collective vulnerability from the contribution of institutional and market structure which allocates infrastructure and income. The stage of vulnerability exists through connecting the core economic and social conditions and energetic adjustment to both factors and the physical environment.

Kelly and Adger (2000) defined social vulnerability as the ability or inability of individuals and social groupings to respond to, in the sense of cope with, recover from or adapt to, any external stress placed on their livelihoods and well-being. Burton, Huq, Lim, Pilifosova, and Schipper (2002) defined vulnerability from the human dimension perspective as the capacity to anticipate, cope with, resist and recover from the impact of natural hazards. When peril arises vulnerability and exposure are associated collectively. Cutter, Boruff, and Shirley (2003) defined vulnerability as: 'the interaction of risk with mitigation to construct the hazard potential'. The hazard potential can be mitigated by geographical factors, people's experience with risk and people's capacity to respond to, cope with, recover from and adapt to peril, shaped by economic, demographic, and environmental factors. The Asian Disaster Reduction Center (ADRC) (2005) verified that vulnerability is a situation of physical, social, economic, and environmental factors in which the processes grow in the community in response to the impact of hazards.

The concept of "architecture of entitlement" is what creates accessibility to entitlement, its progression over time and the extensive political economy of the formation and distribution of entitlements. The association between the "architecture of entitlement" concepts and the social dimensions consisted of individual vulnerability and collective vulnerability (Adger, 1999). Using the entitled ownership, the individual, group or community is able to find a way to deal with or adjust to stress. Kelly and Adger (2000) supported this concept and revealed that the vulnerability assessment to the social dimension can be measured through the concept of "architecture of entitlement", social, economic, and institutional factors in community surroundings which endorse and limit the adaptation process. Furthermore, the theory of entitlement confirmed that people with less power or entitlement will be among the most vulnerable in their community (Liverman, 2001).

Climate change affects the biophysical modifications that harm human welfare as well as influences social vulnerability that causes groups and individuals to suffer stress as result of social and environmental change that is vulnerable to food security, resource dependency, risks to human health, migration, and economic factors (Maciver & Dallmeier, 2000). According to Goulder and Pizer (2006), human welfare has been identified to fall into two categories: market damages that relate to changes in the price and quantity of the marketed goods and production productivity; and non-market damages, meaning loss of welfare which is connected with the loss of biodiversity and ecosystem services. Taking African countries as an example, WorldFish (2007b) revealed that the fisheries dependent farmers were vulnerable due to low capacity to adapt to change and risks because they had few assets and low involvement in small economic activities. As aquaculture provides a farmer's main income, decreasing returns from aquaculture activities due to climate change risks also decreased farmers' capital for agriculture and livestock activities, thereby hindering the potential of income diversity as an approach to adapt to risks.

Socio-economic vulnerability levels in populations differ from country to country. It is differentiated by environmental situation factors, social norms, political institutions, resource endowments, technologies, and inequalities (Adger, 1998). The vulnerability scale from these climatic changes differed according to the unit of exposure (Jones, 2001) or the aquaculture system, type of aquaculture species, farm size, and farmers' capability especially to invest (Smit, Burton, Klein & Street, 1999), production practices and location (Beach & Viator, 2008; Smit et al., 1999).

Dwyer, Zoppou, Nielsen, Day, and Roberts (2004) classified social vulnerability into four levels. The first level is the 'individual' which covers personal attributes towards hazards. The interaction between individuals and other people around them reflects the second level of vulnerability known as 'community vulnerability'. The third level concentrates on the geographical or regional factors to indicate the level of accessibility to resources and services in adapting to risk. The fourth level was the 'administrative' or 'institutional' level that identifies the role of the institution in mitigating risks.

Social vulnerability covers vulnerable groups' livelihood disturbance and safety losses which encompass the underlying economic and social situation. The climate change risks in aquaculture impacted farmers' impermanent or permanent migration in order to recover from losses of land and other resources, to obtain new capital for economic activities and to access better infrastructure for living (Adger, 1998). In impact assessment, economic, and social vulnerability cannot be riven from the process where they will help to perform the sensitivity analysis in physical systems.

Vulnerability to climate change affects economic growth and high-investment; high-risk activities such as aquaculture may be unsustainable. Furthermore, climatic variability also harms the community with rising problems of poverty, a broadening risk to income, common property rights thrash and inefficiency in joint action and investment affects (Kelly & Adger, 1999). Burton, Huq, Lim, Pilifosova, and Schipper (2002) noted that the diversification of research into climate change impact should include the economic, social, political, and environmental aspects.

2.3.6.3 Biophysical and socio-economic vulnerability: The study gaps

Biophysical assessments could help explain the situation of environmental risk and how it harms the population, such as by severe rainfall deficits, drought and flood events, extreme temperatures, and disease. Such environmental risks are the major factors influencing the sustainability of aquaculture production. According to Harwood et al. (1999) and Westlund, Poulain, Bage, and Anrooy (2007) risk increases exposure, which causes people and property to be vulnerable to the hazard. Production risk happens due to the vulnerability of volatile weather features that affect the physical yield of livestock and crops, such as disease and infections. It also harms socio-economic development and raises stress, mainly on the demand and supply of food and also on producers' income levels. Thus, climate change is among the environmental risks and has been classified as an involuntary risk of exposure (pathway between source of damage and the affected population or resource) to an environmental hazard (source of damage or negative externality) (Thomas & Callan, 2007).

Many researchers have focused on biophysical vulnerability in resolving food security failure under different conditions of population growth (Liverman, 2001). Past studies tackling vulnerability problems have been categorized into two types of approaches: the direct method used to address the effects of physical change (climate variability) on yield; and the consequences to the economy and society. The adjoint method measures the sensitivity of exposure units to climate change. The demographic variables are one of the important variables that need to be assessed to identify the degree of biophysical vulnerability that people undergo. Through biophysical vulnerability assessment, changes in the physical environment could be indicated and identified. Moreover, number of fishermen, poverty, proportions of aquaculture export value to fish export value, employment sector size, total production, and daily consumption of fish products were influenced to system sensitivity (WorldFish, 2007a).

Vulnerability has concentrated on issues of rights to use and entitlement to resources, authority connection with government and markets as the institutional, cultural, and historical contacts (Adger, 1998). However, in impact assessment, economic and social vulnerability cannot be split from the assessment where it will help to perform the sensitivity analysis in physical systems. The linkage between vulnerability and economic and social factors, and the adjustment in both factors and the physical environment was highlighted by Kelly and Adger (1999) in their discussion on social vulnerability.

There are arguments concerning the connection of biophysical and socio-economic vulnerability. Some researchers believe that biophysical vulnerability exists due to socio-economic vulnerability; others believe that biophysical and socio-economic vulnerability are independent factors (Cutter, 1996); biophysical vulnerability is a factor of socio-economic vulnerability (Klein & Nicholls, 1999); and social vulnerability is a factor of biophysical vulnerability (Brooks, 2003). Moreover, there are two streams of ideas in biophysical vulnerability studies in the context of aquaculture. The first concentrates mainly on pure scientific research, such as the study by Barange and Perry (2009); the second focuses on biophysical vulnerability combined with the socio-economic impact (Daw et al., 2009). Fussel (2007a) distinguished biophysical and socio-economic vulnerability into two scales or spheres: the internal scale (topography, environmental situation, and land use) and the external (events such as severe storms, earthquakes, and sea level change). The level of sensitivity to climate change impact influenced by the internal biophysical vulnerability is known as the danger, while that of the external biophysical vulnerability influence on the environmental circumstance is known as hazards.

Several studies have attempted to discuss and identify gaps in the general theoretical and conceptual aspects of the biophysical vulnerability of climate change on fishing communities. One such is the case study by Fijian and the Mekong Delta fisheries community (Daw et al., 2009). The current study is an additional attempt to add to the existing literature by focusing on the biophysical vulnerability of climate change on the development of Sarawak's aquaculture sector. Nevertheless, the impact on local communities is much more complicated to capture than that of the Mekong Delta study, given the variation in spatial and regional weather variation. With the exception of demographic factors, the biophysical impacts assessment in this study initially concentrates only on understanding the exposure, sensitivity and effects of the biophysical factors that constitute the physical and ecological constraints to aquaculture production in Sarawak. A clear understanding of the relationship between the biophysical aspects of climate change and the aquaculture sector will also provide further evidence on the socio-economic vulnerability among producers with limited resources.

2.3.7 Theory of Resilience

Holling (1973) developed the theory of resilience in the 1960s and early 1970s. In social vulnerability assessments resilience is one of the important factors that helps one to understand the farmers' capability to adapt and respond to risk. Resilience means the buffer capacity or the capability of the system to take in perturbation or the degree of trouble that can be taken in before the system modifies its formation by altering the indicators and processes that control behavior (Holling, Schindler, Walker, & Roughgarden, 1995).

Adger (2000) defined resilience as ‘the rapidity of trouble improvement by the distinction between resilience and resistance’ to identify the impact. Social resilience means the capability of human populations to survive external shocks or risks to their social infrastructure, such as environmental variability or social, economic, and political disorder. Social resilience is responsive to the institutional context and its study includes economic and social dimensions which are connected to specific discipline. Other researchers have also given several definitions of resilience, according to the nature of their research. Resilience has been known as the competence of a system to take up trouble and re-structure the continuous change yet still effectively preserve a similar function, structure, identity, and feedbacks (Walker, Holling, Carpenter, & Kinzig, 2004).

The link between vulnerability theory and resilience theory can be found through its similarity to identification of the adaptive capacity to cope with, or adjust to climate change risks, and this has been identified in studies by Adger (1999, 2000) and Turner et al. (2003). Both vulnerability and resilience studies focused on handling stress or perturbation (Schoon, 2005). The connection between the theories was also simply explained by the dynamic involvement of social and biophysical components and their interactions in climate change conditions, known as social-ecological systems (SES). The SES is the main subject of both theories and in this study it can be explained by the interaction of climate variability (climate change) with aquaculture production and producers’ livelihoods. The resilience was identified from the changes in the system or ‘system identity’. If the interaction of the SES affects loss in production then the resilience will decrease due to the loss of identity and vice versa (Cumming et al., 2005).

The concepts of resilience are highly connected to environmental issues and problems of social dilemma (such as poverty, famine, and food security). Furthermore, resilience is also related to other critical studies such as the spatial dimension of the scale of social process. Social vulnerability due to environmental degradation (or climate change in the context of this study) will force individuals and communities to adjust to the changing environment to release the stress on their livelihoods (Adger, 2000).

Resource dependency influences social resilience through the factor of social order, livelihood and stability, and dependency behavior which affects income stability, social stability and migration. The community depends on the resources and this promotes the economic activities that develop revenue for livelihoods, increase the variance of income and at the same time also cause risks for a person and for society itself. The community used the resources from ecosystems to conduct economic activities and this leads to a loss of resilience in the ecosystem and decreases its stability. This is because resource dependency raises risks due to the output's up-and-down cycles and the threat of technological innovation. Environmental variability also increases risks for the person who is resource dependent, especially in the case of agricultural activities, due to catastrophic events and also the dispersion of pests and disease. Without control, the scarcity of resources will have direct negative consequences on livelihoods and destroy the collective institutional resilience in common property management (Adger, 2000).

Stability from the point of view of economic aspects refers to livelihood security in discrepancy of income, institutions, and social infrastructure (Ruttan, 1999). The stability of social systems will benefit society through the development of technology and innovation and also good utilization of human capital (Hayami & Ruttan, 1985; Stern, 1995). Sustained economic growth and various economic connections cause the equitable distribution of assets among the public. At the individual level, income is an indicator that is able to explain stability, livelihood choices, and social investment at the household level. From the demographic point of view, migration is an indicator that is often used to assess social resilience. The diversification of activities will occur through people's circular and seasonal migration whereby they gain the remittance income that will be used for future consumption, such as investment in education or in agricultural capital (Adger, 2000).

The resilience theory promoted the idea of implementation of adaptation, learning, and self-organization in social-ecological systems to assess the ability to resist disturbance (Folke, 2006). Moreover, the resilience theory focuses on the elements of adaptive capacity and adaptive process which tolerate and deal with modifications that arise in the system. Adaptive capacity (also known as adaptability) determines people's capacity in a social-ecological system to build resilience through collective action (Berkes et al., 2003). Gallopin (2006) and Adger (2003) have also discussed the connection between resilience and adaptive capacity (capacity of response to vulnerability).

Studies on social-ecological resilience have three perspectives: social-ecological resilience could relate to the attraction capacity to the amount of trouble in a system while maintaining the state or domain of attraction; it could be accepted as the factor of the system's self-organization capability; and it could be accepted as the condition where the system is able to construct and boost the capacity of learning and adaptation. Risk assessment, risk valuation, and uncertainty could be included in the resilience and the system shifts study (Peterson et al., 2002). Furthermore, a vulnerable social-ecological system will lose resilience and result in loss of adaptability.

Adaptability in a social-ecological system refers to the adaptive capacity to react within the social area and also counter and figure ecosystem dynamics and change in the current situation (Berkes et al., 2003). On the other hand, adaptability has been described as the capacity of people in a social-ecological system to build resilience through collective action (Walker et al., 2004). Adaptability can be achieved through the adaptive management process where humans will react by adjusting to, and confronting, a change in natural resources. Policies, through adaptive management, will fulfill social goals and persistence change, and supply adaptation strategies. The element of transformation also takes into account the perspective of resilience. Transformability means the capacity of an individual to develop a new social-ecological system when ecological, political, social or economic conditions make the existing system indefensible (Walker et al., 2004). Thus, the resilience potential develops the observation and models to integrate actors and interest groups in adaptive management and learning of ecosystem processes.

2.3.8 Adaptation Theory

The IPCC TAR 2001, defined the adaptation to climate change as: 'the adjustment in ecological, social or economic system in response to observed or expected changes in climatic stimuli and their effects and impacts in order to alleviate adverse impacts of change or take advantage of new opportunities'. It is a continuous process comprising the flow of activities, actions, decisions, and attitudes which explain decisions in overall aspects of life and hence replicates social processes and standards.

Previous research has supplied various definitions of adaptation referring to the social perspective. Burton et al. (1992) indicated that adaptation could be a process of reduction of the adverse effects of climate on people's physical condition and welfare that help them benefit from the opportunities that their climatic environment provides. Smit (1993) defined adaptation as: 'an adjustment to improve the social and economic activities capability and decrease the vulnerability of climate-like current variability and catastrophic and extreme events'. Meanwhile, Smith and Lenhart (1996) defined adaptation as: 'an adjustment that comprised of behavior or economic structure that diminishes the vulnerability of society to changes in the climate system'. Watson, Zinyowera, and Moss (1996) added that adaptation can be classed according to the type of adjustment (passive, reactive or anticipatory) that is useful to refine the consequences of climate change. Adaptation can be spontaneous or planned adjustment that is applied to react to and predict variability, while the degree of practicing, processing or structuring this system is known as adaptability.

Howden et al. (2007) mentioned that adaptation evaluation is important in the application of effective management practices in mitigating possible climate impacts. Adaptation helps agriculture stakeholders make decisions about how to face the implications of climate change risk over the short term or long term. The short term adaptation strategy is able to benefit the long term strategy as it helps stakeholders determine the proper solutions to overcome climate change vulnerability in the future. Burton (1997) considers that adaptation is not capable of avoiding serious climate harm, but it is able to ease harm extensively. Thus, in the aquaculture sector, the adaptation process works to minimize the loss in biophysical aspects in farmers' environments and economy. Preparedness to adapt means farmers really perceive the possibility of severe climate harm to their farms.

Adaptation contributes to positive outcomes, whether in the short or long term. It is believed that a long term adaptation period would be able to affect the reliability of climate models (Burton, 1997; Howden et al., 2007). This argument is relevant because climate change events usually appear over a long period of time and continuously increase with time. However, an adaptation which takes longer imposes a high cost to act on. The timing of adaptation also influences the economic efficiency of adaptation actions.

Adaptation studies can be focused on climate change, change and variability or just on climate and reactions to the vulnerabilities or opportunities. They can relate to current (actual) or projected (anticipated) conditions, changes or consequences. In other words, the adaptation process is due to the sensitivity of systems to climate change risk. Studies can concentrate on individual, area, regional, and national scales or at the global level and production systems with different characteristics. Adaptation also involves differentiating who takes action and what is modified. Lastly, these elements focus to the procedure and structure of adaptation (Smit et al., 1999).

In defining clearly the concepts of adaptation, Smit et al. (1999) introduced a model that comprises four important criteria that need to be observed, namely: climate and related stimuli (adaptation to what?); system (who or what adapts?); types (how does adaptation occur?); and evaluation (how good is adaptation?). These four questions address the necessary fundamentals of adaptation by specifying phenomena due to climate characteristics and their relation to the system which adapts according to long-term changes in the means and norms, inter-annual or decadal variability and isolated extreme events or catastrophic weather conditions and vary from year to year. However, previous studies have identified three adaptation issues including: the existence of inconsistency in private and public agents; institutional interactions at different scales that do not follow the natural pattern dependent on the physical risk; and that adaptations across scales in ecological systems add complexity since different biological and ecosystem processes dominate at different levels (Adger et al., 2004).

Tol, Fankhauser, and Smith (1998) revealed that adaptation is the best action to reduce the negative impacts of climate. Adaptation has a link to climate change impact assessment and the fundamentals of vulnerability. Vulnerability to climate change is a factor in system sensitivity to adjust the climate and ability of system of adaptation to make the adjustment. Four assumptions are made about adaptation: it is slightly unrealistic; it is greatly influenced by the sign and magnitude of estimated impacts; its costs are rarely or usually unreported; and limited information is available to decision makers. However, a few adaptations also bring negative effects in some cases and may twist the increase of failures. Adaptation also necessitate complex behavioral, technological, and institutional adjustments by all communities (Tol et al., 2004).

Adger et al. (2004) advocate that adaptation works in three ways: it reduces the system's sensitivity to climate change; alters the system's exposure to climate change; and increases the system's resilience to cope with changes. Adaptive capacity indicates the producers' resilience in countenancing climate change risks, which can be identified through the producers' level of vulnerability. Adaptation models explain the behavior model of related decision makers, which will be positive when describing decisive actions or normative when recommending the way to act (Tol et al., 1998).

People, social, and economic sectors and activities form a system that manages or does not manage natural or ecological systems, practices, processes or systems' structures and they involve in the adaptation process. The system adaptability or vulnerability, as a component of adaptation, will be identified as the unit of analysis, exposure unit activity of interest or sensitive system (Carter, Parry, Harawasa, & Nishioka, 1994). The implementation of adaptation has been observed due to the adaptation process (whether reactive, anticipatory, spontaneous, or planned) and outcomes. It also takes into account processes modifying the system. Sensitivity, vulnerability, susceptibility, and resilience are among the elements that are able to determine adaptation and adaptability outlooks (Smit et al., 1999). Adaptation will be evaluated according to costs, benefits, equity, efficiency, urgency, and implementability (Smit et al., 1999). Adaptation is a beneficial process that can be applied to ease the burdens of the impacts of climate change.

Adaptation is autonomous and reactive if it happens in an uncontrolled natural system and planned and anticipatory if it is commenced by the public (Maciver & Dallmeier, 2000; Smit et al., 1999). Adaptation techniques that are individual actions or do not involve the intrusion of knowledgeable decision makers are called autonomous adaptation. Autonomous adaptation is reactive where it is implemented after the impacts of climate change. Tol et al. (1998) explained that autonomous adaptation shows the behavioral adjustments of human, animals, and plants with respect to climate change. Planned adaptation, by contrast, is executed by decision makers' collective action to create strategic actions in response to climate variability. Planned adaptation is reactive (like autonomous adaptation) and also pro-active if done before the climate vulnerability phenomena happen (Maciver & Dallmeier, 2000). Planned adaptation is recognized as conscious or purposeful adaptation, where governments or organizations organized strategic adaptation to predict or react to climate change (Tol et al., 1998).

Analogue methods (spatial and temporal analogue) are used to identify the method of adaptation. The spatial analogue concerns adaptations of society in different locations and climates to hold up a wide range of adaptation measures which may overlook the process and the cost of adaptation. Meanwhile, the temporal analogue is related to the adaptation of societies in one location being faced with severe past climate variability. This assessment is appropriate to identify autonomous adaptation but less relevant to recommend apologetic adaptations to decision makers (Tol et al., 1998).

Smit et al. (1999) stated that impact assessment and evaluation of response options are two major roles in basic adaptation. Adaptation requires the identification of forces of risk and impacts on systems. The variability in risk management entails decision makers really understanding the climate in order to select effective options. Maciver and Dallmeier (2000) posited that risk and opportunities assessment is important in alleviating the impacts of climate change uncertainty stress. Risk analysis should cover high-impact and low probability phenomena which elevate the impacts of climate change. Hence, there is a connection between a management unit's decision time and climate information. The technical effectiveness of adaptations and their adoption rate shows the consequences of adaptation.

Options for adaptation to climate change are developed based on the scale value of normal climate in the climate change period. The level of change was indicated by the change between two climatic periods and addresses the probabilities of current climate distributions (Burton, 1997) and major distress to aquaculture activities. Nevertheless, Smith et al. (1999) emphasized that objective, time-frame, temporal and spatial scope, effects, form, and performance are key factors that differentiate adaptations.

2.3.8.1 Adaptation evaluation methods

Reilly and Schimmelpfennig (1999) introduced two approaches for evaluating climate impact studies. The first approach is a structural model of the farming activities and the farmers' economic or management decisions based on theoretical specifications and evidence from controlled experiments. This needs sufficient structure and output detail in response to different conditions, known as detailed experiments. Detailed farm management allows direct modeling of the timing of operations, seed choices and decisions effects on cost and revenues. However, this approach may indicate that farmers do not operate as profit maximizers as the models fail to consider some of the factors that farmers take into account, such as risk, lack of immediate employment alternatives etc.

Another approach relies on the observed responses of producers and production to varying climates through spatial analogues, which provided some of the earliest estimates of potential effects. This approach applied statistical analysis of data across regions to separate climate from other factors. By so doing, researchers were able to explain production differences across regions and use the estimated statistical relationship to estimate climate change impacts (Reilly & Schimmelpfennig, 1999).

Another method to measure the impact of climate change is to predict time series behavior using cross section variation, known as ergonomic economics. However, for findings to be valid three assumptions must be met: variations over time and space must be equivalent; there are transitivity occurrences per set of exogenous conditions; and a few climatic variables capture all the relevant information about climate change and its impacts on agriculture (Reilly & Schimmelpfennig, 1999).

Jones (2001) used probability procedure in a semi-quantitative method to rank qualitative responses to the hazards and portray risk by calculating the level of probability due to impact risks. The probability calculation is based on changes in scale between two climatic periods; past and present. However, Pittock, Jones, and Mitchell (2001) have criticized this method, arguing that calculation of probabilities in prediction of future climate in socio-economic disciplines seemed tough to impossible. The model is not frequentist but Bayesian, where reference is made to prior knowledge or assumptions stated in the various models and input. Thus, a more accurate measurement of probability still needs to be developed. Furthermore, researchers believed that probabilities are useful in cultivating resilience and adaptive capacity.

Adger et al. (2004) discussed stated or revealed preferences for non-marketed goods based on reference points of non-sustainable and distorted priced marketed goods. The prices of trade goods which form the basis of valuations of the costs and benefits of non-traded goods are the prices that led to non-sustainable exploitation of resources in the first place. Meanwhile, Ngathou, Bukenya, and Chembezi (2005) note that the expected utility approach is useful in modeling behavior under risk. The utility theory explains the individuals' acceptance of risk and measures subjective values by taking advantage of an individual's perception of risk. According to the theory, decision makers are allowed to make decisions based on their subjective perception of probabilities. Furthermore, Goulder and Pizer (2006) suggest that the stated preference approach and contingent valuation method are the best techniques to evaluate the effects of climate change on non-market damage such as environmental degradation and loss of biodiversity. They also recommended the computable general equilibrium (CGE) model which is capable of indicating the connection between production input and output in a consistent direction of the economy. Integrated assessment models are also useful to measure cost efficiencies with the intention to relate cost to mitigation advantages.

2.3.8.2 Effective adaptation factors

This study focuses in depth on adaptation aspects as a strategy to face climate change impacts. Adaptation is focused on impact analysis with the possible involvement of society's ability to adapt, in order to comprehend the cost of climatic variability. The problem of climate change is tackled by accelerating the system's flexibility such that it can overcome climatic shocks and be ready to function.

Adaptation is a continuous practice in part of good risk management. The aim of adaptation is to adjust and reduce risks and maximize social welfare. Adger et al. (2004) assert that the accomplishment of adaptation refers to the achievement of the objectives and goals of adaptation. The measurement of accomplishment is based on a clear definition of adaptation and assessment of who adapts to the risks of climate change, and why. Adaptation needs co-operative action among economic actors, governments and individuals. Adjustment contributes to social and ecological change due to numerous factors. Synergy between mitigation, adaptation and valuable or non-valuable cost or benefit analysis was needed to maximize social welfare. Adaptation is pushed by economic well-being, protection, and safety development. These are hierarchical structures that interact with each other when adaptation is implemented.

Constraints to the individual action arise because of regulatory structures, property rights, and social norms with rules.

Adaptation cost is one of the important elements in measuring the effectiveness of adaptation. The assessment of the economic efficiency of adaptation requires the distribution of costs and benefits of the actions, the costs and benefits of changes in those goods that cannot be expressed in market values and timing of adaptation options (Adger et al., 2004). Tol et al. (1998) state that climate change costs follow the transaction costs coupled with alteration of the system to a new equilibrium. Meanwhile, residual cost refers to the costs of adaptation and of climate outside adaptation. The economic cost of climate change evaluation is a combination of adaptation cost and residual cost. This combination resulted in the aggregate damage-cum-adaptation. Burton (1997) reported that the cost of preventing disasters due to climate change is minimal compared to the cost of recovery after a catastrophe. However, the stakeholders' experience, time horizon, and risk taking tendency motivate these people to contribute to adaptation cost.

Fankhauser, Smith, and Tol (1999) added that successful adaptation is determined by timely recognition where the reliable, detailed information and capability to process information could be accessed. Moreover, successful adaptation depends on the proper incentives to enable the economic agents to implement government decisions. Ability to adapt is also one of the characteristics that affect the success of adaptation.

The key accomplishment of adaptation is effectiveness of meeting objectives. Therefore, the principle of policy could be used to evaluate the existence of accountability and effective, efficient and legitimate action that complements sustainability. The economic efficiencies were derived from the public agents' decision-making to achieve the best value in implementing objectives. Effectiveness levels could be measured by reducing impacts and exposure to them or reducing risk and avoiding danger and promoting security. Effectiveness levels were also influenced by the time element. Key indicators of an adaptation's effectiveness are that it is robust to uncertainty and flexibility or has the ability to change in response to altered circumstances. Effectiveness also depends on the spatial and temporal scale (Adger et al., 2004).

However, two considerations that reject this assumption of effectiveness were that the action might be successful in one target objective, but it caused externalities at other spatial and temporal scales or it may be successful in the short term but less successful over the long term. Second, the adaptation may affect the adapting agents but cause negative externalities with increasing impacts to non-adapting persons. Successful adaptation depends on the spatial and temporal scale and is not easily evaluated due to the stated objectives of the individual adaptors (Adger et al., 2004).

Equity, legitimacy, and economic efficiency determine the effectiveness of adaptation to climate change. Equitable adaptations are measured from the outcome perspective (win-lose situation) and who decides on the adaptation to make. Equity is the main aspect that researchers rarely touch on in their studies to the impacts of climate change (Tol et al., 2004). Equity refers to the level of decision-making in adapting to climate change. Equity in outcome means the identification of who gains or loses from the impacts of adaptation policy. Equity is important for instrumental reasons; an inequitable development undermines the potential for future welfare gains and developments that lack legitimacy have less chance of full implementation (Adger et al., 2004). Legitimacy is a basic concept in entitlement theory. Legitimacy explains the participants' and non-participants' acceptance of the decision. Economic efficiencies were derived from public agents' decision-making to seize the best value in implementing objectives. The decisions made and the underlying distributions of power influence the legitimacy of the decisions. Legitimacy and trust are also scale dependent (Adger et al., 2004).

Capability to adapt to short term climate variability with the higher revenues and adjusted systems results in an economically efficient response to climate change (Adger et al., 2004). Furthermore, the practical way to adapt to future climate is by developing adaptation to climate variability events and reducing exposure to overwhelming events (Burton, 1997). Reilly and Schimmelpfennig (1999) add that a fundamental of climate impact studies is to measure the impact on production that also contributes to an evaluation of the impacts on society and the economy. Therefore, in high-risk production investment decisions, Fankhauser et al. (1999) emphasized the importance of measuring adaptation time. The optimal investment timing shows that it is better to defer investment as long as the advantages of deferred exceed the associated costs of climate change damage. Early adaptation is significant for long term investment. Uncertainty and extreme weather events may obscure timing decisions because extreme climatic occurrences could be more rapid than climate means predict.

Fankhauser et al. (1999) explained that one of the ways to adapt to climate change is by adjusting the capital stock. Climate-sensitive capital investment requires the future climate to be forecasted as the venture needs to react with the faster-changing weather factors. Investors also should consider whether capital is valuable when the cost of non-replacement exceeds the advantages of delayed investment costs. The economic duration and technical duration will be less due to the increment of delay cost due to climate change. This total economic evaluation is an appropriate technique to use to assess aquaculture development as it engages with non-market or incompletely marketed resources. The sustainability of aquaculture development could be improved by selecting the best species to culture (i.e. socially and economically adequate); usage of technology which is suitable for aquaculture; practicing environmentally friendly culture techniques and building co-operative arrangements to seize the benefits (Tisdell, 1999).

Howden et al. (2007) consider that the climate change risk policy should synchronize with structural adjustments to the risk. The analysis will influence governments to decide for or against investment in present and future strategic decisions. Furthermore, farmers would be able to alleviate production failures by implementing best management practices, diversification or self-insurance. Diversification in adapting to production risks includes: Farming different species at one time and vertical integration into other activities related to aquaculture and that involve off-income (Beach & Viator, 2008). The small-scale and aquaculture-dependent farmer was advised to diversify his livelihood and find alternative ways to support himself in order to adapt to vulnerability. Diversification of livelihood helps reduce poverty, recover farmers' resource accessibility and encourage farmers' adaptive capacity to cope with risks (Baran, Schwartz, & Kura, 2009).

The study of climate change necessitates careful interpretation to avoid mischaracterizing the results. Adoption of technology is one of the measurements to identify the effectiveness of adaptation. Appropriate technology used according to climate conditions is able to result in successful adaptive responses. The new or adapted aquaculture technology helps improve the farming systems and management and prepare the farmers for successful adaptation (WorldFish, 2007b). Responses to adaptation were characterized by training and education; identification of present vulnerabilities, agricultural research, studies on genetic resources and intellectual property rights protection, agricultural extension, food security, marketing and distribution systems, and commodity and resource policy reform (Reilly & Schimmelpfennig, 1999).

Howden et al. (2007) explained that climate risk assessment and response strategies devices must consider the uncertainty in causal socio-economic, political, and technological drivers and how they affect the climate system. Adaptation also needs systematic changes in resource allocation. Plans for adaptation should include consideration of climate variability, market dynamics, and specific policy domains. However, adaptation has to confront the involvement of comprehensive and dynamic policy approaches over different issues and at different scales and from the farmers up to the market. It is also a merged or collective action engaging farmers, agribusiness and policy makers, leveraging off substantial collective knowledge concerning agricultural systems, and focusing on values of importance to stakeholders. Adaptation failure or mal-adaptation can happen due to weaknesses in implementation actions in adapting. However, it could be a dynamic learning process and could be treated with careful consideration of external drivers, cross-sectoral, and cross-regional impact analysis in specific case studies (Maciver & Dallmeier, 2000).

2.3.9 Sustainable Livelihood Approach (SLA) model

The SLA is a general framework that combines the role of micro and macro units of the community to achieve sustainable livelihood outcomes. The term sustainable livelihood was introduced in the 1990s, and Chambers and Conway verified its meaning in 1991. This definition has four main aspects: the means of livelihood (people and their capabilities) means of living (including income, food, and asset); tangible and intangible assets that people can maintain and access; environmental sustainability; and social sustainability. Environmental sustainability can be achieved if the resources on which livelihoods depend can be preserved and improved by generating value for them and for other livelihoods. Social sustainability means people's capability to deal with, and recuperate from the stress and shocks now and in the future.

The sustainable livelihood approach is useful to more completely understand the vulnerability impacts of climate change. The sustainable livelihood assets or capital is adapted from the asset-based approach and cover in scope the community system and the socio-economic and physical environment. An understanding of people's livelihoods makes it easy to understand how climate change impacts will affect people, how they respond with the resources they have and how these conditions can be reflected and built upon for successful adaptation strategies. Chambers and Conway noted in 1991 that; "the livelihoods are sustainable if they can cope with and recover from stress and shocks, maintain or enhance the livelihoods capabilities and assets, and provide sustainable livelihood opportunities for the next generation, and contribute net benefits to other livelihoods at the local and global levels and in the short and long term."

The original work on the sustainable livelihood approach comprised several approaches and was developed by various organizations and agencies. However, this study only applies part of the framework, concentrating on the relationship between the climate change impacts (vulnerability context), producer's assets and capital (social and economic aspect), and the potential livelihood strategy options (adaptation) by producers in aquaculture activities. Thus, this study will only focus on a single group of aquaculture producers (and not a community) in Sarawak that owned or used the natural resources for production and to increase their income. The components of the original framework that will be studied and analyzed are the aspect of vulnerability context, livelihood assets or capital, and livelihood strategy (adaptation strategy) to identify the producers' potential autonomous adaptation options. Due to data constraints the institutions and processes (IPs) aspects that were included in the former SLA model will not be directly included, however, the study will highlight the policies that influence support for, and improvement of the sustainability of producers' livelihoods. This will help in assessing the aquaculture producers' limitations, capabilities, and roles that influence the selection of the best solution for autonomous adaptation to climate change.

The Department for International Development (DFID) in the United Kingdom published the Sustainable Livelihoods Guidance Sheets in 1999. The vulnerability context in the sustainable livelihood approach concerns people unable to control the external environmental factors that are beyond their limits. Thus, shocks are an extreme, sudden, and unexpected variability in producers' livelihoods through disaster and disease. Meanwhile, seasonality refers to seasonal weather and other factors. Climate change impact is classified as vulnerability context in the aquaculture sector, where risk presents shocks to farmers and seasonality due to climate events such as floods and drought cause production losses. Two factors that have significantly contributed shocks are the impacts of climate change (natural shocks) and livestock health shocks.

The livelihood assets or capital identifies with the resources the producers own and transform to gain benefits and increased income and to profit from the production for their livelihood. Basically, the producers can access and develop capital assets belonging to the following five groups: human, natural, financial, physical, and social. However, this study will select and examine only four of the five groups of livelihood assets: Human, natural, financial, and physical capital. Human capital covers the aquaculture producers' skills, experiences, and knowledge. Natural capital represents the environmental qualities that affect the producers' lives, production, and income. Financial capital represents the producers' income (on-farm and off-farm income, savings, loans, and social schemes). Physical capital comprises the infrastructure focused on the physical environment that is needed for basic needs and the producers' good, i.e. tools and equipment for production and for a productive livelihood.

The livelihood strategies include intensification and extensification activities, livelihood diversification, and migration (Scoones, 1998). However, in the case of this study, the researcher considers adaptation as the livelihood strategy. Reid and Huq (2005) verified that the community in vulnerable surroundings tries to learn and adjust to the foreseeable changes in its adaptation strategy. The household and community usually do the best as they can to adapt to the climate change impacts and threats and will search for chances in assets, technologies and livelihood strategies, and adjust to the presence of hazards. However, the ways they adapt differ from each other and depend on their capacity and capabilities. Thus, households owning few assets are those who have to struggle the most in adapting to the impacts of climate change (Heltberg et al., 2009).

2.4 Conceptual Framework

This study is conceptualized based on five main studies; the Vulnerability Model proposed by Allison and Horemans (2006) and Allison et al. (2009); the Fussel and Klein (2006) study framework of vulnerability and adaptation; and Chambers and

Conway's (1991) and DFID's (1999) Sustainable Livelihood Approach (SLA) framework to identify the linkages between the vulnerability context and livelihood assets in determining vulnerability and adaptation strategies to climate change in Sarawak's aquaculture sector. Fussel and Klein's (2006) vulnerability framework involved the use of both climatic and non-climatic indicators to assess the vulnerability level and adaptive capacity or adaptation to climate change risk. This study assesses vulnerability by focusing on the vulnerable system and multiple stresses. The sensitivity of the system to climatic changes and exposure was affected by non-climatic factors such as environmental, economic, social, demographic, technological, and political factors.

Based on Vulnerability Model (Allison & Horemans, 2006; Allison et al., 2009), the theory of vulnerability encompasses two categories of vulnerability: Biophysical vulnerability and socio-economic vulnerability. Biophysical vulnerability concentrates on the effects of climate change on aquaculture production. Socio-economic vulnerability explains the aquaculture farmers' sensitivity to the climate change risks that affect their livelihoods. The adaptive capacity measures the aquaculture farmers' ability to be sensitive to the changes and risks and to cope with the hazards.

Fussel and Klein's (2006) vulnerability framework involved the use of both climatic and non-climatic indicators to assess the vulnerability level and adaptive capacity or adaptation to climate change risk. This study assesses vulnerability by focusing on the vulnerable system and multiple stresses. The sensitivity of the system to climatic changes and exposure were affected by non-climatic factors such as environmental, economic, social, demographic, technological, and political factors. According to resilience theory, if the farmers' resilience increases, their adaptive capacity will also increase. The previous discussion on resilience covered more on the adaptive capacity or adaptation concepts of this study.

Jones (2001) and Michaelowa (2001) indicated the best adaptation strategies to climate change. Jones and Michaelowa suggested that the assessment should cover the biophysical (environment) and socio-economic systems where both are known as the exposure unit of vulnerability to climate change. Thus, this study focuses on anassessment of vulnerability in terms of biophysical and socio-economic factors due to the impacts of climate change on aquaculture production and seeks to identify potential adaptation strategies in the aquaculture sector. Figure 2.2 lays out the conceptual framework followed in this study.

The framework includes components of exposure and sensitivity in order to measure the potential impacts of climate change on the aquaculture sector in Sarawak. Exposure (E) refers to the influence of climate that causes physical effects on the aquaculture sector (Adger, 2000). Thus, the results of the biophysical effects of climate change in the aquaculture sector will represent the level of exposure of aquaculture production to climate change risk (Cutter, 1996; Jones, 2000; Kasperson & Kasperson, 2001; Klein & Nicholls, 1999; Michaelowa, 2001; Sarewitz, Pielke, & Keykhah, 2003). The exposure will be measured using meteorological information or climate indicators such as temperature (Allison et al., 2009), rainfall, humidity, and sunlight intensity. In addition, the size of aquaculture farms (in ha) for ponds and (in m^2) for cages will be included as a measurement of biophysical effects where the data show the pattern of land-use for aquaculture activities.

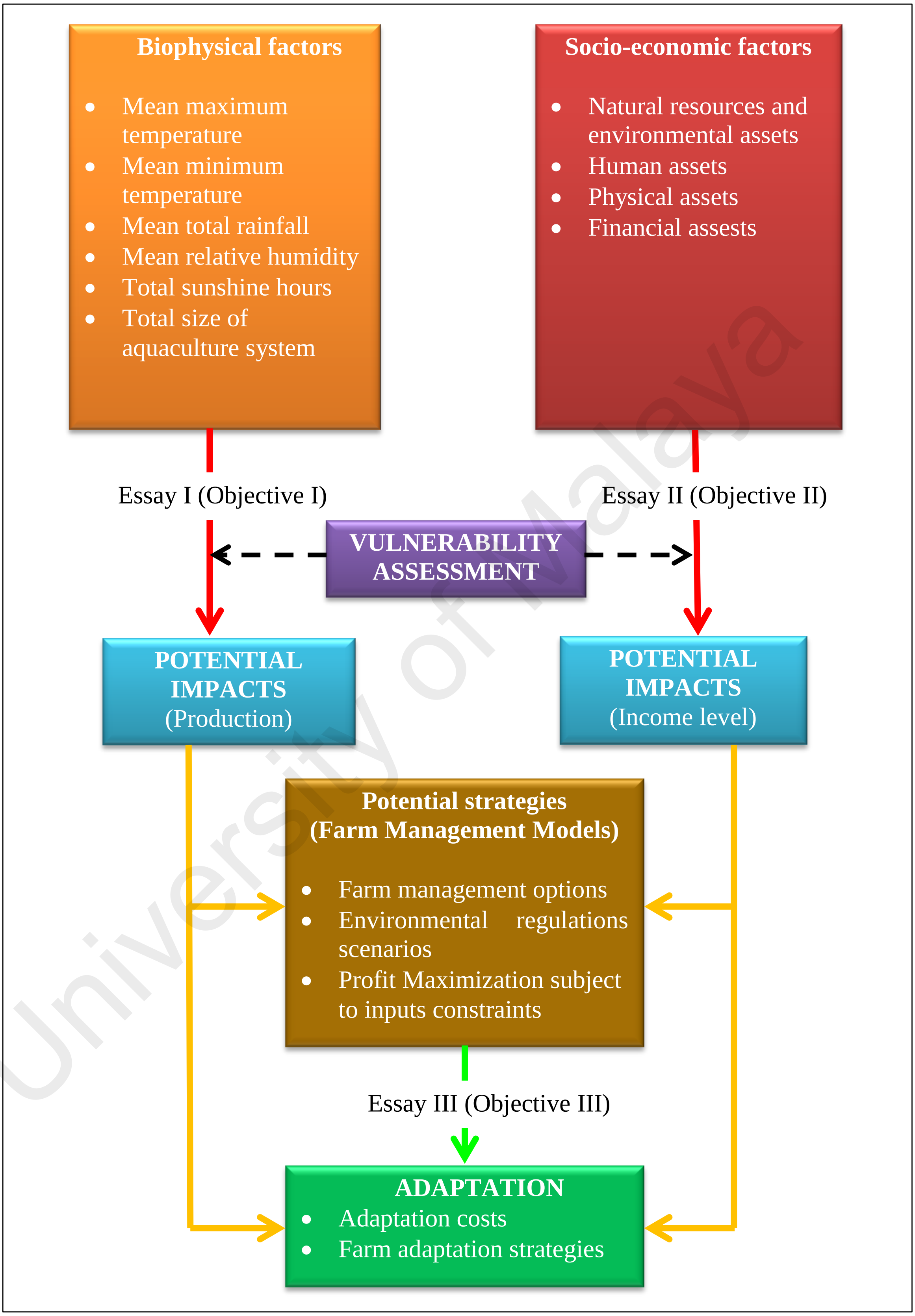

Figure 2.2: Conceptual framework

Note: Adapted from Vulnerability Model (Allison & Horemans, 2006; Allison, et al., 2009)

The biophysical factors will be represented by the climate variability assessment (Burton, 1997; Howden et al., 2007). According to Molua (2002), climate extremes and disease during climate fluctuation events will reduce production yields. Siwar et al. (2009), Tisdell (2001), and Tisdell and Leung (1999) revealed similar findings. The climate variability assessment will identify the change in several climatic variables such as rainfall, temperature, and humidity, that effect production. This can be done through identifying the probabilities of climate distributions (Burton, 1997) or the changes in scale between past and present climatic periods (Jones, 2001). Probabilities in the prediction of climate in the socio-economic discipline seemed tough to impossible but are useful to cultivate resilience and adaptive capacity, as mentioned by Pittock et al. (2001).

Water quality assessment is one of the biophysical factors that will be examined in this study. Water quality assessment will be used to identify the occurrence of water degradation, stratification or eutrophication due to climatic variability and the aquaculture activities' effects on the water (Lee, Ting, & Ling, 2002; Miod, Ling, Lee, Norhadi, & Emang, 2009). The valuation of total production will also help to identify the biophysical vulnerability. Moreover, the number of species affected by disease during production activities enables us to recognize the incidence of biophysical activities. Furthermore, the economic and management aspects of production are greatly influenced by the environmental aspects. If the environment degrades or the climate changes increase the production will decrease due to natural risks (FAO, 2008a).

The sensitivity (S) generally means the degree of climate change risk effects on biophysical, social, and economic conditions (Adger, 1998, 2000; Allison et al., 2009; Fussel, 2007a; Kelly & Adger, 1999, 2000). In this context, sensitivity was represented by the effects of climate change on the aquaculture farmers' socio-economic aspects where it was assumed that the climate change effects on biophysical factors would directly affect the farmers' socio-economic aspects as aquaculture dependence. This adapted conceptual framework differed from the original model in terms of the measurement of sensitivity where the study concerns and concentrates on the farmers' socio-economic aspects as individual dependence instead of dependence from a national or macro level economic perspective. Meanwhile, the adaptive capacity measures the aquaculture farmers' capability to be sensitive to the changes and risks to cope with the hazards.

In understanding and measuring sensitivity to climate change, the entitlement theory (Sen, 1984) coupled with the components of the SLA framework (DFID, 1999) was adapted to present the indicators appropriate to measure socio-economic vulnerability. The entitlement theory and SLA framework verified that the assets owned by farmers will influence the farmers' vulnerability levels to climate change risks. The more assets a household owns or is entitled to, the less the households' level of vulnerability to exposure to risks or hazards. The values of equity, poverty, and marginality as indicators of vulnerability were hard to measure quantitatively.

Thus, the SLA framework-proposed asset based approach (natural capital, human capital, physical capital, financial capital, and social capital) can help to identify assets as proxies to these indicators (DFID, 1999). However, indicators from only four components of livelihood assets (independent variables), excluding social assets, will be used to measure the sensitivity and socio-economic vulnerability of aquaculture farmers. The indicators for sensitivity measurements were based on socio-economic assessment of the farmers' assets, such as education, gender, number of family members, farm years' of operation, working hours per week, non-aquaculture income, the variable costs of production, number of production losses in respective years, and consumption of technology. The climate risk variables comprise farmers' perceptions of the types of climate risks that had influenced their production (Bard & Barry, 2000; Dwyer et al., 2004). These variables comprise water quality risks such as an increase or decrease in pH and dissolved oxygen, climatic risks such as rain, temperature increases or decreased, catastrophic events such as droughts, floods, massive wave, and disease threats.

The adaptive capacity or potential adaptation strategy used by aquaculture farmers in Sarawak to cope with climate change risks was measured by quantifying the potential abatement costs and resource allocation using information from farm activities and related farm costs. In production theory, the changes to farmers' welfare due to the effects of climate change on production can be identified through the farms' decisions on production and risk (Mcconnell & Bockstael, 2005). The farm decision variables include aquaculture yields, output price, fish feed cost, labor used, feed wasted, land, labor, and feeding costs. There was also an indication that profit can be used to measure the impacts of climate change on farms. Furthermore, quantification of the potential abatement costs can identify changes in producer surplus at different levels of climate change impacts as the producer surplus represents the producers' welfare (Vincent, 2008). In conducting farm decision assessments, EUT was applied to assess the individual decisions under risk with a probability based estimation as the risk management tool (Lempert et al., 2004). The farmer's risk attitude can be identified through the EUT. Tompkins and Adger (2005) revealed that the farmer's attitude to risk and uncertainty were important in achieving effective adaptation. The farmer's attitudes lead to strong capacity building in providing the best adaptation options for their production.

2.5 Conclusions

This chapter had emphasized the theories underpinning the assessment of climate change impacts on the biophysical and socio-economic vulnerability and potential adaptation strategies to cope with the climate change risks in the aquaculture sector. The initial discussion on the progression of environmental economics theory helps one understand the foundations of the research as well as the development of the environmental economics theory to the economics of climate change theory.

This study has been developed based on a combination of six major theories (the theory of production, the theory of the firm, externalities and market failure, the EUT and risk, the theory of vulnerability, and the theory of adaptation. These include the classical and neoclassical theories of economics and the economics of climate change. Further discussions of these main theories have been supported by the theory of entitlement and theory of resilience. Then, Fussel and Klein’s (2006) vulnerability and adaptation framework and DFID’s (1999) SLA model were adapted, combined, and constructed in this study to connect all the theories and conceptualize the framework of this study.

Reviews of the relevant literature have been ordered according to the objectives of the study and are discussed further in chapters 3 to 5 in keeping with this study’s is organized following the essay based approach. These theories will be tested, compared and further discussed in the following chapters, which consider whether they significantly support the empirical findings of the study.

CHAPTER 3: A BIOPHYSICAL VULNERABILITY ASSESSMENT OF CLIMATE CHANGE AND AQUACULTURE PRODUCTION IN SARAWAK

3.1 Introduction

Fish is the main protein source for the majority of households all over the world. The demand for fish for food products for daily consumption in almost all countries in the world, including Malaysia, keeps on increasing. Therefore, enhancing sustainable aquaculture production growth is the major problem that fish farmers in many countries need to face. The major factors ensuring the aquaculture sustainability include the financial, technical, market, human, and stakeholder factors. These factors are manageable and farmers can control them. The environmental factors, however, are uncontrolled factors with high significant impacts on aquaculture sustainability. Externalities and the environmental variability may lead to aquaculture production failures.

Ecological factors, both abiotic and biotic, have a significant influence on the sustainable growth of aquaculture. However, the global environmental issue of climate change has disturbed the stability of the biophysical factors important in providing quality ecological systems for aquaculture production. Climate change threatens to change the biophysical factors and modify the normal ecological patterns that support fish growth (Tidwell et al., 1999).

This study concerns the impacts of climate change on aquaculture production. The study focuses on assessing Sarawak's aquaculture sector development biophysical vulnerability due to climate change from the economic point of view, including both the macroeconomic and microeconomic viewpoints. The study attempts first to understand the biophysical factors’ effects that constitute physical and ecological constraints on aquaculture production in Sarawak and the relationship between each effect and aquaculture production, based on macroeconomic data assessment. Six relationships will be identified:

1) the relationship between mean maximum temperature and aquaculture production
2) the relationship between mean minimum temperature and aquaculture production
3) the relationship between mean percentage relative humidity and aquaculture production
4) the relationship between mean total rainfall and aquaculture production
5) the relationship between total sunshine hours and aquaculture production
6) the relationship between the total size of aquaculture ponds or cages and aquaculture production

The biophysical vulnerability assessment based on microeconomic data along with the socio-economic vulnerability assessment will be covered in chapter 4. A clear understanding of the relationship between the biophysical aspects of climate change and the production of the aquaculture sector will also provide further evidence for the socio-economic vulnerability among producers with limited resources.

3.2 Biophysical Vulnerabilities of Climate Change on Aquaculture

The IPCC TAR (2001) defined biophysical vulnerability as a function of hazard, exposure, and sensitivity. The term ‘biophysical’ refers to the physical components with hazards and it is a first order physical and biological impacts or social component with the property in affected systems that acts to reduce the damage from impacts. Biophysical vulnerability concentrates on the impacts of hazards that is, the amount of damage in a system in an encounter with a hazard (McCarthy, Canziani, Leary, Dokken,

& White, 2001). The meaning of biophysical vulnerability varies and Blaikie et al. (1994) elaborated biophysical vulnerability as the measure of hazards or exposure. Subsequently, Brooks (2003) advocated that biophysical vulnerability results of harms due to the interaction of hazards with social vulnerability. Nevertheless, Fussel (2007a) has defined biophysical vulnerability as the measurement of climate impacts on destruction or understanding the climatic situation in one place with the biophysical impacts assessment of climate change; and related to system properties studied by physical sciences.

Fewer studies have looked at biophysical vulnerability from the socio-economic context and adaptation in the fisheries sector. A study of the biophysical conditions helps in defining vulnerability and its assessment and assists in the explanation of environmental risk (Liverman, 2001). Furthermore, the combination of risk-based and vulnerability-based approaches enables us to identify the various potential future threats from the impacts of climate change and non-climate hazards (Brooks, 2003).

Biophysical vulnerabilities due to climate change events such as severe rainfall deficits, drought and flood events, extreme temperatures, and diseases harm the population. Such environmental risks are the major factors influencing the sustainability of aquaculture production. According to Westlund et al. (2007), risk gathers exposure, which affect people and property and causes vulnerability to the hazard. Production risk increases due to the system's vulnerability to volatile weather features that affect livestock and crops' physical yields, and the disease outbreaks and infections in agriculture activities (Harwood et al., 1999; Westlund et al., 2007). It also harms socio-economic development and raises stress levels, especially as regards food demand and supply and also producers' income levels. Thus, climate change is an environmental risk and has been classified as an involuntary risk of exposure (pathways between a source of damage and the affected population or resource) to an environmental hazard (source of damage or negative externality) (Thomas & Callan, 2007).

The study of biophysical vulnerability assessment in understanding and resolving the failure of food security measures has been covered by many researchers from different aspects of population growth (Liverman, 2001). Previous studies have taken two types of approaches to tackle vulnerability problems: the direct method used to outline the relationship of the physical change (climate variability) to yield; and the identification of the consequences for the economy and society. The adjoint method measures the sensitivity of exposure unit to climate change. Nevertheless, demographic variables are among the important variables that need to be assessed in order to identify the degree of biophysical vulnerability that people suffer. Through biophysical assessment, changes in the physical environment could be identified.

Two types of biophysical vulnerability study have been identified in the context of aquaculture. The first, exemplified by Barange and Perry's (2009) study, mainly on explanations from the scientific perspective. The second includes the combination of biophysical with the socio-economic impacts (Daw et al., 2009). Bryant et al. (2000) follow Barange and Perry (2009) by verifying three ways to model the biophysical vulnerability assessment in the Canadian agriculture sector. The first model concentrates on the agro-climatic properties (the study used different models with different assumptions according to regional climate variations). The second modeling practice focused on crop development and yields. Fluctuations in agricultural productivity were assessed according to the climate variability over a certain period but this modeling practice was used less in evaluating the farmers' adaptive behavior. The third modeling practice covered the assessment of land and regional production potential. The potential of agriculture to increase or decrease in productivity was identified based on the modification of agricultural activity patterns under conditions of climate change. Salim and Islam (2010) addressed the effects of climate change on agricultural productivity. However, it is difficult to quantify the climate change conditions so different proxies can be used to present the climate change variables, including weather factors.

3.3 Biophysical Vulnerability Factors and the Impacts on Aquaculture Production

Maintenance of sustainable growth and the demand for aquaculture production are great challenges currently faced by fish farmers in many countries in the world including Malaysia. Furthermore, of the factors that influence aquaculture development in Malaysia (including financial, technical, market, human, and stakeholder factors) (Idris, Shaffril, D'Silva, & Man, 2013), environmental risks such as climate change are among the crucial problems and major threats to the fisheries sector, which is sensitive to, and directly affected by uneven or severely changing climatic patterns.

Environmental factors determine the sustainability of aquaculture production; a suitable atmosphere for aquaculture activities will increase fish survival, growth, and reproduction (Sungan, 2001). Aquaculture activities are influenced by the hydrological processes in rivers and lakes and oceanographic processes in the case of marine activities. Fishes are poikilotherm species and very sensitive to environmental change. The IPCC Fourth Assessment Report [FAR] (IPCC, 2007) indicated that climate change has heightened the risks to aquatic systems as it has had an uncertain effect on the acidification of oceanic water, coral bleaching, uneven distribution and timing of freshwater flows, and diminished coastal wetlands. Climate change has direct effects on aquaculture as many climatic factors influence fish growth. The impacts of climate change on aquaculture production differed due to location or region, aquaculture practice system, space, time, size, and changeability (De Silva & Soto, 2009) and the physical impacts of climate change differ from one place to another and their effects on humans and the environment also vary (World Bank, 2010).

Climate change hazards affect worldwide aquaculture production, although the production is expected to grow due to the demand for fish for consumption. Humans and the environment have to acclimatize to ecosystem pressures and failures, biodiversity degradation, variations in the length of the growing season, coastal erosion and aquifer salinization, river and sea water acidification, and also uneven series of pests and diseases threats. Climate change has contributed to climate variability, such as rising temperatures, a rise in sea level, exposure to ultraviolet radiation, unbalanced rainfall patterns, and severe weather events (Akegbejo-Samsons, 2009; CICS, 2000). Brander (2007) considers the drivers of climate change that threaten aquaculture activities to include pressures from temperature changes, oxygen demand and decreased pH, alterations in, and uncertainty of water supply, severe climatic events, the regularity activities of disease outbreaks and toxicity, a rise in sea level, and the uncertainty of fish supply due to capture for aquaculture feeds. Ficke, Myrick, and Hansen (2007) and Handisyde et al. (2006) also emphasized the impacts of these climatic factors on the aquaculture sector. Other climate change risks to the aquaculture sector include changes in humidity and sunlight intensity, oceanographic factors, the modification of hydrological processes causing changes in dissolved oxygen in water and pH (De Silva & Soto, 2009), floods and precipitation, drought events, and water stress. These risks affect production in that they diminish fish growth rates and cause the fish to become sluggish and extremely susceptible to disease which then becomes a major cause of fish death (Hambal et al., 1994).

Temperature is the major common climatic factor that influences fish survival and growth. Fish species differ in their water temperature tolerance ranges. Warmer-water species grow well at 20°C and above or between 23.9°C - 32.2°C; cool water species at 18.3°C – 23.9°C; while cold-water species tolerate lower temperatures of 12.8°C - 18.3°C (Boyd & Pine, 1981; Swann, 1997). Temperature affects fish metabolic rate and growth and fisheries distributions. When growth rates increase the feeding pattern will increase with an increase in temperature (Johnston et al., 2009). The optimal tolerance limits or upper and lower fatal temperatures differ according to fish species. The spatial distribution of aquaculture species is influenced by temperature variability due to climate change. In brackish water systems, climate change usually affects salinity and temperature and exploiting the aquaculture growth with the uneven environments (De Silva & Soto, 2009).

High temperatures in inland water surpass the temperature level suitable for cultivated species (World Bank, 2010), increase water stratification and reduce production. Rising temperatures cause oxygen depletion that encourages the growth of algal blooms that release toxins into the water and result in fish death. The 2^{o}C increase in temperature above preindustrial levels is another cause of water stress (World Bank, 2010) and has also caused a rise in sea level due to the melting of ice (Ong, 2001). Fish growth rates are also reduced due to a rise in the metabolic rate in line with temperature, causing feeding insufficiency (Akegbejo-Samsons, 2009) and causing disease to spread to the cultured species (World Bank, 2010). The fish will be more resilient and resistant to disease in the temperature range that is appropriate for the species (CICS, 2000). An example from aquaculture production in Mekong Delta shows that the cultured fish are threatened by inadequate saline tolerance because of the sea level rise, frequent severe storms, and saltwater intrusion into the main river deltas (World Bank, 2010).

Aquaculture species are exposed to the risk of disease when water availability is low and there is a temperature imbalance in the aquaculture surroundings (Ficke et al., 2007; Johnston et al., 2009). The temperature increase towards the limits of tolerance for the species causes stress so the fish become more susceptible to diseases and attack by parasites (Boyd & Pine, 1981). In Norway warming water due to climate change has influenced the frequency and intensity of disease outbreaks in the aquaculture sector (Schjolden, 2004).

Air humidity significantly affects the levels of evaporation in aquaculture ponds and cages. As the degree of humidity increases, evaporation decreases. This will influence the moisture levels in the cultured species and the volume of fish food and chemicals required for aquaculture (Kutty, 1987). An increase in mean relative humidity will result in high expenditures on maintenance and high management costs for aquaculture production and thus contribute to lowering farmers' returns from aquaculture.

Sunshine is important to aquaculture as it supplies light and effect water turbidity that influences the fishes' food intake. The higher the water turbidity, the lower the water temperature and the less the sunlight that penetrates the pond water, causing pond vegetation to decrease (Aquaculture, 2003). Insufficient light intensity in aquaculture areas has an effect on aquatic organisms, the food chain and the final returns from fish production (Tawang, Ahmad, & Abdullah, 2002).

The dissolved oxygen contained in water is influenced by water temperature, stocking rates of fish in ponds or cages, water salinity, the amount of aquatic vegetation, and the number of organisms in the ponds or near the cages. Furthermore, phytoplankton and zooplankton blooms limit the photosynthetic process that produces oxygen in water. Variable weather, such as a sequence of warm, then cloudy then windless days, can cause dissolved oxygen levels to decrease too. Meanwhile, water stratification leads to a drop in dissolved oxygen levels at the bottom of ponds (Aquaculture, 2003).

Another impact of climate change on aquaculture production is a change in water pH. During the day, the pH of the water increases as carbon dioxide is absorbed due to photosynthesis. At night the pH decreases with the increase in carbon dioxide due to the respiration of water organisms. Sub-optimal water pH levels have similar impacts to those of increased water temperature: increased vulnerability of fish to disease, slow fish growth rates and a decrease in production. The increase in pH and temperature in water will increase the level of ammonium ions in the water and cause ammonia in water to reach toxic levels.

The dry seasons that result in droughts lead to water stress problems for aquaculture activities, especially in Lawas and Limbang, Sarawak. During droughts the water quality deteriorates due to a decrease in water availability and slower rates of flow in rivers (Handisyde et al., 2006). Small increases in water temperature due to hot weather affects fish growth rates and large increases may increase the risk of water stratification - a major cause of fish deaths. Logging activities near rivers result in the discharge of muddy water into the rivers during the rainy season and cause sedimentation so that the river becomes shallower during periods of drought. Thus, farmers have to shift their cages far away from river banks in order to access good quality water. Moreover, drought causes the oxygen in the water to decrease and changes the normal physiology of the fish.

Long rainy seasons lead to salinity changes, especially in brackish water pond aquaculture. Regular rain, coupled with storm surges and high waves, will lead to flood events. Floods are also caused by increases in the intensity of the monsoon and increase inter-annual variability. Changes in water salinity during floods will encourage the occurrence of disease and predator attacks. Moreover, farmers will bear higher capital costs and major losses as a result of structural damage and escape of stock (Handisyde et al., 2006).

Ocean acidification, habitat damage, changes in oceanography, disturbance to precipitation patterns, and lack of availability of freshwater may increase probabilities of disease outbreaks that cause mass fish mortality and such occurrences thus affect marine and freshwater fisheries and aquaculture productivity (Daw et al., 2009; Mohanty, Mohanty, Sahoo, & Sharma, 2010). Coastal aquaculture areas are also exposed to frequent severe weather events, erosion, storm surges, and high waves that damage aquaculture infrastructure, especially cages, and result in the escape of cultured fish, leading to farmers' loss of livelihood (Brander, 2007; De Silva & Soto, 2009; O'Brien, Sygna, & Haugen, 2004). A rise in sea level, storm intensity and frequency, extreme weather events or a wide range of human pressures affect fishing communities, and economic activities in the vicinity of coastal and low lying zones (De Silva & Soto, 2009; O'Brien et al., 2004). Such events also affect water quality in the brackish water ponds and cages of inland and coastal fisheries, due to drastic water flow changes that cause salinity problems and can also bring effluents and sediments into the aquaculture areas, especially if the production sites are near to the sites of other agricultural and industrial activities from coastal to inland areas and *vice versa* (De Silva & Soto, 2009).

The physical factors that influence inland and coastal aquaculture in Malaysia are affected by flooding events, variability in accessible water and siltation problems in the aquaculture area. Flooding events reduce water quality due to the increased amounts of deposited solids and silt and threaten to reduce the high rate of water-flow. This threatens mainly to cage aquaculture systems. Drought events lead to water stress that affects aquaculture activities. The clearance of mangrove forest for agricultural and other developments escalates water acidification due to water leaching from the acid sulphate mangrove soils to the water sources during the rainy seasons. This has poisoned cultured fish and prawns in Perak and Johor (Hambal et al., 1994).

Climate change will also modify evaporation and precipitation cycles and harm mostly salt water aquaculture. Storm surges, waves, and coastal erosion have the most harmful effects on aquaculture production and other coastal activities. Severe storms will cause farmers to suffer large losses due to the serious damage to assets and high cost of recovery (CICS, 2000). Moreover, alteration to river surface and inland water temperatures are among the major drivers of change that modify the physiological, ecological, and operational aspects of aquaculture activities and exacerbate the negative impacts on the world's aquaculture systems (De Silva & Soto, 2009; World Bank, 2010).

Climate change events increase the costs of aquaculture sector operations due to rising managerial costs (especially for fish feed and quality fries); increased competition for good natural resources for aquaculture activities; and restructuring or repairing damage to aquaculture infrastructure. The impacts of climate change on aquaculture production differ with location (e.g. region), the aquaculture practice in use, space, time, size, and changeability (De Silva & Soto, 2009).

Biophysical vulnerability studies on aquaculture production have been conducted in several countries. In Nigeria the sensitivity of aquaculture production to climate change is influenced by the type of aquaculture systems, scale of production, intensity, and cultured environment. Climate change results in physiological stress, which exacerbates disease problems and thus increases risks to aquaculture production and reduces aquaculture farm revenues (Oguntuga, Adesina, & Akinwole, 2009). Changes in precipitation result in more flooding and damage aquaculture areas. A rise in sea level leads to a smaller appropriate environment for fish growth (Akegbejo-Samsons, 2009).

A study in Norway shows that climate change has both direct and indirect effects on the various biophysical processes such as temperature, wind speed and direction, shifting of streams, a rise in sea level, the availability of sunlight, and storm events. Increases in temperature exacerbate disease and encourage the growth of poisonous algae and parasites. This has caused the spread of diseases that led to losses of 6.1% or 17.2 million salmon and 4.9% or 2.5 million trout in production in 2000 (Schjolden, 2004).

The Mekong Delta region aquaculture farmers consider on-farm and off-farm cost and the social optimal in implementing the sustainable aquaculture practices. The careful selection of cultured species and suitable technology, the use of environmental friendly practices, and development of good regional networks are among the several factors that determine the sustainable development of aquaculture (Tisdell, 1999).

Producers find sustainable farming practices very tough to achieve and have to ensure that overall operations result in their products being produced at maximum efficiency to minimize the environmental degradation (Martinez-Cordero & Leung, 2004).

3.4 Methodology

Details on the nature of the data used in the analysis and how it was gathered are followed by a description of the data analysis techniques and the model specification of the study. The section on data analysis techniques and model specification includes the variables used in the study, the main analysis used to identify the relationship between the variables and the diagnostic tests used to check how accurate the analysis is.

3.4.1 Data Description

The study employs annual data from pond and cage aquaculture systems spanning 21 years (1993 to 2013). The data for total annual aquaculture production and total aquaculture size were gathered from the Agricultural Statistics of Sarawak, DOA Sarawak and the Annual Fisheries Statistics, DOF Malaysia. The production data refers to total annual production in tonnes for each aquaculture system. The total aquaculture area was the total area of aquaculture ponds in ha or cages in m^2.

The climatic data for the same period were sourced from the Yearbook of Statistics, DOS Malaysia, Agricultural Statistics of Sarawak, DOA Sarawak, and from the MMD, Kuala Lumpur. The climatic data comprises of mean maximum air temperature in °C, mean minimum air temperature in °C, mean total rainfall in mm per day, mean percentage relative humidity (%) and total hours of sunshine per day. Boyd and Pine (1981) opine that air temperature can be used to represent the water temperature because the temperature values are close. Furthermore, these biophysical variables can also be used to measure climatic impacts quantitatively (Fussel & Klein, 2005). Empirical estimations were carried out using the time series econometric package Eviews 8.0.

3.4.2 Stationarity of the Data and Unit Root Tests

Before constructing the multivariate econometric models, it is important to carry out the non-stationarity or unit root tests for checking the time series data properties. The stationary time series is ensemble distribution where the mean and variance of the distribution are independent of time. The non-stationary time series occur due to the random walk process and the existence of a unit root. According to Brooks (2008) and Asteriou and Hall (2011), the notion of stationary or non-stationary series were based on the following reasons:

1) The stationary or non-stationary of a series can strongly influence its behavior and properties. In stationary time series, the shocks (a change or an expected change in a variable or value of the error term in a particular time period) will be temporary. Over time, the effects will be eliminated as the series relapse to their long-run mean values. Whereas in non-stationary time series, the persistence of shocks will always be infinite or hold permanent components. The behavior of time series can only be a study of the time period under consideration.

2) The non-stationary data can cause spurious regressions. In standard Ordinary Least Squares (OLS) regression procedures, the non-stationary data will result a very high of R^2 and very high values of t-ratios while no interrelationships (no economic meaning) between the variables from the analysis if the two variables are trending over time. In contrast, the value of R^2 would be low and the t-ratios

would not to be significantly different from zero if two stationary variables are generated as independent random series.

3) The variables from non-stationary regression model verifies that the standard assumptions for asymptotic analysis will invalid. That is because the t-ratios will not follow t-distribution and the F-statistics will not follow F-distribution.

4) As the lag length increases, the theoretical correlogram of stationary series will die out rapidly while the non-stationary time series will lessen or tend to zero. However, this statement is vague due to the probability of having the same shape of autocorrelation function (ACF) as real unit-root process and lead for confusing whether the results being appear to be a unit root or stationary process.

The autoregressive AR(1) model presented by equation (3.1) explains the relationship between unit root and non-stationary series,

$$y_t = \emptyset y_{t-1} + e_t \tag{3.1}$$

Where e_t is a white-noise process and the stationary condition is $|\emptyset| < 1$. If $|\emptyset| < 1$, the y_t is stationary and the y_t explodes if $|\emptyset| > 1$. On the other hand, the y_t has a unit root and is non-stationary if $\emptyset = 1$. Then, the equation (3.2) explains that y_{t-1} is deducting from both side of equations and having $\emptyset = 1$, which represent as,

$$y_t - y_{t-1} = y_{t-1} - y_{t-1} + e_t$$

$$\Delta y_t = e_t \tag{3.2}$$

e_t is a white-noise process, so Δy_t is a stationary series. Thus, the stationarity of the series are obtained after differencing y_t. The stationarity will cause two condition, first, the series y_t is integrated of order one (denoted by y_t ~ I(1)) and contains a unit root if y_t is non-stationary but Δy_t is stationary. Second, a non-stationary series y_t is integrated of order d (denoted by y_t ~I(d)) if it attains stationary after being differences d times where $\Delta y_t = y_t - y_{t-1}$ and $\Delta^2_{y_t} = \Delta(\Delta y_t) = \Delta y_t - \Delta y_{t-1}$. The presence of the stationary relationship between the series shows that they are not independent and co-integrated. This information shows that the series needs to be differences in order to become stationary.

Gujarati (2003) revealed that in any regression analysis, the data to be analyzed should be stationary for getting a robust and credible results. This study uses a short time series data (T = 21) and based on Arltová and Fedorová (2016), suitable tests for short periods of data are Augmented Dickey Fuller (ADF) and Phillips-Perron (PP) tests. These tests are based on the null of a unit root against the alternative of stationary. The hypothesis for the ADF and PP tests are the same, in which the null hypothesis claims the presence of a unit root, while the alternative hypothesis indicates the absence of unit root. However, the major critical problem of the ADF test refers to the difficulty selecting the appropriate lag length p. If p is too small, the test can get bias result because of the remaining serial correlation in the errors. Otherwise, if p is too large, the power of the test will be affected. Together with some suggestions in the literature to mitigate this issue, the statistical software Eviews 8.0 fortunately allows lag length to be selected automatically regarding Akaike Information Criteria (AIC) and Schwarz Information Criteria (SIC), with a maximum lag length set equal to 9 (Ng. & Perron, 1995).

3.4.2.1 Augmented Dickey-Fuller (ADF) test

In this test, Dickey and Fuller (1981) modified the former Dickey Fuller (DF) test to higher order autoregressive process by suggesting an augmented version of the test which consists of extra lagged terms of the dependent variables in order to reduce autocorrelation. The Akaike Information Criterion (AIC) was used to determine the lag length. The ADF test estimates the following regression:

$$\Delta y_t = a_0 + \gamma y_{t-1} + a_2 t + \sum_{i=1}^{p} \beta_i \Delta y_{t-i+1} + u_t \qquad (3.3)$$

where $\gamma = -(1 - \sum_{i=1}^{p} a_i)$, $\beta_i = -\sum_{j=i}^{p} a_j$ and p is the number of lagged differences in the dependent variable that solve the serial correlation. The deterministic element a_0 and $a_2 t$ shows the difference and this determines which appropriate statistic to use in the regression equation. τ statistic is used if the deterministic components without an intercept and trend, τ_μ statistic is used if it is with only the intercept and τ_τ statistic is use when the deterministic components with both intercept and trend. The system has a unit root if $\sum a_i = 1, \gamma = 0$ where the null and alternative hypotheses of the ADF test are:

$$H_0: y_t \sim I(1)$$

$$H_1: y_t \sim I(0)$$

The ADF test used a null hypothesis of non-stationarity of the time series against the alternative hypothesis of stationarity of the time series under investigation.

3.4.2.2 Phillips-Perron (PP) Test

The Phillips-Perron (PP) test is the alteration of the ADF test for a more comprehensive theory of unit root non-stationary to allow for autocorrelated residuals.

Dickey Fuller and Augmented Dickey Fuller test follow the assumption that the error terms are statistically independent and have a constant variance. Phillips and Perron use nonparametric statistical method to take care of the serial correlation in the error terms without adding lagged difference terms. Thus, PP statistics are only taking into account the less restrictive nature of the error process. The test regression for the PP test is the AR(1) process expressed as follows:

$$\Delta y_{t-1} = \alpha_0 + \gamma y_{t-1} + e_t \tag{3.4}$$

The ADF test corrects for higher-order serial correlation by adding lag difference terms on the right-hand side while the PP test makes a correction to the t-statistic of the coefficient γ from the regression to account for the serial correlation in e_t. In term of lag length specification, the PP Test is more powerful than the ADF test. However, there were problems of "bandwidth" parameter selection as part of the Newey-West estimator but this can be solved by allowing the bandwidth to be selected automatically using the kernel function Bartlett in Eviews software. The null and alternative hypotheses under PP test is similar as ADF test that is

$$H_0: y_t \sim I(1)$$

$$H_1: y_t \sim I(0)$$

The PP test used a null hypothesis of non-stationarity of the time series against the alternative hypothesis of stationarity of the time series under investigation.

3.4.3 Model Specification and Data Analysis Techniques

The methodology adopted in this study was designed to meet the study's first objective, that of identifying the relationship between the biophysical vulnerability of climate change and aquaculture production in different aquaculture systems. The model specification for pond and cage aquaculture can be expressed as:

$$Y_{t_{pond}} = f(maxt_t, mint_t, humid_t, rain_t, sun_t, size_t) \quad (3.5)$$

where pond aquaculture production (Y_t) is a function of mean maximum temperature in ºC ($maxt_t$), mean minimum temperature in ºC ($mint_t$), mean percentage relative humidity ($humid_t$), mean total rainfall in mm per day ($rain_t$), total hours of sunshine per day (sun_t), and total size of aquaculture ponds ($size_t$) in ha.

$$Y_{t_{cage}} = f(maxt_t, humid_t, rain_t, sun_t, size_t) \quad (3.6)$$

In the case of cage aquaculture, the aquaculture production per cage (Y_t/cage) is a function of mean maximum temperature in ºC ($maxt_t$), mean percentage relative humidity ($humid_t$), mean total rainfall in mm per day ($rain_t$), total hours of sunshine per day (sun_t), and total size of aquaculture cages ($size_t$) in square meters per cage (m^2/cage). The variable $Y_{t_{pond}}$ refers to the total aquaculture production of freshwater and brackish water ponds whilst $Y_{t_{cage}}$ refers to the total aquaculture production per cage for cages in freshwater and brackish water.

Multiple linear regression using the secondary data was employed as one of the assessment techniques for environmental impacts (Barthwal, 2002; Basu & Lokesh, 2014) to identify significant relationships between the climate change risk factors and aquaculture production. The forecast of the relationship among variables based on past production can help farmers to make decisions on future production plans (Ozkan & Akcaoz, 2002). This analysis is used to find a good estimation of parameters that fit a function, f(x), of a data set, $x_1 \ldots x_n$, in identifying the significance of climate and aquaculture farm size to aquaculture production. The general form of linear regression models in this study is;

$$lY_{t_{pond}} = \alpha + \beta_1 lmaxt_t + \beta_2 lmint_t + \beta_3 lhumid_t + \beta_4 lrain_t + \beta_5 lsun_t + \beta_6 lsize_t + \mu_t \quad (3.7)$$

$$Y_{t_{cage}} = \alpha + \beta_1 maxt_t + \beta_2 humid_t + \beta_3 rain_t + \beta_4 sun_t + \beta_5 size_t + \mu_t \quad (3.8)$$

where,

Y_t	= total annual production of each aquaculture system; tonnes for pond aquaculture and tonnes per cage for cage aquaculture.
$maxt_t$	= mean maximum temperature in °C
$mint_t$	= mean minimum temperature in °C
$rain_t$	= mean total rainfall in millimeter/day (mm/day)
$humid_t$	= mean relative humidity as percentage
sun_t	= total sunshine hours per day (hrs/day)
$size_t$	= total size of aquaculture ponds (ha) or cages (m^2/cage)

The mean minimum temperature is not included in the cage aquaculture model as this factor has less influence on the biophysical effects model in cage aquaculture. Nevertheless, the total production and farm size in cage activities were transformed and divided by the number of cages to minimize the data and make the coefficient of variables easier to explain without changing the meaning of the data.

All variables in the pond aquaculture biophysical assessment model were in logarithmic form to remove the systemic change or variance of errors that may have a problem of heterocedasticity, and, at the same time, linearize the relationship between the dependent and independent variables. Meanwhile, for the cage aquaculture biophysical assessment, all variables were in linear form. The coefficients (β) of maximum temperature, humidity, rainfall, and sunshine are expected to be negative while the coefficients of minimum temperature and total size are expected to have positive impacts on aquaculture production.

3.4.4 Diagnostic Test.

Four assumptions need to be tested (by a diagnostic test) to achieve accurate multiple linear regression results. The diagnostic test inspection for the models include the goodness-of-fit, normality test, serial correlation, and homoscedasticity (Osborne & Waters, 2002).

3.4.4.1 Goodness-of-fit

The coefficient of determination is a summary measure that tells how well the sample regression line fits the data. R^2 (coefficient of determination) is commonly used to measure the goodness-of-fit of a regression line. R^2 measures the proportion or percentage of the total variation in the dependent variable, Y, explained by the regression model. R^2 has two properties: 1) it is a non-negative quantity; and 2) the limits for R^2 =1 mean a perfect fit and R^2=0 means there is no relationship between the regress and the regressor. The true relationship between the explanatory variable and dependent variable can be explained by R^2. The R^2 value presents the percentage of the total variation in the dependent variable that is explained by the explanatory variables. The regression fits best if the R^2 value lies near to 1.

3.4.4.2 Normality test

The Jarque-Bera test developed by Bera and Jarque (1981), also known as the good-of-fit test, is used to test whether the kurtosis and skewness of sample data are identical normally distributed. The normal distribution is achieved if the distribution is symmetric and mesokurtic. Non-normally distributed variables that have substantial outliers or are highly skewed affect the relationships of the variables (Osborne & Waters, 2002). In the Jarque-Bera test the sample data are normally distributed if the histogram is bell-shaped and the Jarque-Bera statistic is not significant. The p-value of the normality test should be >0.05 in order not to reject the null of normality at the 5% level (Brooks, 2008). Under the null hypothesis that the residuals are normally distributed, the Jarque-Bera statistics in the equation follow the chi-square distribution with two degrees of freedom (df). The Jarque-Bera test of the normality of regression residuals can be performed using the following equation,

$$X_N^2(2) = n(\frac{1}{6}b_1 + \frac{1}{24}(b_2 - 3)^2) \tag{3.9}$$

Where skewness= $\sqrt{b_1} = \frac{m^3}{m_2^{3/2}}$; and kurtosis= $\frac{m_4}{m_2^2}$; $m_k = \sum_{t=1}^{n} \frac{(x_t - \bar{x}\ )^k}{n}\ , k = 2, 3, 4.$

3.4.4.3 Serial correlation test

In the regression model the error, u_t, should not have a serial correlation problem. Moreover, the presence of autocorrelation in OLS estimators will no longer be efficient, although it is still linear unbiased, consistent, and asymptotically normally distributed. Given autoregressive, AR (1) scheme,

$$var(u_t) = E(u_t^2) = \frac{\sigma_\varepsilon^2}{1-p^2} \tag{3.10}$$

$$cov(u_t, u_{t+s}) = E(u_t, u_{t-s}) = p_1^s \frac{\sigma_\varepsilon^2}{1-p^2} \tag{3.11}$$

$$cov(u_t, u_{t+s}) = p^s \tag{3.12}$$

where $cov(u_t, u_{t+s})$ is the covariance between the error terms, s periods apart and $cor(u_t, u_{t+s})$ is the correlation between the error terms, s periods apart. Several methods are able to indicate a serial correlation problem in the series. These include the Durbin-Watson d Test, Breusch-Godfrey (BG) test (Gujarati, 2003); Box Pierce Q statistics and the Ljung-Box statistics (Pesaran & Pesaran, 1997). The serial correlation test is applied by using the BG Test. The BG Test (Godfrey 1978) is performed based on the Langrange Multiplier (LM) version of the test statistic through the following equation:

$$X_{SC}^2(p) = n\left(\frac{e'ols\, w(w'\, M_X MW)^{-1} W'_{eOLS}}{e'_{OLS} e_{OLS}}\right) \overset{a}{\sim} X_p^2 \tag{3.13}$$

Where $M_X = I_n - X(X'X)^{-1}X', e_{OLS} = (e_1, e_2, \dots, e_n)', p$ is an order of the error process. The F-statistic of the LM statistic, which is known as the modified LM statistic, is presented by:

$$F_{SC}(p) = \left(\frac{n-k-p}{p}\right)\left(\frac{X_{SC}^2(p)}{n-X_{SC}^2(p)}\right) \overset{a}{\sim} F_{p,n-k-p} \tag{3.14}$$

where $X_{SC}^2(p)$ and $F_{SC}(p)$ are the tests of residual serial correlation that are asymptotically equivalent to the null hypothesis of no serial correlation. The F-statistic cannot be rejected if the LM statistics is smaller than the critical chi-squares, X^2.

3.4.4.4 Homoscedasticity test

The variance is homoscedasticity when residuals have the same or constant variance of errors. If the sample varies substantially in different observations, the variance of errors may have a heterokedasticity problem. The autoregressive conditional heterokedasticity (ARCH) or generalized autoregressive conditional heterokedasticity

(GARCH) present the form of heterokedasticity in time series models. Engle (1982) formulated ARCH as follows:

$$\sigma_{ut}^2 = \alpha_0 + \alpha_1 u_{t-1}^2 + \ \dots + \alpha_p u_{t-p}^2 \tag{3.15}$$

The lags of the squared residuals indicate the changes from the previous period. The variance of u_t is the conditional disturbance or conditional on information available up to time t-1 that can be written as follows:

$$\begin{aligned}\sigma_{ut}^2 &= var\left(u_t \middle| u_{t-1}, \dots, u_{t-p}\right) \\ &= \left(u_t^2 \middle| u_{t-1}, \dots, u_{t-p}\right)\end{aligned} \tag{3.16}$$

In time series, heterokedastic disturbances exist when trends occur in the observations of time series data and are able to induce trends in the variance of the variables. The existence of heterokedasticity in the residuals causes underestimated standard errors and overestimated t-values. Symbolically, the heterokedasticity is present as:

$$E(u_i^2) = \sigma_i^2 \tag{3.17}$$

If the homoskedasticity assumption is violated the variance of error terms depend on which observation is $var(u_i) = \sigma_i^2$, where σ^2 is the conditional variances of u_i or conditional variance of Y_i that no longer have an asymptotic chi-square distribution. The presence of heterokedasticity can be detected from the regression of squared residuals on squared fitted values as follows:

$$\hat{u}^2 = \delta_0 + \delta_1 \hat{Y}^2 + \varepsilon \tag{3.18}$$

where $H_0\colon \delta_1 = 0$ is the null hypothesis. The $R_{\hat{u}^2}^2$ from the above regression is used to compute the LM statistics and F-statistic as follows:

$$LM = n^* R^2_{\hat{u}^2}, \quad F = \frac{R^2_{\hat{u}^2}/k}{\left(1-R^2_{\hat{u}^2}\right)(n-k-1)} \tag{3.19}$$

If the p value of the LM and F-statistics is very small, a decision is made to reject the null hypothesis of homoskedasticity.

3.5 Empirical Findings

3.5.1 Descriptive Statistics

Descriptive statistics of the variable used in the regression analysis are shown in Table 3.1. From 21 years' observation of Sarawak's weather, the maximum mean maximum temperature was 32.2°C (recorded in 2013). The minimum mean maximum temperature was 31.1°C. (recorded in 2005 and 2006). Meanwhile, the mean minimum temperature maximum and minimum were 24.4°C and 23°C respectively (recorded in 2004 and 1993 respectively). The maximum mean total rainfall within the period was 20.6mm/day and the minimum was 12.7 mm/day. This shows that 2003 was the driest year and 1994 was the wettest year, within the period.

Table 3.1: Descriptive summary of production and biophysical factors

Dependent Variables		Maximum	Minimum	Mean	Std. Dev.
Mean maximum temperature (°C)		32.2	31.1	31.6	0.30
Mean minimum temperature (°C)		24.4	23.0	23.5	0.39
Mean percentage relative humidity (%)		86.9	79.5	83.9	2.00
Mean total rainfall (mm/day)		20.6	12.7	16.5	2.11
Total sunshine hours (hrs/day)		6.3	5	5.7	0.28
Aquaculture production	Pond (tons)	11,648.60	567.41	5,594.46	4,001.15
	Cage (tons)	5,909.81	947.84	3,483.66	1,805.89
Size of aquaculture farm	Pond (ha)	7,277.75	163.01	1,336.49	1,503.76
	Cage (m^2)	80,558.00	7,968.00	46,655.12	24,623.94

Note: Std. Dev. = standard deviation

For mean humidity values, the highest was 86.9%, in 1998, and the lowest was 79.5%, in 2005. The longest daily period of sunshine was 6.3 hours/day, recorded in 2013, and the shortest was 5 hours/day, in 2000. The maximum size of aquaculture activities was 7,277.75 ha (in 2000) for pond aquaculture farms and 80,558.00 m^2 (in 2010) for cage aquaculture.

Pond aquaculture activities registered the largest size and production for brackish water systems in Sarawak. They covered on average 830.81 ha of production area and produced on average 3,861.64 metric tonnes of fish. In the case of cage aquaculture activities in Sarawak the largest size and production was from the freshwater system with, on average, a total production area of 28,272.19 m^2 producing 509.74 metric tonnes. Pond aquaculture was actively conducted in Kuching and Samarahan districts. The largest freshwater aquaculture cages operated in Batang Ai, Sarawak whilst the largest brackish water cages were concentrated in Kuching and Lawas districts.

3.5.2 Unit Root Tests

The ADF and PP test statistics are performed based on the model with intercept ($\boldsymbol{\tau_\mu}$), and with trend and intercept ($\boldsymbol{\tau_\tau}$). The ADF test and PP test for the levels and first differences are shown in Table 3.2. In pond and cage aquaculture biophysical factors, unit root tests are performed on the total aquaculture production, mean maximum temperature, mean minimum temperature (except for cage aquaculture biophysical model), mean total rainfall, mean relative humidity, total sunshine hours, and total size of aquaculture ponds and cages. The computed t-statistics and critical values provided in Table 3.2 are compared to determine the occurrence of a unit root. The computed t-statistics, which excesses the critical value at 1% and 5% level of significance means the null hypothesis of a unit root cannot be accepted.

Table 3.2: Unit root tests for pond and cage aquaculture

	Augmented Dickey Fuller (ADF) H_0: Unit Root			Phillips Perron (PP) H_0: Unit Root		
Series	Level		Difference	Level		Difference
	Tμ	Tτ	Tμ	Tμ	Tτ	Tμ
Pond aquaculture (1993 – 2013)						
$lY_{t_{pond}}$	-1.3351[0]	-1.2535[0]	-3.0648[0]**	-1.3469[1]	-1.5556[2]	-3.0787[1]**
$lmaxt_t$	-1.8085[0]	-2.3669[0]	-5.8977[0]*	-1.8085[0]	-2.3669[0]	-6.0746[2]*
$lmint_t$	-2.5097[0]	-2.5317[0]	-4.7920[0]*	-2.5121[1]	-2.5649[1]	-4.8814[3]*
$lhumid_t$	-1.4728[0]	-1.2607[0]	-3.9005[0]**	-1.5417[1]	-1.3775[1]	-3.9005[0]*
$lrain_t$	-2.5503[2]	-3.2650[1]	-5.7705[1]*	-5.8503[0]*	-5.6698[0]*	-10.8050[1]*
$lsun_t$	-2.2019[0]	-2.2348[1]	-6.8235[0]*	-2.1017[1]	-3.2640[4]	-7.3853[5]*
$lsize_t$	-2.2502[0]	-3.1680[0]	-6.0872[0]*	-2.2502[0]	-3.1680[0]	-7.1860[4]*
Cage aquaculture (1993-2013)						
$Y_{t_{cage}}$	-1.3886[0]	-2.2455[0]	-5.0452[0]**	-1.3316[1]	-2.2455[0]	-5.1971[2]*
$maxt_t$	-1.7944[0]	-2.3597[0]	-5.9012[0]*	-1.7944[0]	-2.3597[0]	-6.0776[2]*
$humid_t$	-1.4747[0]	-1.2656[0]	-3.9616[0]*	-1.5359[1]	-1.3722[1]	-3.9616[0]*
$rain_t$	-1.8990[3]	-3.2103[1]	-5.5369[1] *	-5.8502[0]*	-5.6828[0]**	-10.9299[1]*
sun_t	-2.0217[0]	-3.1973[0]	-6.6875[0]*	-1.9045[1]	-3.1106[1]	-7.0691[4]*
$size_t$	-2.0916[0]	-3.2613[1]	-5.1290[1]*	-2.0308[1]	-3.1055[6]	-5.4653[1]*

Notes:
1. * and ** represents a significant level at 1% and 5% respectively. τμ represents the model with intercept; and ττ is the model with trend and intercept. Numbers in brackets are number of lags used in the ADF test in order to remove serial correlation in the residuals.
2. At n=21, the ADF critical values are -3.80 (1%), -3.02 (5%) and -2.65 (10%) for intercepts (τμ); -4.53 (1%), -3.67 (5%) and -3.27(10%) for trend and intercept (ττ).
3. At n=21, the PP critical values are -3.80 (1%), -3.02 (5%) and -2.65 (10%) for intercepts (τμ); 4.49 (1%), -3.65 (5%) and -3.26 (10%) for trend and intercept (ττ).

The unit root tests results showed that the ADF test of both aquaculture systems are not sufficiently large to reject the null hypothesis of a unit root in the level series with intercept (τ_μ), and, with trend and intercept (τ_τ). This suggests that the level data for pond and cage aquaculture biophysical factors contains unit root I(0) or not stationary at their levels. The presence of unit root is rejected for all variables when first difference data are employed, enable the variables to be stationary after differencing one I(1).

Under the PP test, the rejections of the null hypothesis of a unit root are failed for a majority of all variables at levels form, but statistically reject the null hypothesis in the first differences. Nonetheless, the presence of unit root is rejected in level series for the variable of mean total rainfall for both models (pond and cage). This suggests that the variable of mean total rainfall does not contain a unit root in the level form and not integrated at the order of I(0). The findings from the unit root tests show that the same order of integration among the selected variables is sufficient to apply the cointegration test of Johansen techniques since the ADF test show that all variables are integrated in the same order of I(1).

3.5.3 Multiple Linear Regression Results

The results of the multiple linear regression analyses are presented in Tables 3.2 (pond aquaculture production) and 3.3 (cage aquaculture production). The findings for the pond and cage aquaculture systems are compared. The Jarque–Bera diagnostic tests had a *p*-value >0.05 verifying that the models are normally distributed for all aquaculture systems. The BG LM test showed no evidence of autocorrelation and the Breusch Pagan Godfrey (BPG) test no evidence of heteroscedasticity in both aquaculture systems.

3.5.3.1 Diagnostic test results

The diagnostic test results in Tables 3.2 and 3.3 were applied to the models in order to test the validity of the estimation of biophysical factors' effects on aquaculture production in all observed aquaculture systems. Generally, the diagnostic test results for the two different models of aquaculture systems are acceptable. The results also indicate that of the two different models, the pond aquaculture model has very high goodness-of-fit (R^2) as the independent variables jointly explain almost 92.7% of the relationship with the dependent variable. Meanwhile, the cage aquaculture diagnostic results show that 48.4% of the variation in aquaculture production is explained by the variation of independent variables included in the model. All the variables are jointly significant, as shown by the significant F-statistics.

The statistical validity of serial correlation, functional form, and heterokedasticity are indicated using chi-square (X^2) and F-statistics. Hence, the chi-square statistics are also used to verify the normality distribution. The Jarque-Bera normality test results for all aquaculture systems indicate that the null hypothesis of normality in the residuals do not rejected. The F-statistics calculated for the BG Serial Correlation LM test for higher order serial correlation are 0.22 in the pond aquaculture model and 2.84 in the cage model, indicating that the null hypothesis of absence of serial correlation cannot be rejected in the residuals. The calculated F-statistics for the BPG test results show that the assumptions of multiple linear regression are fulfilled; both models show no evidence of heterokedasticity.

3.5.3.2 The relationship of biophysical factors to pond aquaculture production

The findings show that 93% of pond production variation is explained by the variation in the observed independent variables from the R^2 (Table 3.2). Mean maximum temperature, mean minimum temperature, sunshine hours, and farm size are factors that have positive significant effects on aquaculture production.

In pond aquaculture the mean maximum and mean minimum temperatures have positive impacts (significant at the 10% level) on aquaculture production. A 1% increase in mean maximum temperature will increase pond aquaculture production by 25.3%. Meanwhile, a 1% increase in mean minimum temperature will increase pond production by 14.4%. Furthermore, an increase of 1% in daily sunlight hours will significantly increase the pond production, by 4.2%. Pond size has a positive impact (significant at the 1% level) on pond production where a 1% increase in pond size will increase production by 0.7%.

Table 3.3: Climate variability relationship in pond aquaculture production in Sarawak

Variables	Pond aquaculture production
C	-90.8594 (-2.0359)
$lmaxt_t$	25.2983* (1.8049)
$lmint_t$	14.3696* (1.7972)
$lhumid_t$	-10.7986 (-1.5542)
$lrain_t$	0.6953 (1.0636)
$lsun_t$	4.2479* (1.9696)
$lsize_t$	0.7142*** (5.7621)
R-squared	0.93
Adjusted R-squared	0.90
Standard error of regression	0.36
Sum of squared residuals	1.85
F-statistic	29.72
Serial correlation	0.22
Heterocedasticity	7.19
Normality	1.10

Notes: *significant at the 10% level; **significant at the 5% level; ***significant at the 1% level

Mean percentage relative humidity and mean rainfall do not significantly impact pond aquaculture production but the results show that both variables have normal expected signs of relationship with pond aquaculture production. An increase in percentage humidity has a negative effect on pond production whilst an increase in rainfall had positive effects on pond production.

3.5.3.3 The relationship of biophysical factors to cage aquaculture production

The findings show that 48% of the variation in cage production is explained by the variation in the observed independent variables from the R^2 (Table 3.3). The mean maximum temperature and mean percentage humidity were two factors with a significant impact on cage aquaculture production in Sarawak. The results indicated that a 1°C increase in mean maximum temperature will decrease cage production by 0.72 units, while a 1 unit increase in the mean percentage humidity increases cage production by 0.08 units.

Table 3.4: Climate variability relationship in cage aquaculture production in Sarawak

Variables	Cage aquaculture production
C	-14.9919 (2.109)
$maxt_t$	-0.715** (-2.835)
$humid_t$	0.075 (2.008)*
$rain_t$	0.0422 (1.255)
sun_t	0.2191 (0.7604)
$size_t$	-0.0095 (-0.9019)
R-squared	0.48
Adjusted R-squared	0.31
Standard error of regression	0.29
Sum of squared residuals	1.26
F-statistic	2.81
Serial correlation	2.84
Heterocedasticity	9.21
Normality	1.62

Notes: *significant at the 10% level; **significant at the 5% level; ***significant at the 1% level.

The results indicated that biophysical factors have a minimal effect on cage aquaculture as compared to pond aquaculture. This may be influenced by the nature of aquaculture farm management activities. Nevertheless, mean total rainfall and sunshine hours have a positive relationship with cage production and the farm size shows a negative relationship with the production.

3.6 Discussion

Discussions on the effects of biophysical vulnerability caused by climate change on Sarawak's aquaculture sector concentrate on the severity of extreme weather events associated with ecological changes and physical aspects as proxies for the biophysical factor effects on aquaculture production. Besides, the findings will help to identify and assess the critical factors that affect production risks in Sarawak's aquaculture sector. The expected signs and direction of the effects of climate and physical factors in the Multiple Linear Regression Model findings imply a relationship between biophysical factors and aquaculture production in Sarawak.

In pond aquaculture the expected sign of the variables shows difference in mean maximum temperature, mean total rainfall, and sunshine hours. In cage aquaculture the contrast expected sign was shown by the mean percentage humidity, mean total rainfall, sunshine hours, and farm size. The contradictory results for the biophysical vulnerability assessment posit that climate change impacts may not have totally negative effects on aquaculture production. This may indicate that the impacts of climate change on aquaculture production in Sarawak may still be moderate. These results also reveal and support the evidence for a theory of vulnerability which shows indirectly that risk, exposure, and sensitivity in aquaculture activities do exist due to the impacts of climate change, as Badjeck et al. (2010) postulated.

3.6.1 The Effects of Variability in Maximum Temperature, Minimum Temperature and Rainfall on Aquaculture Production in Sarawak

The climatic indicators in aquaculture activities, especially temperature, had the most influence on the total production. The multiple regression analysis model results showed that the increase in maximum temperature has a significant negative impact on cage aquaculture production but a positive impact on pond aquaculture production in Sarawak. Meanwhile, the mean minimum temperature had a statistically significant impact on pond aquaculture production.

Temperature is the primary abiotic factor that controls key physiological and biochemical process in the life of fish. Being a cold blooded organism, fish body temperature changes according to the temperature of the environment (Bhatnagar & Devi, 2013). High temperatures of high inland water surpass the maximum temperature suitable for cultivated species (World Bank, 2010), increase water stratification, and reduce production. Water temperature increases affect the quantity of oxygen dissolved in the water, evaporation, and aquaculture productivity directly (Kutty, 1987). Fish growth is also reduced in line with temperature due to insufficient feeding (rising metabolic rates) (Akegbejo-Samsons, 2009) and the spread of disease to the cultured species (World Bank, 2010).

The effects of an increase in maximum temperature in pond aquaculture can be controlled through suitable farm management techniques and the use of water aeration systems in the ponds. However, cage aquaculture, which is operated in natural ecosystem of fish in open water bodies, was influenced by variation in the maximum temperature as a result of climate change, and this had an impact on production. These results are congruent with those of De Silva and Soto (2009). The raising of the maximum temperature in water bodies will negatively affect cage aquaculture production. The fish will experience stress and the threat of disease will rise when the temperature increases to the maximum tolerable temperature or fluctuates suddenly. The aquaculture species grew dynamically at the optimal minimum and maximum tolerance limits of temperature. Rapid temperature variation will have a negative effect on aquaculture species' growth due to a reduction in dissolved oxygen in the warmer water.

Changes in temperature will change the feeding patterns, nutrients, and growth of the fish because it increases the rate of metabolism, chemical reactions, and oxygen consumption (Ficke et al., 2007; Johnston et al., 2009; Tidwell et al., 1999). Boyd and Pine (1981) verified that, according to van't Hoff's law, an increase of 10ºC within the temperature tolerance range doubled fish respiration and growth. A temperature increase that brought the temperature beyond the fish species' tolerance range caused severe death in the cultured fish population. An increase in water temperature will cause oxygen depletion in the water that encourages the growth of algae blooms which produce toxins in the water and cause fish to be exposed to diseases and parasite attack (World Bank, 2010). Modification of the biophysical conditions due to temperature changes will affect fisheries production or result in unproductive growth. It will reduce farmers' returns from aquaculture production and increase farm operational costs.

Furthermore, the results also indicated that an increase in rainfall has positive effects on both pond and cage aquaculture production. Sarawak has a high potential for pond aquaculture activities due to geographical factors (there are many rivers and small streams and regular rainfall naturally replenishes the water supply). The extreme frequency of rainfall sometimes causes flood problems and hazards to pond aquaculture activities. Extremely high rainfall had serious effects on brackish water ponds and cages due to saltwater intrusion and salinity reduction (Handisyde et al., 2006).

Increased rainfall and massive flood events sometimes cause hazards to freshwater cage aquaculture activities, especially if the area is located near housing or industrial or agricultural activities. The information given in interviews indicated that severe flood events caused cultured fish in freshwater cages to die in large numbers as well as to suffer severe disease in the Kuching area in 2010. This was due to the flow of sediments from a nearby industrial area and also from the Batu Kitang water treatment plant. Moreover, the extreme water flows during the flood caused cages to be wrecked with high costs due to loss of assets and production. Water quality that is so bad that it exceeds the tolerance limits may kill fish or cause disease problems. Massive floods can cause severe damage to farm infrastructure and productive assets and result in major fish escape events and decreased production volume due to fish loss and death.

The positive effects of rainfall on aquaculture activities were supported by Shelton (2014), who verified that flooding under some conditions has a positive effect on fish productivity. The effects of rainfall on cage activities in open water systems are less severe than that on the pond activities operated in reservoir water under controlled conditions. Freshwater aquaculture cage activities in Sarawak are mostly located in the Batang Ai reservoir where surroundings are conducive and hardly polluted. The Batang Ai aquaculture area contributes more than half the freshwater aquaculture cage production volume in Sarawak. Increased rainfall in freshwater rivers and streams will benefit aquaculture activities through water circulation and salinity process in rivers and streams.

Climatic events that led to changes in temperature and precipitation were the major causes of pond aquaculture production failure. The seasons of drought and flooding result in water stratification that harms cultured species (especially shrimp) production. However, effective pond management by farmers will help reduce the risks. Idris et al. (2014) reported that temperature rises and heavy rainfall were climate change threats to brackish water cage activities in other states in Malaysia. Baharuddin (2007) indicated that increasing temperatures and changes in rainfall were crucial and caused vulnerability to aquaculture production in Northern Peninsular Malaysia as well as in coastal Sabah and Sarawak.

3.6.2 Effect of Humidity on Aquaculture Production in Sarawak

The air relative humidity factor shows different effects on pond and cage aquaculture production in Sarawak. An increase in air humidity has a significant negative effect on pond aquaculture production but a positive effect on cage aquaculture production. Air humidity has a significant relation to water evaporation in ponds and cages. An increase in humidity will decrease the evaporation of water and contribute to an increase in moisture in the cultured species as well as an increase in the volume of fish food required and the use of chemicals in aquaculture activities.

The results also imply that relative humidity has a large effect on cage aquaculture activities which are environmentally dependent, being located in the open water system. Meanwhile, water quality in pond aquaculture farms was usually monitored. Large scale pond aquaculture farms commonly used a machine to aerate the water such that it was suitable for aquaculture growth. Small scale pond aquaculture farmers changed the water regularly in order to minimize evaporation due to the humidity.

3.6.3 The Effects of Sunlight on Aquaculture Production

Sunlight intensity is usually related to an increase in mean maximum temperature. Sunlight or solar radiation, in terms of length of daily sunshine, benefits aquaculture, and is one of the important components for its sustainability. The study results indicated that sunlight has significant positive impacts on pond and cage aquaculture systems. The aquaculture ecosystem needs a source of light to boost phytoplankton growth and speed up biological process such as metabolism in the cultured species (Lee & Wendy, 2010). Phytoplankton biomass and productivity are important factors as phytoplankton is a natural fish food that increases through the bottom up control of productivity dependent on the availability of plant nutrients and the quantity of light that falls on the water (Boyd & Tucker, 1998; Kutty, 1987).

Sunlight, for certain periods and at certain intensities, is known to desiccate and disinfect water contaminated by aquatic macrophages and other organisms (Scarfe, Lee & O'Briyen, 2008). However, an increase in light intensity will result in evaporation (Kutty, 1987). The growth of blue-green algae species in pond aquaculture prevents the penetration of sunlight for photosynthesis and this will affect water stratification and cause anoxia in deep water that lacks oxygen and contains a high concentration of carbon dioxide, causing fish death (Bhatnagar & Devi, 2013).

The negative sign in the effects of sunlight on freshwater ponds implies that there is tendency for pond water to have high pH values. Tucker and D'Abramo (2008) indicated that ponds with clear water usually supported filamentous algae. The penetration of sunlight deep into the water increased the growth of floating mats of algae, the domination of which caused problems of high pH in pond water resulting from an increase of the sunlight driven processes of photosynthesis and carbon dioxide removal from water by algae and underwater plants. Therefore in order to reduce the pH, light penetration needs to be reduced by adding herbicides or keeping water turbid by stirring up mud from the bottom of the ponds using aeration machines.

3.6.4 Effect of Farm Size Expansion on Aquaculture Production in Sarawak

The development of new aquaculture areas is expected to contribute to the positive effects on aquaculture production. However, the results show a positive relationship between farm size and pond aquaculture production but a negative relationship between farm size and cage aquaculture production. This implies that climate change risks make the expansion of cage aquaculture inadvisable in Sarawak. The climate change effect is greater in the cage aquaculture system than in the pond system.

Climate change risks have a higher impact on cage aquaculture than on pond aquaculture because the activities are operated in natural, open water river systems with less technological assistance to manage production. The river's natural ecology is sensitive to the increased impacts of climate variability that harm fish growth. Furthermore, areas for aquaculture cages are very limited due to lack of suitable locations and competition from other marine activities and also exposure to the hazards and pollution that arise from housing and from industrial activities.

Pond aquaculture systems, which are carried out in stored water (controlled environment) and depend on, or are influenced by the soil content, are more sensitive to changes in temperature and humidity than are cage culture systems. Water quality problems are a major concern in pond systems due to the aforementioned reasons. However, with effective farm management and technological assistance, the threats of climate change on production can be minimized.

Most of the aquaculture activities in Sarawak are conducted in low intensity operations by small family-owned operations, especially in the case of pond aquaculture. Small scale farmers are unable to survive in this sector due to increasing production costs and lack of support systems to protect production from the impacts of production risks. The farmers' failure to produce and the decline in food production leads to famine and poverty traps due to permanent losses of human and physical capital (Heltberg et al., 2009).

3.7 Conclusions

Macro-level data analyses to assess the biophysical vulnerability of Sarawak's aquaculture sector showed that the mean maximum and mean minimum temperature, sunlight intensity, and farm size were factors with significant impacts on pond aquaculture production. In the case of cage aquaculture, the significant factors were only mean maximum temperature and mean percentage relative humidity. The difference in sign (positive or negative) between the expected and the actual results for some biophysical factors verified that climate change impacts on aquaculture production in Sarawak are still moderate and do not cause extreme negative impacts on aquaculture development. However, it can be posited that climate change had impacted some biophysical factors. Without early action the impacts may severely affect the future development of aquaculture.

It is not sufficient merely to understand the significance of climatic effects and biophysical factors for aquaculture production if one wishes to address the effects of the whole gamut of climate change directed vulnerability aspects on aquaculture production in Sarawak. The relationship between biophysical factors and aquaculture production has been explained scientifically but it has not been possible to fathom the connection between climate change effects and socio-economic impacts on farmers. In-depth studies were therefore conducted to investigate the significance of climate change effects on farmers' socio-economic status and environments in order to bridge the connection between climate change vulnerabilities in terms of biophysical and in terms of socio-economic aspects, and to cover the gaps in, and limitations of, the secondary data in explaining the vulnerabilities. A further biophysical vulnerability assessment from the micro-level perspective will be carried out to further support this study

CHAPTER 4: SOCIO-ECONOMIC VULNERABILITY IMPACTS ASSESSMENT OF CLIMATE CHANGE ON AQUACULTURE FARMERS' LIVELIHOODS

4.1 Introduction

A holistic understanding of Sarawak's aquaculture production vulnerability due to climate change risks requires an assessment of the socio-economic aspects, and the biophysical vulnerability assessment was crucial to enable such an assessment. Klein and Nicholls (1999) highlighted the importance of the biophysical assessment and emphasized that biophysical vulnerability was a factor of socio-economic vulnerability. Johnston et al. (2009) agreed that socio-economic vulnerability in the aquaculture sector has a direct relationship with the increase in biophysical vulnerability. Biophysical vulnerability affects production risks to aquaculture activities that have resulted in major production losses and reduced farmers' livelihoods. The climate change risks affect basic human rights, especially those of small scale farmers whose livelihoods depend greatly on climate and natural resources (Johnston et al., 2009). Thus, aquaculture production losses due to biophysical risks to aquaculture production have affected vulnerable farmers' socio-economic status.

FAO (2008b) verified that more studies were needed to provide a better understanding of the vulnerability of fisheries and aquaculture to climate change in order to prioritize adaptive strategies. Akegbejo-Samsons (2009) revealed that research that focuses on identifying the relationship between the biophysical impacts of climate change and the livelihood vulnerability of poor fishing communities is insufficient. The study scope needs to include market responses to changes which will have implications for prices, economic returns, and sector investment. The study on market responses will have major impacts on sector performance, employment, food security, and long-term development. Farmers, consumers or people dependent on aquaculture production are vulnerable to the direct and indirect impacts of predicted climatic changes. Thus, this study attempts to highlight climate change impacts on farmers' socio-economic status.

The biophysical vulnerability assessment in chapter 3 identified the climate change drivers that affect Sarawak's aquaculture production from the macroeconomics points of view and related the aggregate data of Sarawak's aquaculture sector to climate information. Meanwhile, this study will explore the connection between biophysical vulnerability and the socio-economic impacts that Daw et al. (2009) have highlighted as one of the streams in climate change studies. Based on Johnston et al.'s (2009) and Klein and Nicholls' (1999) assumptions, biophysical vulnerability has a direct relationship with socio-economic vulnerability. As the study's main concern was to indicate the climate change impacts, the analysis was further extended to concentrate on identifying the specific environmental risk types that influence aquaculture farmers' level of income as well as production. As the climate change drivers relate to aquaculture production risks, the specific objectives of this essay are:

1) to indicate the biophysical vulnerability effects on aquaculture production in Sarawak based on farm level analysis
2) to identify the relationship between socio-economic vulnerability factors and aquaculture farmer's livelihoods based on demographic factors and capital assets due to biophysical impacts of climate change

In socio-economic vulnerability assessment the farmers' demographic factors and the capital assets they owned were assessed because these factors assist them in production and to gain a livelihood. The farmer's income variability is subject to the capital assets they own, whereby the lower the value of the capital assets owned by farmers, the more vulnerable they are to the climate change risks. Thus, the socio-economic assessment will test the following hypotheses,

H_1: There is a significant relationship between farmers' human capital assets and socio-economic vulnerability.

H_2: There is a significant relationship between farmers' physical capital assets and socio-economic vulnerability.

H_3: There is a significant relationship between financial capital assets and socio-economic vulnerability.

H_4: There is a significant relationship between natural resourcers and environmental capital assets and socio-economic vulnerability.

H_5: There is a significant relationship between farmers' demographic factors and socio-economic vulnerability.

According to the vulnerability theory, socio-economic vulnerability comprises the individual and collective vulnerability. However, to study both aspects requires a wide study scope and furthermore, vulnerability, especially collective vulnerability, is difficult to assess due to limitations in institutional data and information. Thus, the scope of this assessment will be limited to assessment of the individual vulnerability using primary data and information collected from individual farms.

4.2 Climate Change Challenge and Aquaculture Farmers' Socio-economic Vulnerability

Socio-economic vulnerability has different levels in different production systems, households, communities, nations, and regions. Climate change pressures the demographics and market to change as a result of the hazards that worsen the present condition of the natural resources, productive assets, information, and technology disparity that cause poor and marginalized groups that rely to aquaculture activities to be vulnerable (WorldFish, 2009). The negative impacts are indicated by the relationship between various climate changes and fish farmers' livelihoods with rising socio-economic costs. The productivity and profitability level of aquaculture production depended on the direct positive or indirect negative effect of climate change on natural resources for aquaculture, such as land, water, seeds, feed and energy (Oguntuga et al., 2009).

The impacts of climate change on the biophysical aspects of aquaculture production had direct effects on the farmers' socio-economic situation. The climate change risks caused an increase in production costs in managing aquaculture farms efficiently (Sulit et al., 2005) and minimized their production. This caused small scale farmers to be unable to survive in the aquaculture sector due to the rising production costs and lack of a support system to cover the risk of impacts and production losses. A continuous decline in aquaculture production caused production failure which led to famine (Sen, 1981) and poverty traps (Heltberg et al., 2009). Under the worst case scenario the severe climate change events diminished the growth of aquaculture development, caused permanent losses of human and physical capital, and negatively affected the farmers' livelihoods (Heltberg et al., 2009).

The extreme weather also caused catastrophic events such as sea level rise and severe storms and floods which caused operational problems and cost increments. Damage to, or wreckage of physical structures, productive assets and aquaculture infrastructure influenced a major flight from aquaculture production and decreased the volume of aquaculture (Badjeck et al., 2010; Schjolden, 2004). Moreover, farmers suffered due to their physical capital, such as house, public infrastructure, and services that sustained their livelihood, being diminished or destroyed. Farmers were also faced with limitations to markets access, increase of fish food, and goods prices (Badjeck et al., 2010).

Scarcities of natural resources due to the impacts of climate change on aquaculture production raised the level of competition among farmers and other economic sector users. The climate uncertainty resulted in aquaculture farmers suffering water scarcity; the risks and hazards of shortages include future increases in water stress and competition for access to quality water due to increased demand for water in the long run for aquaculture and other economic activities (Vorosmarty, Green, Salisbury, & Lammers, 2000). Many countries in Asia have been identified as experiencing a short supply of quality water for aquaculture activities (Bates, Kundzewicz, Wu, & Palutikof, 2008). The operation of industrial developments near potential aquaculture areas has threatened the potential of the sectors' growth (Hambal et al., 1994). Furthermore, the sensitivity of fish culturing procedures to climate-change induced variability, in terms of type, scale, intensity, and location of fish culture, results in negative outcomes on aquaculture farmers' livelihoods and also various socio-economic costs (Oguntuga et al., 2009).

Several studies have revealed the socio-economic impacts of climate change on farmers' aquaculture activities in. In Asian countries climate change has affected conflicts between aquaculture and the environment as well as poor farmers' livelihoods. Poor farmers were unable to survive in the field of aquaculture due to the high costs of acquiring the technologies and capital needs (Kamaruddin & Siwar, 2008). Moreover, low aquaculture production affects the demand for fish protein, fish market prices, and put pressure on marine ecosystem protection (World Bank, 2010).

A study in the aquaculture sector in Hoang Bo and Xuan Thuy districts in Vietnam verified that storm surges, a rise in sea level, high waves, and strong winds caused severe damage and loss to aquaculture production and increased inequality in the communities that depend on the sector (Kelly & Adger, 1999). The frequent flood events resulted in fish and shrimp farms in the Red River Delta, Central Region and Mekong Delta in Vietnam losing 16,215 kg. The temperature increase caused increased fish fatality and spread of viruses and diseases (Asian Development Bank [ADB], 2009). The disease and virus outbreaks resulted in a profit decrease in shrimp aquaculture activities in Thailand (Flaherty et al., 1999). Climate change risks have caused competition among Malaysia's aquaculture farmers for the natural resources for production and thereby produced social conflict (Kamaruddin, Siwar, Jaarfar, & Mokhtar, 2008).

Most people in rural areas in developing Asian countries depend on the fishery sector (fishing and aquaculture). Fisheries activities support people by providing the rural and coastal community many employment opportunities and enhance their food security and access to income (De Silva & Soto, 2009). A study on vulnerability in the fisheries sector in Cambodia found that people highly dependent on the fisheries sector were suffering from the impacts of climate change on fisheries production and as a result, suffered poverty, marginalization, and a reduction in alternative income that prevented them from coping with the problems (Baran et al., 2009).

It was important to evaluate the environmental and social aspects of the impacts of climate change, as these factors ensure the sustainability and safety of aquaculture production (Anon, 2003). The social dimension is important for the improvement of policy and practice in coping with the climate shocks (Kelly & Adger, 2000). In terms of environmental aspects of aquaculture, future studies need to concentrate on solution of the environmental problems in terms of assessments of how to improve management, make technical improvements, and plan strategically (Hambal et al., 1994).

4.3 Socio-economic Vulnerability: Collective and Individual Vulnerability

Many people are under the impression that vulnerability is similar to poverty. However, vulnerability and poverty are two different entities. Cannon (1994) criticized the misconception of assuming vulnerability and poverty are the same because vulnerability covers the economic factors, is reliant on people's resources and income accessibility and risk defense factors whereas poverty refers to the difference between class and ethnic position, not the different level of risk impacts. However, Blaikie et al. (1994) contradicted this and emphasized that poverty is one of the factors that reflect on vulnerability, as it relates to individuals' accessibility to resources that influences vulnerability and the ability to cope with risk.

Income was used as the indicator, external measure, and proxy for access to resources in vulnerability assessments as the meaning of poverty is subjectively interpreted. In Sen's (1984) theory of entitlements poverty occurred due to an individual's low capability to gain access to markets. Under some countries' regulations and customs the individual who has access to resources is unable to increase his income and evade poverty due to limitations in the ability to buy or sell resources in the market (Adger, 1998). Poverty was not only influenced by income - location also had an influence. Remote areas, where facilities are lacking and access difficult, will have high marginal access costs and high vulnerability to hazards (Adger, 1998).

Johnston et al. (2009) considered that generally wealth, income sources diversification, education, infrastructure and technology accessibility, and broad-based agricultural development will enhance rural societies ‘adaptive capacity and build their resilience to reduce poverty. Badjeck et al. (2010) added that the diversification of fishery livelihood systems can increase adaptive capacity and will better adapt to climate disturbance. The diversification of fishery livelihood consists of job multiplicity and job mobility, geographical mobility and on-farm or within sector diversification. The inability of farmers’ households to adapt to environmental change causes not only poverty but also a specialization trap due to dependence on a single activity.

Vulnerability can be assessed by identifying the changes over time of the combination of socio-economic factors and environmental risks where risks are the external factors in the social system. Liverman (2001) also distinguished vulnerability as individual vulnerability and social vulnerability. Individual vulnerability was influenced by the right to use resources, income diversification, and the social status of individuals or households in society. However, social vulnerability was based on institutional and market structures, infrastructure, and income. Meanwhile, Adger (1998) highlighted that communities ‘social vulnerability included relative income distribution, diversification of and accessibility to economic assets and informal social security. The social vulnerability changes included livelihood modification according to the climate variability and also adjustment in institutional and political structures.

Social vulnerability occurs due to inequality in the social factors that cause farmers hazards, known as collective vulnerability. Collective vulnerability occurs at various levels, from individual to national, and increases directly with the increase of inequality within a society or a group at the level of infrastructure and institutional awareness (Adger, 1998). Geest and Dietz (2004) indicated that collective vulnerability was influenced by the natural environment, economic environment, socio-cultural environment, and political institutional environment. The institutional and market structure plays an important role in collective vulnerability, solving it by endorsing the implementation of social security, whether formal or informal, insurance protection, infrastructure, and income (Vincent, 2004). Collective vulnerability at the community level was exaggerated by income distribution, economic assets accessibility and diversity, and formal and informal institutional managing system (Adger, 1999). Income and wealth were important factors for coping with risks.

Cannon (1994) identified four major dimensions of socio-economic factors that had relationships to the levels of vulnerability: class, gender, ethnicity, and state. Class incorporated factors such as income allocation, assets held, education, and opportunity. Household security, nutrition, and health were factors for gender. The ethnicity dimension related to income, assets, livelihood, and discrimination. Meanwhile, institutional support, training, and district unfairness were considered to represent state domination. This study will focus on only two dimensions of socio-economic factors, i.e. class and ethnicity. Nevertheless, Liverman (2001) concluded that environmental and technological conditions, social relations, demography, health, land use, ownership, economy, and institutions were useful indicators to identify the condition of vulnerability in society.

Inequality and vulnerability were in direct relationship. Farmers' alternatives when faced with hazards were very limited and indirect, which raised the problems of poverty and resource scarcity. Inequality from this perspective relates to the community's capability to access private and common resources. Inequality of income is the important indicator to measure collective vulnerability. If inequality increases within a population or between communities over time, the collective vulnerability will also increase. The communication constraints of various institutions reflect the increase of collective vulnerability. Inequality, per capita GDP, and qualitative variables of institutional arrangements can be used as a measurement of collective vulnerability (Adger, 1999). Per capita GDP and income inequality were quantitative factors that proxy for collective vulnerability (Cha, 1998; Geest & Dietz, 2004).

The type of risks involved and the institutional arrangements to manage social risk determined the direct or indirect relationship between inequalities in collective vulnerability (Adger, 1999). Moreover, Kuznets (1955) explained the connection between income, inequality, and vulnerability as farmers' inequality and vulnerability increasing in the earlier stages of aquaculture production. As income increases after a certain level of production, the inequality will decrease and the farmers are able to cope with the vulnerability by distributing their income and assets to reduce production risks (Adger, 1998).

Institutional effectiveness, which has the power to determine the use of resources, assets, and income distributions within society, also influenced collective vulnerability. However, Gore (1993) mentioned that a few researchers had criticized the role of the institution in mapping society entitlement, by believing that the people or household itself must make the decision on endowments and entitlement. Meanwhile, Adger

(1998) stated that an effective and efficient strategy to cope with the external threats and climate change risks depends on institutions‘capability to communicate with the people and stakeholders and also having consistent preventive measures. Leach et al. (1999) added that institutions will influence the social action in deciding the climate change adaptations and mitigation strategies. A strong and effective institutional setting can help reduce collective vulnerability by ensuring appropriate hazards monitoring and effective information distribution to the public and the allocation of emergency attentiveness and pre-disaster planning.

Individual vulnerability, in contrast to collective vulnerability, consists of the resource dependency factors. Dependency relates to society and individuals who are directly dependent on resource production and the localized economy. People who depend on single economic activities will be highly vulnerable to risks (Cutter et al., 2003). The individual with low resources will come under stress due to increased inconsistency of income and the collapse of accessible resources. Resource dependency can be measured by identifying the percentage of confidence in climate-induced resources, change of income diagonally with time, migration, and other factors related to social stability and resilience. Adger (1998) considers that the factors that determine resource dependency are reliant on constitution and income range, social stability, and flexibility. Thus, migration, either seasonal or circular and due to social instability and stress as a result of a lack resources, will occur as a way to enhance the sustainability and stability of individual livelihoods and reduce the resource dependency level in certain places. Two factors that influenced migration are the push factor, based on diminishing resources or harmful events (such as loss of assets) in the original place, and pull factor, due to the attraction of good job opportunities and good infrastructure in other places.

4.4 Demographic and Capital Assets as the Factors of Socio-economic Vulnerability Assessment

Cannon (1994) noted that income and assets can be used to assess vulnerability. Income is an indicator that can explain stability at the individual level; choices of livelihood and social investment at the household level (Adger, 2000). The farmers' use of assets by to cope with risks results in maximizing productivity - a practice known as the asset-based approach. Farmers whose assets were limited in quantity and quality were more vulnerable to the risks due to the low returns and high variance of returns in their production (Cannon, 1994; Heltberg et al., 2009). Based on Sen's (1981) entitlement theory, the asset-based approach was able to explain the connection between the risks, human exposure and sensitivity, adaptation, and household vulnerability outcomes. This approach was linked with livelihood approaches and posited that household wellbeing is multi-dimensional and directly linked to command over assets and livelihood strategies (Heltberg et al., 2009).

The asset-based approach is based on the idea of the ownership of several productive assets (human, natural, physical, and financial assets), social and political assets and assets of location. The advantage of the asset-based approach is that it represents social differentiation. Discrimination always existed in accessing markets and community assets. Risks, assets, policy and the institutional, and structural context were elements that determined household's livelihoods, livelihood resilience, and well-being (Heltberg et al., 2009). However, in some situations, economic criteria were not suitable to assess the vulnerability. This contrasts with the argument that vulnerability was a component of structured entitlement (Adger & Kelly, 1999).

Demographic indicators can also be used as the indicators of individual vulnerability (Fussel & Klein, 2006). The gender factors commonly show that women are more vulnerable than men due to lower capacity for recovery and family responsibilities (Cutter et al., 2003; Dwyer et al., 2004); there were gaps between males and females in relation to exposure to hazards. Women were the most vulnerable groups as they were the majority of fisheries industries workers, for example in India, Cambodia, and Ghana, being influenced by physical and emotional capability compared to men. (Badjeck et al., 2010; De Silva & Soto, 2009). Thus, reduced production due to climate change will jeopardize both employment and food security in fisheries' dependent livelihoods.

Education is another important indicator that can be used to measure socio-economic vulnerability. Higher educational attainment ensures higher earnings and benefits livelihoods. A lower level of educational achievement will limit the farmer's capability to receive and access vital information (Cutter et al., 2003) and limit the alternatives to cope with and reduce risks (Badjeck et al., 2010). Jacob and Christianah (2013) noted that well-educated farmers found it easier to access loans and were able to increase their productivity. Furthermore, with a good education, literate farmers would be able to adopt new innovations in aquaculture practices and manage farms effectively. This finding further supported the significant role of education in farmers' adaptive capacity that Badjeck et al. (2010), Cutter et al. (2003), and Johnston et al. (2009) had highlighted. Family size influences vulnerability due to large families, having high expenditures to support the dependents compared to small families. The active role and great responsibility of family members developed the individual's resilience and his ability to protect the dependents from risk (Cutter et al., 2003; Dwyer et al., 2004).

In the social cultural context the vulnerability study aims to differentiate vulnerability to climate hazards across different sectors and social groups and to identify the most vulnerable groups within the district and the most vulnerable sectors (Vasquez–Leon, West, & Fuan, 2003). Differences in ethnicity, social class, and gender can be a factor identifying how different groups within a system might be more or less vulnerable to change. This will provide insights into why, who, and what are vulnerable (Brugere & De Young, 2015).

Ethnicity was also an important factor in assessing the socio-economic vulnerability in the social cultural context (Aquaculture for Food Security, Poverty Alleviation and Nutrition [AFSPAN], 2014, 2015; Lyn, MacKendrick, & Donoghue, 2011).According to the ADB (2014), traditional culture remains strong among the ethnic minority groups and influences livelihood choices. Ethnicity also influences gender relations, such as the way of life of women and men and their resilience. Thus, success or failure of intervention initiatives by outsiders in communities conducting aquaculture activities was strongly influenced by ethnicity. Rich local knowledge and practices to support, maintain and improve livelihoods through natural and community-built resources exist in the diverse ethnic, social and cultural groups (MOSTE, 2015).

AFSPAN (2015) reports that ethnic minorities were more vulnerable to climate change risks. Racial prejudice and location in a remote area were reasons for the often active discriminate against them. The existence of climate threats and increasing pressures from socio-economic changes present future challenges and opportunities to the ethnic communities in an area while cultural conceptions of ethnic minorities influence what is an acceptable choice of livelihood, which in turn limits livelihood diversification options (ADB, 2014). Equitable access to, and quality of, services emerged as a key issue for the community limitations where services barrier and security risks constrain the options to strengthen and diversify livelihoods to manage climate risk (CARE Poverty, Environment and Climate Change Network [PECCN], 2011). As a result, ethnic communities are being forced to change their way of life. They are constrained by their geographic location, climate conditions, and strong cultural traditions that limit them to a few options for adaptation.

The source of financing for aquaculture farmers was from income, occupation, savings, and credit or loans (Ali, Hossain, Hassan, & Bashar, 2008). The farmers' income will usually be allocated to consumption, savings, and capital to manage or expand the farm in the future. The savings capacity assist to expand the size of aquaculture farms depended on the affordable cost of farming and usually was limited due to the priority of use of income for self and family's future protection and security (Jacob & Christianah, 2013).

Afolabi (2010) and Shresta, (1989) discussed the significance of loans to farmers' income level, where loans or credit for agriculture helped increase the farm's yield by supporting the inputs, such as wages for labor, purchase of fertilizers and seeds, expansion of ponds or cages, and maintenance costs. Credit or loans as financial assets indirectly bring social benefits, especially to poor farmers, and increase their income as well as consumption and welfare, strengthening their physical assets. Furthermore, access to financial and social assistance can provide a safety net, especially to smallholder aquaculture farmers, to face problems of price volatilities in aquaculture inputs, such as fish feed, chemicals, and seeds at the beginning of the production cycle. Farm financing through credit or loans would also benefit the government in reducing agricultural subsidies and motivate farmers to be competitive and work hard on achieving high production (Khandker & Faruqee, 2003).

Aquaculture farmers' decisions on obtaining loans were influenced by farm size (the money is used for farm management and expansion activities) (Shrestha, 1989). Unfortunately, a lack access to loans and inadequate working capital were among the obstacles to the expansion of aquaculture projects. This has become a problem for maximization of the farms' profits. Engle (2010) highlighted the reasons for lack of funds for aquaculture activities, where private lenders were less keen to fund aquaculture projects due to the perception of high risk in this sector. Furthermore, the lenders' poor knowledge of the nature of aquaculture production and business led to the procedure in getting the aquaculture financing becoming complicated. Aquaculture is a new development sector and investors or creditors are unfamiliar with its potential. Further factors resulting in a lack of credit and poor cash flows in aquaculture projects were a problem of weak property rights and less confidence in the farmers' ability to use the farm as collateral against loans or credit (Hishamunda & Ridler, 2006). Furthermore, there are constraints in making aquaculture sustainable due to the high cost of seed, poor marketing channels, inadequate capital, and high costs of investment which slow down the aquaculture productivity (Jacob & Christianah, 2013).

Some farmers obtain loans with the help of family members who are working in government and the private sector who are eligible for, and qualified to access personal loans. Khandker and Faruqee (2003) support this premise, and state that farmers who have educated family members with a stable salary and with more land, found easy access to formal credit loans to finance their aquaculture farms. Farmers who have a lot of experience in aquaculture repaid loans as their knowledge and skills in practicing good farm management enabled their income to increase together with their capacity to repay loans. Owning large areas of land for aquaculture production will increase the level of production and income and increase loan repayment capacity. Furthermore, farmers' loan repayment capacities were also influenced by their marital status - married status and a larger family size and non-farm expenses had negative effects on the capacity to repay (Afolabi, 2008). However, most farmers did not take any loans due to the difficulties and restrictions on access to formal loans or credit, but started to fund their project using their savings and assets. With limited financial resources, farmers' savings were the main source of capital to reinvest and expand farms as well as to cover the farms' costs and losses.

Another important approach in assessing individual level vulnerability and adaptive capacity was diversification of income (Adger, 1998). Kelly and Adger (2000) consider that lack of income diversification is one of the root causes of income inequality. The risks and uncertainty in farm production and businesses caused farm profitability to fluctuate and raised the financial stress on farmers. When the farmers are faced with production risks or climate change events a secure off-farm income or income diversification and assets would help them recover losses. Off-farm employment is the autonomous adjustment that farmers, especially those in rural areas and without the government assistance, independently practice. The duration for which farms or households were involved in gaining off-farm income, either over the long or the short term, depend on the households' needs. The other autonomous adaptation that farmers usually practice is known as on farm strategy, such as expanding the farm size and adopting technologies, or non-farm strategy, through intensification of the current enterprise or joining a co-operative or shared farming enterprise (Raymond & Robinson, 2012).

Several researchers have mentioned the benefits of income diversification to farmers' sustainable livelihoods. The off-farm income played a multitude of roles in promoting equity in farmers' livelihoods, poverty reduction, and food security (Dixon, Gibbon, & Gulliver, 2001), encouraging transferable skills and abilities and farmers' household participation in a wide labor market (King, Lane, MacDougall, & Greenhill, 2009), supporting farm capital management (Afolabi, 2010), and reducing income vulnerability and increasing the effective risk aversion (Slater, Mgaya, Mill, Rushton, & Stead, 2013).

The diversification of activities through circular and seasonal migration will gain remitted income that can be used for future consumption, such as investment in education or agricultural capital (Adger, 2000). Job or livelihood diversification promoted multi-tasking that solves the problem of the specialization trap among farmers, improves farmers' adaptive capacity, and minimizes the risk of exposure (Badjeck et al., 2010; Mortimore & Manvell, 2006). Farmers' and their households' involvement in non-agricultural activities helped to reduce income inequality, helped them exit from poor livelihoods and reduced vulnerability by spreading risks among farmers (Adger, 1997). Under some conditions aquaculture activities were recognized as alternative income sources for fisherman or a source of food for poor rural farmers or small scale aquaculture farmers (Bostick, 2008) and marginal groups with limited access to the production resources of land and financial capital (Pemsl, Dey, Paraguas, & Bose, 2006). Furthermore, farm strategy, such as intensification in production, diversification, and farm size expansion, were among the strategies to improve the farmers' livelihoods. Off-farm income can play a major role in improving living standards but this depends on employment occupancy or market offers in the area where farmers were staying – areas with low potential had limited jobs to offer compared to areas with high potential (King et al., 2009).

Mortimore and Manvell (2006) reported that effective livelihood diversification needs technical options that solve problems concerned with entry barriers, cost and benefit factors, trade-offs, and constraints affecting income diversification. Off-farm income will result in trade-offs with risky specialization among the farmers and farmers' ability to overcome this effect will benefit them in terms of transfer of capital and extra funds on facing any risk or production failure from merging and sharing the different sources of income. Belton, Little, and Grady (2009) further highlighted the social, cultural, and economic perspectives of livelihoods and adaptable institutions and policies were also important in farmers' livelihood diversification strategy. An example from Thailand in aquaculture expansion as an economic growth recovery strategy after the Economic Crisis of 1997, shows that the change of structure of off farm labor markets increased opportunity costs and the demand for labor in the agriculture sector due to a decline in real wages in the services and industry sector and a decrease in the size of on-farm family labor due to the contributions from youths in the family from other employment outside the sector.

Another aspect that needs to be tackled is regarding aquaculture production scales, which influence the farmers' sustainable livelihoods and the efficiency of aquaculture production. Adger (1997) highlighted that the change in land ownership structure influences income inequality. Land ownership is related to the ability to access natural resources such as water and land. Aquaculture production success is determined by the scale of aquaculture production, the land size and quantity of fish produced (Bosma & Verdegam, 2011). The expansion of farm size showed the capability of farmers to use their production assets to increase their level of livelihood. However, the expansion of size must be associated with a conducive natural environment (land or space for fish production) and depends on water availability and also competes with other users of the space for other economic activities (FAO, 1984; Holmer, Hansen, Karakassis, Borg, & Schembri, 2008). Furthermore, the farmers had to maintain good aquaculture production facilities needed to keep aquaculture sustainable (Lichtkoppler, 1993).

Small farmers were usually unable to intensify their farms due to insufficient capital generation (Bosma & Verdegam, 2011). However, under other situations and in the worst case scenario, Islam, Milstein, Wahab, Kamal, and Dewan (2005) discovered that higher investments in fixed costs for large sized farms were not be able to be recovered by production yield. Production returns contributing to farm profit would sometimes be achieved in the long run but not immediately. Therefore, small scale farm production with low cost technologies would significantly contribute to global aquaculture production through an increase in the number of ponds or cages. Managing large size aquaculture farms and aiming to increase the productivity while maintaining the environmental sustainability was a greater challenge.

Small scale farmers were indicated to be having difficulties in managing their farms, for example, in stocking fingerlings, controlling the carnivorous wild fish, immature growth of fish, and high fish mortality (Edwards, 2000). Limited suitable sites, environmental impact awareness and multi-use conflicts on land and water bodies were among the main constraints to aquaculture activities. The intensive use of the natural coastal and inland habitat and ecosystems for modern aquaculture often caused natural resources to become depleted, disease spread and a reduction in the long term growth of aquaculture activities as well as environmental degradation (Frankic & Hershner, 2003).

Bolton et al. (2009) revealed that semi intensive production contributes to the maintenance of sustainable livelihoods for farmers with a fairly heterogeneous mix of assets, capabilities and aims, depending on the scale practiced. However, intensive production in small scale aquaculture enterprises is risky due to the probability of experiencing substantial financial losses when fish harvesting results in poor yields. Intensive large scale production was more economically sustainable due to the rotation in harvesting, apportioning the risk of mortality or growth between different ponds or cages, increasing revenue and practicing flexible harvesting times based on market value and demand.

Intensive or large scale aquaculture production seems to face the highest sustainability risks as the activities still require environmental goods and services (Beveridge, Phillips, & Macintosh, 1997). The practices of poor and small farmers have the potential to be sustainable due to the resource productivity and livelihood intensity. Meanwhile, medium sized operations appear to be a more stable farming system as they are capable of adapting to market requirements and changes in the socio-economic environment and stabilizing farmers' livelihoods (Bolton et al., 2009).

Sustainable aquaculture practices and production need practical technology that can provide efficient supply chain as well as eradicate limitations in production. The two main roles of technology in aquaculture are culture technology, for breeding the aquaculture species and using local methods to culture fingerlings; and production technology, which controls the whole production process up to the point of supply of the products to the customer (FAO, 1984). Technology is also important to control disease outbreaks due to climate change uncertainties and impacts on water quality, by formulating vaccines to manage the stock and improve its health (McCausland, Mente, Pierce, & Theodossiou, 2006). For instance, such technology has been implemented in Thailand through genetic techniques to pre-test larvae before stocking ponds and to develop progressively lower salinities in rearing techniques for post-larvae hatchery acclimatization (Lebel et al., 2002). Technology in the United Kingdom and Denmark has successfully solved the problem of limited access to potential areas for cage aquaculture expansion and environmental and ecological friendly aquaculture practices (Huntington, 2009).

Migration and factors of production such as land, labor, capital, and knowledge, determine the benefits or success of technology adoption in aquaculture (Edwards, 2000; Adger, Kelly, Winkels, Huy & Locke, 2002; Ahmed & Lorica, 2002). However, most of the aquaculture farmers in most countries of the world only have low-input technology that limits the advantages of the system (Ahmed & Lorica, 2002). A knowledge on the environment of aquaculture production, limitation of resources and available capital, and local environmental necessity were important in appropriate technology selection because the effectiveness of a technology depended on its nature, the size of the population that adopts the technology and the population's wealth level (Srinath, Sridhar, Kartha & Mohanan, 2000; Subangsihe, 2003).

Suitable techniques required effective communication networks, reliable information and decision making processes in choosing the best production systems and species suitable for the farm environment. The advancement of technology in aquaculture provides a wide range of newer techniques including sustainable stock enhancement, natural resources use for nutrient stabilization, environmentally integrated systems such as recirculating systems, integrated water use, and artificial upsurge ecosystem food management (Subangsihe, 2003). Furthermore, the environmentally friendly technology that is developed must be integrated with the industrial organization and knowledge system (Lebel et al., 2002) and include aspects of aquaculture management activities such as fish species breeding, fertilization, feeding, harvesting strategies, and marketing or aquaculture production processing (De Silva & Turchini, 2009; Huntington & Hassan, 2009; Prein & Ofori, 1996a).

Regardless of the high costs, technology can be developed in small scale aquaculture operations with the participatory planning approaches which integrate the role of farmers, institutions, and credit supports. Technology modification encouraged new markets for aquaculture products that transformed products into higher value products that were believed to be going to have high demand (Wijkstrom, 2009). Furthermore technological, economic, social, environmental, and commercial aspects were important in the improvement and development of effective fisheries management systems (Huntington & Hassan, 2009). The use of technology would not promise successful return to production without the synergy of other factors. For example, farmers in Thailand failed in stocking fingerlings due to high densities in ponds which caused fish mortality due to lack of fertility, insufficient food, lack of growth, or threats from carnivorous fish (Edwards, 2000). Imbalance in income and technology distribution in farms will result negative impacts or spillovers that cause the misuse of open-access resources due to differences in access and entitlements to scarce environmental resources (Adger, Kelly, Winkels, Huy, & Locke, 2002).

4.5 Research Methodology

The assessment of socio-economic vulnerability is based on farm level data and employs primary data analysis.

4.5.1 Design of the Questionnaire

This study focuses on the assessment of climate change impacts on pond and cage aquaculture farms. These aquaculture system activities were selected because the production activities are dependent on the natural environment with direct and indirect effects from the changing climate. Two sets of questionnaires were designed for the survey, adapted to the characteristics of aquaculture pond and cages activities. The questionnaire items were designed based on similar studies by Ngathou et al. (2005) and Vergara, Coble, Knight, Patrick, and Baquet (2001), and aquaculture handbooks (undated) prepared by Department of Fisheries, Malaysia. Some questionnaire items were also adapted from Universiti Kebangsaan Malaysia research on aquaculture practice codes and from Kamaruddin (2009). The pond aquaculture farmers' questionnaire comprises 60 items questionnaire and that for cage aquaculture farmers, 55 items. The items were divided into five sections. The difference of five items between the two questionnaires is in section four; the remaining sections have the same number of questions. The five sections and number of items for each for both questionnaires is shown in Table 4.1.

Table 4.1: Questionnaire sections and number of items included (Kamaruddin, 2009; Ngathou et al., 2005; Vergara et al., 2001)

Section	Aquaculture system and number of items	
	Pond	Cage
Section 1: Demographic factors	6	6
Section 2: Producers' asset information	12	12
Section 3: Aquaculture activities information	10	10
Section 4: Climate change impacts assessment	12	7
Section 5: Adaptation strategies to climate change risk	20	20

Section 1 covers the respondents' demographic profiles (age, ethnicity, gender, marital status, highest educational qualification, and number of family members). All items except for age and number of family members were measured via a closed-ended question format.

Section 2, covers aquaculture farmers' asset information, categorized based on four assets factors: natural and environmental assets; physical assets; financial assets and human assets. The questions comprised multiple choices, open and dichotomous questions.

Section 3 includes questions on aquaculture farms activities and management information. The questions relate to operation years, production area, types of cultured species, aquaculture project investment, aquaculture project economic information, the performance of aquaculture projects, and the information on production total loss due to environmental risks. Most of the questions are open-ended. The questions on aquaculture project investment had four attributes while those concerning economic information had seven attributes. The respondents were required to choose among six Likert scales (between 1= not sure, 2= highly decreased, 3=decreased, 4=no difference, 5= increased, and 6= highly increased) to answer 10 attributes for questions on the performance of socio-economic factors of aquaculture farmers.

Section 4 encompasses the questions on climate change impacts assessment in aquaculture production. The first question required the respondent to choose the percentage of risk effects estimation that contributes to production loss due to 13 climate change attributes. There percentage of risk effects fell into six intervals: 1 = 1-20%, 2 = 21-40%, 3 = 41-60%, 4 = 61-80%, 5 = 81-100%, and 6 = no effect. The next question asks about the number of productions affected by disease. Subsequent questions concentrate on water quality and disease control management and include 10 related questions for pond aquaculture questionnaires and five for cage aquaculture.

Section 5 comprises questions on adaptation strategies to climate change risk and requires a respondent to answer based on their experiences in aquaculture farm activities. The questions relate to needs for climate change information, needs and willingness to pay for aquaculture insurance, the technology used, and off-farm income benefit.

4.5.2 Sampling Design and Sample Size

The target respondents for this study are aquaculture farmers who employ freshwater and/or brackish water pond and cage systems. The study used random stratified sampling in order to understand the differences between key demographic subgroups within the population. The selected sample is separately and equally selected from each of the subgroups (Leedy & Ormrod, 2005). In this study, respondents were stratified by types of aquaculture system and population data obtained from the Department of Agriculture, Sarawak. The advantages of random stratified sampling are that:

a) it results in greater accuracy than a simple random sample of the same size,
b) it is controlled against an unrepresentative sample and balances the sample characteristics,
c) It ensures sufficient sample points to support a separate analysis of any subgroup.

The sample size was determined using proportionate stratification. In this study, the proportionate stratification was calculated based on types of aquaculture system and districts. The survey was conducted in six instead of 11 divisions in Sarawak and in 18 selected districts under these divisions. This study follows the formula created by Yamane (1967) to calculate the sample size. The overall population was 660 people, namely farmers who had a registered (by the DOA Sarawak) aquaculture license and were in active production. The sample size of this study was calculated by the following formula:

$$n = \frac{N}{1 + N(e)^2} \tag{4.1}$$

n = sample size, N = population size (660 people); e = level of precision (0.05). Thus, the sample size for this study was 249 people.

The stratum sample size was determined by the following equation:

$$n_h = (N_h / N)*S \tag{4.2}$$

n_h = sample size of each type of aquaculture systems / sample size of aquaculture systems in district

N_h = population size of aquaculture farmers in each type of aquaculture system / population size of farmers of aquaculture systems in districts

N = total population of aquaculture farmers for all types of aquaculture system in Sarawak (660)

S = sample size (249)

Table 4.2 and Table 4.3 show the outcome of proportionate stratification of sample measure.

Table 4.2: Stratified sample size calculation according to type of aquaculture system

Aquaculture system	N_h	N_h / N	(N_h / N)*S
Freshwater ponds	469	0.71	177
Brackish water ponds	13	0.02	5
Freshwater cages	55	0.08	20
Brackish water cages	123	0.19	47
Total	660		249

Table 4.3: Stratified sample size calculation according to type of aquaculture system by district

District	Freshwater ponds		Freshwater cages		Brackish water ponds		Brackish water cages	
	Farmers	n_h	Farmers	n_h	Farmers	n_h	Farmers	n_h
Kuching	28	11	20	7	-	-	48	18
Bau	115	43	-	-	-	-	-	-
Lundu	10	4	-	-	-	-	-	-
Siburan	53	20	-	-	-	-	-	-
Samarahan	31	12	-	-	-	-	-	-
Asajaya	13	5	-	-	-	-	-	-
Serian	46	17	-	-	-	-	-	-
Pantu	12	4	-	-	-	-	-	-
Engkelili	4	2	-	-	-	-	-	-
Lubok Antu	3	1	-	-	-	-	-	-
Batang Ai	-	-	35	13	-	-	-	-
Batang Lupar	40	15	-	-	12	5	-	-
Betong	6	2	-	-	-	-	-	-
Saratok	32	12	-	-	1	-	-	-
Sarikei	18	7	-	-	-	-	7	3
Maradong	24	9	-	-	-	-	-	-
Limbang	27	10	-	-	-	-	20	8
Lawas	7	3	-	-	-	-	48	18
Total	469	177	55	20	13	5	123	47

4.5.3 Data Collection

The data collection process in this study consisted of two phases. First, a questionnaire was designed and pre-tested in a pilot study to examine the content validity of questionnaires in order to ensure the measurement instruments reflect the contents or variables being measured (Leedy & Ormrod, 2005). Next, the data were collected during fieldwork.

4.5.3.1 Pilot study

The purpose of the pilot study was to verify whether the respondents understood the questionnaires. The pilot study was conducted during August 2012 at the cage aquaculture area in Santubong river, Kuching and Temaga river, Lundu, Sarawak, during which time 12 farmers were interviewed, and in December 2012 for the pond aquaculture system in Hulu Langat, Selangor, where four farmers were interviewed. Feedback from the pilot surveys was considered in the redesign and improvement of the questionnaire contents.

4.5.3.2 Survey method

Face to face interviews were conducted in order to achieve high response rates and ensure data accuracy. The survey was begun in May 2013 and completed by October 2014. The survey took almost one and a half years due to location factors, time constraints and safety issues and resulted in data collection from just 255 farmers. The long time-frame of the survey was due to the distances between farms and districts. Furthermore, the data collection fieldwork was carried out with the assistance of an officer from the DOA due to the locations and distances and for safety reasons, and thus mostly followed the officer's schedule. Six of the 255 respondents were disqualified and withdrawn from the sample and the final data set was thus gathered from 249 respondents.

The survey was conducted in six divisions of Sarawak: Kuching, Samarahan, Sri Aman, Betong, Sarikei, and Limbang divisions. The survey was not limited to covering the items on the questionnaires; semi-structured interviews were also conducted during sessions in order to collect as much additional qualitative information as possible. This helped the researcher achieve a better understanding of the related issues and obtain important information to fulfill the study objectives.

4.5.4 Data Analysis Techniques and Model Specification

This study employed descriptive analysis, factor analysis, reliability tests, and multivariate logistic regression to profile the respondents' demographic and socio-economic data and identify the relationship between the endogenous and exogenous variables. The computer software used to perform these analyses includes Statistical Packages for Social Sciences (SPSS v. 21) and Stata Statistical Software (STATA 11.0).

4.5.4.1 Descriptive analysis

Descriptive analysis was used to test the assumptions made by the individual tests (Pallant, 2010) and was usually conducted to describe demographic variables and the number of respondents involved in the survey (Ananda, 2009). As this study attempts to identify the relationship between socio-economic aspects and climate change risks, the analysis began by explaining the respondents' overall demographic profile, followed by the performance of socio-economic factors under the uncertainties of climate change risks and the percentage contribution of climate change risk to production loss.

4.5.4.2 Factor analysis

Factor analysis is one of the multivariate data analysis techniques that is well-known as a data reduction technique that works on summarizing large sets of latent variables into a small set of factors or components. The variables were refined and reduced to bring the coherence subscales to a more manageable number (Pallant, 2010). This analysis was used to understand the structure of a set of variables and to measure the variables in constructing the questionnaires (Field, 2009). As some of the items on the questionnaires were self-designed, this study employed the exploratory factor analysis to identify the underlying structure to the entire set of variables by gathering information on the interrelationships among the original variables. Furthermore, the dimensions of specific items can be evaluated where the specific variables become composite and easily interpreted and described. However, these composite variables cannot be indicated as either independent or dependent variables (Soon, 2007).

To indicate the dimensions of factors that influenced Sarawak's aquaculture productivity, the factor analysis is purposely used not only to refine and reduce the less important or insignificant variables in the study, but also to assess farmers' (the respondents') perception of the important factors that are significant to aquaculture sector productivity through the construction or analysis of composite indices of weighted each of the variables in the index (Organization for Economic Co-operation and Development [OECD], 2008).

This study conducted two separate factor analyses to classify the effects of socio-economic factors under the uncertainty of climate change risks and to identify the climate change risk drivers that effect production loss based on farmers' experience. These factors were chosen because the vulnerability was influenced by factors of environmental risk, economic, and institutional aspects (Adger, 1998). Thus, the latent variables in this study are socio-economic effects and environmental effects on aquaculture production. The observed variables in factor analysis were indicated from the responses to the related questions. The respondents were asked to rate their perception on various socio-economic effects that were significant to their livelihood and production, and to rate the percentage of the environmental risks effects on their aquaculture production. The mathematical models for factor analysis of socio-economic effects is:

$$socio - economic\ effects = c_1V_{1i} + c_2V_{2i} + c_3V_{3i} + c_4V_{4i} + c_5V_{5i} + c_6V_{6i} + c_7V_{7i} + c_8V_{8i} + c_9V_{9i} + \varepsilon_i \quad (4.3)$$

Where,

$c_1, c_2, .., c_m$ = factor loadings related to socio-economic effects

$V_{1i,} V_{2i,..,} V_{mi}$ = common factors

ε_i = the unique factor

V_{1i}	= income increase	V_{6i}	= technology usage increase
V_{2i}	= aquaculture revenue increase	V_{7i}	= labor increase
V_{3i}	= sales increase	V_{8i}	= labor wage increase
V_{4i}	= farm size increase	V_{9i}	= savings increase
V_{5i}	= technical knowledge increase		

Meanwhile, the mathematical model for environmental effects is:

$$environmental\ effects = c_1V_{1i} + c_2V_{2i} + c_3V_{3i} + c_4V_{4i} + c_5V_{5i} + c_6V_{6i} + c_7V_{7i} + c_8V_{8i} + c_9V_{9i} + c_{10}V_{10i} + c_{11}V_{11i} + c_{12}V_{12i} + c_{13}V_{13i+}\varepsilon_i \quad (4.4)$$

Where,

$c_1, c_2, .., c_m$ = factor loadings related to socio-economic effects

$V_{1i,} V_{2i,..,} V_{mi}$= common factors

ε_i = the unique factor

V_{1i}	= less dissolved oxygen	V_{8i}	= long rainy seasons
V_{2i}	= decreased water temperatures	V_{9i}	= long drought seasons
V_{3i}	= increased water temperature	V_{10i}	= experiencing hurricane/ storm/ waves / strong water currents

V_{4i} = water pH less than 6.5 (acidic)

V_{5i} = optimal alkaline water

V_{6i} = water pollution due to water transportation

V_{7i} = water pollution due to housing, industry, agriculture and trade activities

V_{11i} = floods and erosion

V_{12i} = pandemic disease

V_{13i} = non-pandemic disease

The orthogonal rotation (varimax) was employed to factorize the items while the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, Barlett's test of sphericity and the anti-image correlation and covariance matrices were analyzed as they are the important output in this analysis (Field, 2009). As Kaiser (1974) recommended, a KMO above 0.5 is acceptable. Based on Hutcheson and Sofroniou (1999) in Field (2009), the summary of sampling adequacy level by KMO values is presented in Table 4.4.

Table 4.4: Kaiser-Meyer-Olkin measure of sampling adequacy

Measurement value	Level
Above 0.9	Superb
0.8 – 0.9	Great
0.7 – 0.8	Good
0.5 – 0.7	Mediocre
Below 0.5	Not applicable

4.5.4.3 Reliability analysis

The reliability analysis was conducted to measure the consistency and stability among the variables in every factor extracted by factor analysis. Cronbach's alpha coefficient was used to determine the reliability scale where the data were split in two in every possible way and correlation coefficients for each split were computed. According to Pallant (2010), Cronbach's alpha was considered accepted if it fell at values above 0.7 but values above 0.8 were better, however Hair et al. (2010) noted that the values of 0.6 to 0.7, were acceptable.

4.5.4.4 Multivariate logistic regression

This study employed multivariate logistic regression analysis using the STATA 11.0 software. The dependent variable of study is the farmers' level of income, categorized as poor and non-poor income. The poor and non-poor income levels were based on the poverty line income (PLI) level in Sarawak for the year 2009 (an average monthly income of less than RM 940 for poor-income farmers and more than this for non-poor income farmers (Mohd, 2015).

By adapting the measurement of vulnerability in the SLA model (Chambers & Coway, 1991) using the asset-based approach, the socio-economic factors were indicated and categorized into four different types of capital or assets, known as the productive assets (Heltberg et al., 2009). The productive assets include physical capital, natural or environmental capital, financial capital, and human capital. Although the social capital is also considered one of the assets in the SLA and is important in assessing farmers' vulnerability to climate change risks, this vulnerability assessment only focused on the individual aspects of farmers and their farm management. Thus, the social assets were excluded from the assets-based approach assessment of the aquaculture activities. In addition to the capital assets, the socio-economic vulnerability assessment also includes the farmers' demographic aspects. These factors were represented as the independent variables in this study. Each of the variables under the capital assets and demography categories are indicated in Table 4.5.

Table 4.5: Summary of variables of socio-economic vulnerability assessment

Factor	Variables
Human Capital	Education years*, aquaculture knowledge, training.
Physical Capital	Structure*, farm size*, technology applied, land ownership.
Financial Capital	Loan, other income*
Natural/ environmental Capital	Land ownership, farm size*, pH decrease, pH increase, temperature decrease, temperature increase, less dissolved oxygen, raining, high waves, pandemic disease and non-pandemic disease.
Demographic	Aquaculture system, production scale, age, gender, ethnicity, marital status, family*.

Note: * continuous variable

The multivariate logistic regression was employed to identify the factors that have a significant association with the incidence of poor income among the aquaculture farmers in Sarawak in which the income category based on the poverty line income represented socio-economic vulnerability. The logistic regression model for estimating the probability of farmers having non-poor income can be written as:

$$P(non\ poor) = \frac{e^{(\alpha+\beta_0 X_1+\beta_2 X_{2+\cdots+}\beta_n X_n)}}{1+e^{(\alpha+\beta_0 X_1+\beta_2 X_{2+\cdots+}\beta_n X_n)}} = \frac{e^{x\beta}}{1+e^{x\beta}} = \Lambda(x\beta) \tag{4.5}$$

equivalent to:

$$P(non\ poor) = \frac{1}{1+e^{(\alpha+\beta_0 X_1+\beta_2 X_{2+\cdots+}\beta_n X_n)}} = \frac{1}{1+e^{-x\beta}} \tag{4.6}$$

where $x\beta = \alpha + \beta_0 X_1 + \beta_2 X_{2+\cdots+}\beta_n X_n$ and Λ is lambda.

The probability of farmers being above the poverty line can be estimated as:

$$P(non\ poor) = 1 - P(\ poor) \tag{4.7}$$

where α is constant, β is a coefficient estimated from the data, X is an independent variable, n is the number of observation and e is the base of the natural logarithm.

Furthermore, the marginal effect, also known as partial effect of the predictors, was also employed in this study in order to predict the increase or decrease of a unit change in the level of income by the dependent variable (Buis, 2010). In economics, the marginal effects results were reported as this analysis is more intuitive in interpreting the variables from a practical standpoint, which cannot be explained by the odds ratio value in logistic regression.

In logistic regression, given $F(x) = P(Y = 1)$ in equation (4.5), the marginal effect of x_k is given by:

$$\frac{\partial p(Y=1)}{\partial x_k} = \frac{e^{x\beta}}{(1+e^{x\beta})^2}\frac{\partial(x\beta)}{\partial x_k}$$

$$= \frac{e^{x\beta}}{(1+e^{x\beta})^2}\beta_k$$

$$= \Lambda(x\beta)(1-\Lambda(x\beta))\beta_k$$

$$= P(Y=1) \times P(Y=0) \times \beta_k \tag{4.8}$$

In categorical variables, by holding the other variables constant in the model, the changes of $P(Y = 1)$ as the categorical predictor changes from 0 to 1 were explained by marginal effects (Williams, 2012). In the linear regression, the marginal effect model was presented as:

$$\frac{\partial Y}{\partial X_1} = \beta_1 \tag{4.9}$$

where Y is the dependent variable, X_1 is the independent variable 1 and β_1 is a constant or marginal effect. For continuous variables marginal effect analysis approximates the amount of change in Y produced by a 1 unit change in X_k whilst for categorial variables this analysis approximates that holding other variables (Williams, 2016). The independent variables that were significant [p-value (<0.05) and p-value (<0.10)], were selected, and will be tested collectively in the final models with multivariate logistic regression to indicate the most significant factors having a relationship or contributing to the poverty income of Sarawak's aquaculture farmers.

The socio-economic vulnerability model analysis in this study was derived from the combination of significant independent variables under each demographic factor, financial capital, human capital, physical capital, and natural resource and environmental capital factor analysis results. The results were discussed based on the regression coefficient for predictors and the odds ratio, which is derived from the exponentiation of predictor coefficient. The odds ratio value was interpreted as, if all other predictors are held constant, the change in the odds of level of income is given by a unit change in the predictor variable (Peng, So, Stage, & John, 2002). Then, the marginal effect results were taken to indicate the instantaneous rate of change in either continuous variables or categorical variables (Williams, 2016).

Based on farm level data gathered from the farmers, the extension of the biophysical vulnerability assessment was further explored by identifying the relationship between level of income and natural and environmental capital. This will assess details of the effects of climate change events or risks on aquaculture farmers' socio-economic status and the third model (equation 4.10) can be derived as:

$$logit[P(Y=1) = \alpha + \beta_1 aqsys + \beta_2 scale + \beta_3 landown + \beta_4 farmsize + \beta_5 pHdec + \beta_6 pHinc + \beta_7 tempdec + \beta_8 tempinc + \beta_9 disolvO2 + \beta_{10} rain + \beta_{11} highwave + \beta_{12} pdisease + \beta_{13} npdisease \quad (4.10)$$

Next, the study concentrates on assessing the socio-economic vulnerability due to climate change. The independent variables under each category of capital assets (environment or natural assets, financial assets, human assets, and physical assets) and demographic factors were analyzed and a significant relationship with the category of income, if any, was noted. The fourth model (equation 4.11) of socio-economic vulnerability assessment can be derived as:

$$logit[P(Y=1) = \alpha + \beta_1 aqsys + \beta_2 scale + \beta_3 eduyr + \beta_4 pHinc + \beta_5 tempinc + \beta_6 disolvO2 + \beta_7 pdisease + \beta_8 loan + \beta_9 offinc + \beta_{10} aptech + \beta_{11} ethnic + \beta_{12} mstatus + \beta_{13} family \quad (4.11)$$

The specification of variables in both models is explained in Table 4.6.

Table 4.6: Specification of variables

Variables	Label	Measurement scale
$[P(Y=1)$	Probability of non-poor income	(0) poor income (1) non-poor income
α	Constant	-
β	Coefficient of predictor variable	-
$aqsys$	Aquaculture system	(0) Pond Aquaculture System (1) Cage Aquaculture System
$scale$	Production scale	(0) small (1) medium
$eduyr$	Education years	Continuous variable
$aptech$	Apply technology	(0) No (1) Yes
$landown$	Land ownership	(0) Self-ownership (1)Temporary Occupation Licence (TOL) land
$loan$	Loan	(0) No (1) Yes

'Table 4.6, continued'

$offinc$	Off-farm income (in RM)	Continuous variable
$farmsize$	Farm size (in ha / m^2)	Continuous variable
$ethnic$	Ethnicity	(0) Non Chinese (1) Chinese
$mstatus$	Marital status	(0) non-married (1) married
$family$	Number of family members	Continuous variable
$pHdec$	pH decrease	(0) no effect (1) effect
$pHinc$	pH increase	(0) no effect (1) effect
$tempdec$	Temperature decrease	(0) no effect (1) effect
$tempinc$	Temperature increase	(0) no effect (1) effect
$disolvO2$	Less dissolved oxygen	(0) no effect (1) effect
$rain$	Rainy	(0) no effect (1) effect
$highwave$	High waves	(0) no effect (1) effect
$pdisease$	Pandemic disease	(0) no effect (1) effect
$npdisease$	Non-pandemic disease	(0) no effect (1) effect

Note: (0) refer to reference or base category

To ensure accurate measurements for the model, several diagnostic tests were used for every model regressed in this study. The model evaluation firstly indicates the Likelihood Ratio (LR) χ^2 value with p-value <0.05. The model specification test is indicated by an insignificant p-value >0.05 of _hatsq. The model goodness-of-fit was evaluated by the Pseudo R^2 value and the significance of Hosmer and Lemeshow's goodness-of-fit test at p>0.05. Lastly, the models were checked for the occurrence of the multicollinearity problem by checking that each variable's value for the Variance Inflation Factor (VIF) is less than 10. The VIF shows how much of the inflation of the standard error could be caused by collinearity.

4.6 Findings

Based on the analysis of data gathered from 249 qualified respondents at the individual farm level, the discussion of the results will begin with a descriptive analysis. This will clarify the respondents' demographic profiles, the performance levels of socio-economic factors under the uncertainty of climate change risks through farmers' experiences and the climate change risk factors that influence production risks and losses in aquaculture activities. The remaining analysis results, factor analysis, reliability analysis, and multiple logistic regressions, are discussed in the following sections.

4.6.1 Demographic Profile of Respondents

The summary of the socio-demography of respondents in Table 4.7 shows that this study involved 224 male and 25 female respondents. Of these, 1.6% were less than 24 years old, 5.2% were between 25 and 34 years old, 17.7% were between 35 and 44 years old, 30.9% were between 45 and 54 years old, 30.5% were between 55 and 64 years old and 14.1% were 65 years old or more. The majority of the survey respondents (103) were from groups classed as Bumiputera, such as Bidayuh, Iban, Bisaya, Lun Bawang, and Kedayan; 80 were Chinese and 66 Malay.

As far as type of aquaculture system is concerned, 51 respondents (20.5%) were brackish water cage farmers, 13 (5.2%) were brackish water pond farmers, and 31 (12.4%) were freshwater cage farmers. The majority of respondents, 154 or 61.8% of the selected samples, were freshwater pond farmers. In terms of educational background, 16 respondents (6.43%) held tertiary education qualifications (a certificate, diploma or degree). Twenty-three (23) (9.24%) had not undergone any formal education while the majority (108 (43.37%)) had attended primary education. Furthermore, 132 respondents had attended secondary education, of which 55 (22.09%) had completed upper secondary school while the remaining 47 (18.88%) had completed lower secondary school.

Table 4.7: Socio-demography of respondents

Variable	Category	Frequency	Percentage
Gender	Male	224	90
	Female	25	10
	Total	249	
Age	≤24 years	4	1.61
	25 - 34 years	13	5.22
	35 – 44 years	44	17.67
	45 – 54 years	77	30.92
	55 – 64 years	76	30.52
	≥65 years	35	14.06
Ethnicity	Malay	66	26.5
	Chinese	80	32.1
	Bumiputera	103	41.4
Aquaculture system	Freshwater pond	154	61.8
	Freshwater cage	31	12.4
	Brackish water pond	13	5.2
	Brackish water cage	51	20.5
Education	Not school	23	9.24
	primary school	108	43.37
	lower secondary school	55	22.09
	upper secondary school	47	18.88
	tertiary education (certificate/ diploma / degree / others)	16	6.43
Aquaculture income	≤RM2,170	62	24.9
	RM2,170.10 - RM9,600	63	25.3
	RM 9,600.10 - RM43,200	62	24.9
	≥RM 43,200.10	62	24.9
Other income	≤RM700	69	27.7
	RM 700.10 – RM 2,000	64	25.7
	RM 2,000.10 – RM 6763	54	21.7
	≥RM 6763.10	62	24.9

The aquaculture income was the approximate annual income received from the sales of aquaculture products. Sixty-two (62) respondents (24.9%) had an income less than or equivalent to RM2,171 whereas four had no income (RM 0) because their aquaculture production was used for personal consumption. Sixty-three (63) farmers (25.3%) received an income of between RM 2,170.10 andRM9,600. Sixty-two (62) farmers (24.9%) had an income from RM 9,600.10 to RM 43,200 and the same number also received the highest category of income of RM 43,200.10 and above from aquaculture production.

In addition to their aquaculture income, some farmers also obtained additional income from off-farm aquaculture activities. Some of the farmers were government servants or private agency staff and a few of them were involved in business or were entrepreneurs. The majority of the farmers were involved in other agricultural activities such as oil palms and rubber plantations, paddy and pepper plantations, and rearing livestock. The majority of cage farmers worked as fishermen. Some of the respondents were pensioners and a few of them worked full time in aquaculture activities and depended entirely on the revenue from aquaculture. The descriptive results showed that 69 farmers (27.7%) had an annual income less than or equivalent to RM 700 whereas 23 were full-time workers in aquaculture production and were not involved in any off-farm aquaculture activities. Sixty-four (64) farmers (25.7%) had off-farm income of RM700.10 to RM2,000 while 54 (21.7%) obtained RM 2,000.10 to RM6,763. The highest off-farm income category, RM 6,763.10 and above, was obtained by 62 farmers, that is 24.9% of the respondents.

4.6.2 Socio-economic Effects Under the Uncertainty of Climate Change Risks

To evaluate the socio-economic vulnerability due to the uncertainty of climate change risks, the respondents were asked to answer nine questions based on their experiences in managing farms and identifying the changes in farm activities over the previous five years of production. The socio-economic effects on farmers’ livelihoods are presented in Table 4.8.

Table 4.8: Socio-economic effects under the uncertainty of climate change risks

Variable	Category	Frequency	Percentage (%)
Income	Decreased	9	3.6
	Slightly decreased	28	11.2
	No difference	23	9.2
	Slightly increased	165	66.3
	Increased	24	9.6
Aquaculture revenue	Decreased	10	4
	Slightly decreased	45	18.1
	No difference	33	13.3
	Slightly increased	142	57
	Increased	19	7.6
Sales	Decreased	8	3.2
	Slightly decreased	38	15.3
	No difference	29	11.6
	Slightly increased	153	61.4
	Increased	21	8.4
Number of ponds or cages	Decreased	2	0.8
	Slightly decreased	17	6.8
	No difference	132	53
	Slightly increased	82	32.9
	Increased	16	6.4
Knowledge of aquaculture technology	Decreased	1	0.4
	Slightly decrease	1	0.4
	No difference	25	10
	Slightly increased	192	77.1
	Increased	30	12
Technology usage	Decreased	0	0
	Slightly decreased	4	1.6
	No difference	186	74.7
	Slightly increased	53	21.3
	Increased	6	2.4
Number of laborers	Decreased	0	0
	Slightly decreased	8	3.2
	No different	221	88.8
	Slightly increased	16	6.4
	Increased	4	1.6
Labor wage	Decreased	0	0
	Slightly decreased	2	0.8
	No difference	220	88.4
	Slightly increased	22	8.8
	Increased	5	2
Savings	Decreased	0	0
	Slightly decreased	6	2.4
	No difference	95	38.2
	Slightly increased	139	55.8
	Increased	9	3.6

The descriptive results showed that the majority of farmers attained a slight increase in aquaculture income (66.3%), aquaculture revenue (57%), sales (61.4%), knowledge of aquaculture technology (77.1%), and savings (55.8%). Meanwhile, 9.6% of farmers had obtained a huge income increment, 7.6% had high additional revenue, and 8.4% were actively engaged in aquaculture sales. However, 14.8%, 22.1%, and 18.5% of farmers had experienced decreases in income, revenue, and sales respectively.

In terms of number of ponds and cages, 53% of respondents did not build any new pond or cage and still managed the same numbers of ponds and cages over the five-year period. However, 7.6% had a decrease in the number of ponds or cages. The decrease in number of ponds and cages was due to damage to ponds and cage structures caused during catastrophic events such as floods and high waves, and obsolete cages.

A proportion (74.7%) of respondents did not use technology in their farm activities, although a total of 89.1% of respondents ranked their knowledge of technology as slightly increased and increased. In Sarawak, most of the farmers were involved in small scale and medium scale production that prevented them from investing or buying modern machinery or aquaculture equipment. Therefore, there was a low usage of technology in pond and cage management among the farmers. Furthermore, a majority of the farmers (88.8%) had no additional laborers and 88.4% of them showed no additional labor salary within the years under study. Most of the aquaculture farmers in Sarawak were managing their own farms with the assistance from family members. They were involved in small scale production and were unable to hire labor. Only 8% of the respondents hired additional labor for activities during the study years.

4.6.3 The Effects of Climate Change Risks on Aquaculture Production

Aquaculture farmers' perception of climate change risks to their activities were evaluated based on their ranking of the risk level for each identified types of risk. Table 4.9 shows that in general climate change risks to aquaculture production in Sarawak may be considered moderate. This finding was based on the frequency (number of farmers experienced) with its percentages of types of risk that occurred in their farm and farmers' rating of risk levels through their experience.

Table 4.9: Climate change risks effects on aquaculture production

Type of Risk	Measurement	Risk level (%)					
		0 (no risk)	1 - 20	21 - 40	41 – 60	61- 80	81-100
pH decrease	Frequency	228	9	2	0	1	9
	Percentage (%)	91.6	3.6	0.8	0	0.4	3.6
pH increase	Frequency	243	6	0	0	0	0
	Percentage (%)	97.6	2.4	0	0	0	0
Temperature decrease	Frequency	242	7	0	0	0	0
	Percentage (%)	97.2	2.8	0	0	0	0
Temperature increase	Frequency	241	8	0	0	0	0
	Percentage (%)	96.8	3.2	0	0	0	0
Dissolved oxygen decrease	Frequency	166	59	5	8	1	10
	Percentage (%)	66.7	23.7	2	3.2	0.4	4
Salinity increase	Frequency	241	6	2	0	0	0
	Percentage (%)	96.8	2.4	0.8	0	0	0
Salinity decrease	Frequency	246	1	2	0	0	0
	Percentage (%)	98.8	0.4	0.8	0	0	0
Water pollution	Frequency	223	8	2	7	2	7
	Percentage (%)	89.6	3.2	0.8	2.8	0.8	2.8
Drought	Frequency	186	31	10	3	0	19
	Percentage (%)	74.7	12.4	4.0	1.2	0	7.6
Precipitation	Frequency	221	18	2	4	1	3
	Percentage (%)	88.8	7.2	0.8	1.6	0.4	1.2
Flood	Frequency	171	18	10	12	7	30
	Percentage (%)	68.7	7.2	4.0	4.8	2.8	12
High wave	Frequency	228	13	1	0	0	7
	Percentage (%)	91.6	5.2	0.4	0	0	2.8
Pandemic	Frequency	209	23	1	6	4	5
	Percentage (%)	83.9	9.2	0.4	2.4	1.6	2
Non pandemic disease	Frequency	232	9	0	1	2	4
	Percentage (%)	93.2	3.6	0	0.4	0.8	1.6

Many farmers asserted that their production was not being badly influenced by, or suffering major losses in respect of several climate change impacts such as pH decrease or increase, temperature decrease or increase, salinity decrease or increase, high waves and non-pandemic diseases. Percentage frequency values showed that more than 90% of the respondents declared no risk due to those events. The percentages of respondents who experienced no problem were: 91.6% in the case of pH decrease, 97.6% for pH increase, 97.2% for water temperature decrease, 96.8%forwater temperature increase, 98.8% for water salinity decrease, 96.8% for water salinity increase, 91.6% for high waves and 93.2% for non-pandemic diseases. However, the production of a small number of farmers was affected by various levels of risks due to those events.

Farmers experienced varying levels of risks due to decreased dissolved oxygen levels in water, water pollution, drought events, precipitation, floods, high waves, and pandemic diseases. The crucial climate risk factors that farmers in Sarawak experienced were a decrease in dissolved oxygen in the water (83 respondents or 33.3%), floods (77 respondents or 30.8%), and drought events (63 respondents or 25.2%). The decrease in dissolved oxygen in water was due to the changing weather and commonly happened at dawn. In the case of this factor 59 respondents (23.7%) experienced 1% to 20% risk, five (2%) experienced 21% to 40% risk, eight (3.2%) experienced 41% to 60% risk, one (0.4%) experienced 61% to 80% risk and 10 (4%) were highly vulnerable to this factor with 81% to 100% risk.

Aquaculture farmers in Kuching, Sri Aman, Sarikei, and Limbang divisions were identified vulnerable to flood risks. Of 77 affected respondents, a large proportion (30 respondents or 12%) was highly exposed to flood risks. The remainder experienced 1% to 20% risk (18 respondents or 7.2%), 21% to 40% risk (10 respondents or 4%), 41% to 60% risk (12 respondents or 4.8%), and 61% to 80% risk (seven respondents or 2.8%) from flood events.

Drought events caused water quality deterioration and had effects on the patterns of fish feeding. In the case of this risk factor, 31 respondents (12.4%) experienced a production loss of 1% to 20%, 10 (4%) had a loss of 21% to 40%, three (1.2%) experienced 41% to 60 % loss while 19 (7.6%) had the highest loss of 81% to 100% of their production.

Changes in precipitation only affected 28 respondents (11.2%). Eighteen (18) farmers (7.2%) experienced 1% to 20% risks while three (1.2%) experienced the highest level of risk (81% to 100%) due to precipitation factors. Another seven respondents (2.8%) experienced risk from 21% to 80% due to changes in precipitation. In the case of the risk of pandemic disease, 23 respondents (9.2%) suffered1% to 20% risk, one (0.4%) suffered 21% to 40% risk, six (2.4%) suffered 41% to 60% risk and four (1.6%) experienced 61%to 80% risk. Furthermore, five of the respondents (2%) experienced a great loss in aquaculture production (81% to 100% risk) due to pandemic disease.

A considerable number of respondents was affected by a decrease in water pH, water pollution problems, high waves and non-pandemic disease. On average, 26 respondents (10.4%) were affected by water pollution problems, 21(8.4%) by high waves, 21 (8.4%) by a decrease in water pH and 16 (6.4%) by diseases, at various levels of risks to aquaculture production.

Water pH increase, temperature decrease and temperature increase carried the lowest risks (1% to 20%) of climate change impacts on aquaculture activities. On average, fewer than 10 farmers experienced loss due to these climate events whilst the rest experienced no production risks at all. An increase in water salinity also carried little risk to aquaculture activities in Sarawak. Six farmers were affected at the 1% to 20% risk level and two at the 21% to 40% level. Meanwhile, a decrease in water salinity affected only three farmers.

4.6.4 Factor Analysis Results

The first two models of the study indicate the dimensions of the factors that are significant to the productivity of Sarawak's aquaculture production, by focusing on the socio-economic effects and climate change risks effects in order to evaluate the extension of biophysical and socio-economic vulnerability assessment based on farm level perspectives.

4.6.4.1 Factor analysis results for the climate change risks effects on aquaculture production in Sarawak

The first factor analysis results show that the environmental risks dimension extraction exhibited that water quality, precipitation change, hydrological events, and drought events were environmental risk factors that influenced sustainable aquaculture production. Table 4.10 shows the factor analysis employed on 11 climate change risk drivers that effect production losses in Sarawak's aquaculture sector.

Table 4.10: Rotated factors and factor loadings for the climate change risk drivers that effect production loss in the aquaculture sector

Factors and Items	Factor Loading			
Water quality risks	I	II	III	IV
Temperature decrease	0.891			
Temperature increase	0.883			
pH decrease	0.692			
Precipitation change				
Precipitation		0.784		
Pandemic disease		0.724		
Drought event risks				
Non pandemic disease			0.698	
Drought			0.621	
Dissolved oxygen decrease			0.587	
Hydrological event risks				
High wave				0.730
Flood				0.636
Water pollution		0.515		0.570
Eigenvalues	2.19	1.54	1.42	1.39
Percentage of variance (%)	19.91	14.03	12.93	12.62
Kaiser-Meyer-Olkin MSA	0.62***			

Note: *** is significant at $p<0.001$

For water quality risk dimensions, the factors and factor loadings comprised water temperature decrease (0.891), water temperature increase (0.883), and pH decrease (0.692). The precipitation change risks were represented by precipitation (0.784) and pandemic disease (0.724). The factors of drought event risks dimensions and factor loadings include non-pandemic disease (0.698), drought events (0.621), and dissolved oxygen decrease (0.587). The hydrological event risks comprised high wave (0.730), flood event (0.636), and water pollution (0.570) factors.

Performing a principal component analysis (PCA) with orthogonal rotation (varimax), the KMO measure verified that the sampling adequacy of the analysis is KMO=0.62, which is mediocre and above 0.5 (Field, 2009). Moreover, all KMO values for individual items were >0.51, which is well above the acceptable limit of 0.5. Barlett's test of sphericity, χ^2(249) = 491.99, p<0.001, reached statistical significance, supporting the factorability of the correlation matrix.

The principal components analysis revealed the presence of four components with Eigenvalues greater than 1, explaining 19.91%, 14.03%, 12.93%, and 12.62% of the variance respectively. Meanwhile, the combination explained 59.49% of the variance. Table 4.10 shows the results of the factor loadings after rotation. The items that cluster on the same components suggest that component 1 represents the water quality risks, component 2 is related to precipitation change risks, component 3 relates to the drought event risks and component 4 represents hydrological event risks. All of the classified factors are the climate change drivers that effect production loss in Sarawak's aquaculture sector.

4.6.4.2 Factor analysis results on the socio-economic effects under the climate change risks and uncertainty

The results in Table 4.11 show the factor loadings after rotation of farmers' socio-economic drivers that have effects on Sarawak's aquaculture sector productivity due to the uncertainty of climate change. The items that cluster on the same components suggest that component 1 demonstrates the financial factors and component 2 demonstrates the technical factors of the socio-economic aspect which affects farmers under the uncertainty of climate change risk.

Table 4.11: Rotated factors and factor loadings of farmers' socio-economic effects under the uncertainty of climate change risk

Factors and items	Factor loading	
Financial factors	I	II
Aquaculture sales increase	0.902	
Aquaculture income increase	0.883	
Aquaculture revenue increase	0.847	
Able to increase savings from the aquaculture income?	0.679	
Number of ponds and cages increase	0.643	
Technical Factors		
Increase in laborers' salary		0.818
Hired additional labor in production		0.815
Used technology in production		0.668
Eigenvalues	3.28	1.97
Percentage of variance (%)	36.39	21.89
Kaiser-Meyer-Olkin MSA	0.78***	

Note: *** is significant at p<0.01

The factor analysis results and the score of factor loadings show financial aspects are important to aquaculture production, as follows: sales (0.902), income (0.883), revenue (0.847), savings (0.679), and number of ponds and cages (0.643). Meanwhile, the labor wage (0.818), increment of hiring labors (0.815), and application of technology (0.688) in farms strengthen the technical aspect of aquaculture production.

A principal component analysis was conducted on the eight (8) items with orthogonal rotation (varimax). The Kaiser-Meyer-Olkin measure verified the sampling adequacy for the analysis, KMO=0.78, which is good, and all KMO values for individual items were >0.62, which is well above the acceptable limit of 0.5. Barlett's test of sphericity, $\chi^2(249) = 851.51$, p<0.001, indicated that correlations between items were sufficiently large for PCA. An initial analysis was run to obtain Eigenvalues for each component in the data. Two components had Eigenvalues over Kaiser's criterion of 1 and in combination explained 58.28% of the variance.

4.6.5 Reliability Analysis

A reliability analysis was carried out on the factors obtained from the principal component analysis to measure the scale's internal consistency and stability between the variables in each factor (Pallant, 2010). In Cronbach's alpha (α) coefficient values above 0.7 are acceptable. However, the Cronbach's alpha (α) with the lowest value is common to the factors with the short scales and can be accepted as above 0.5 by disclosing the mean inter-item correlation for the items (Pallant, 2010).

Table 4.12 shows the reliability results of the total scale of dimensions of climate change risks. Among four dimensions, water quality risk components had high reliability, Cronbach's α = 0.77. Remaining dimensions showed low reliability with the lowest being drought event risks. The Cronbach's α values for precipitation change risks, hydrological events risks and drought events risk were 0.53, 0.42, and 0.29 respectively. The low reliability results were due to the small number of items as this analysis is sensitive to the small numbers (Pallant, 2010). As the number of items is concerned, the mean inter-item correlation, 0.28, was between the optimal value of 0.2 to 0.4, as suggested by Briggs and Cheek (1986) as cited in Pallant (2010).

Table 4.12: Reliability analysis summary for climate change risk drivers that effect production loss in the aquaculture sector

Variables	Number of Items	Cronbach's α for each dimension	Cronbach's α for total Scale
Water quality risks	3	0.77	0.46
Precipitation change risks	2	0.53	
Drought event risks	3	0.29	
Hydrological event risks	3	0.42	

Table 4.13 shows two extracted dimensions for the performance level of farmers' socio-economic factors under the uncertainty of climate change risk with their Cronbach's alpha coefficient values. The financial factor dimensions had high reliabilities or very good internal consistency reliability with the value 0.86 (Pallant, 2010). However, the technical factor dimensions had low reliability, Cronbach's α =0.66. The Cronbach's α for total scale of the variables had a preferable value of 0.8, suggesting that those dimensions are stable and consistent with each other.

Table 4.13: Reliability analysis summary for socio-economic effects under the uncertainty of climate change risk

Variables	Number of Items	Cronbach's α for each dimensions	Cronbach's α for total Scale
Financial factors	5	0.86	0.80
Technical factors	3	0.66	

4.6.6 Environmental and Natural Resource Assets Associated with the Socio-economic Vulnerability of Aquaculture Farmers in Sarawak

A further analysis was conducted to indicate the details of the relationship between the natural resources and environmental assets on the income level of aquaculture farmers in Sarawak. In this third model analysis, the indication of vulnerability was based on the level of income that is 0 for poor income and 1 for non-poor income aquaculture farmers. Under the natural resources and environmental assets, two factors have an effect on the farmers' having a poor income. The first is farmers' access to natural resources such as land or space and good quality water for aquaculture activities; the second is the change in the environment such as climate variability events. In this analysis the natural resources factor was represented by the aquaculture project land ownership whilst the environmental change factor was represented by the effect of climate variability on the aquaculture ecosystem as well as production. The aquaculture system and production scale were included in the model as the control variables in the analysis.

The third analysis model (equation 4.12) to assess the relationship between income levels as the socio-economic vulnerability measurement with natural resources and environmental assets was estimated as:

$$
\begin{aligned}
Z &= -0.287 - 1.939 aqsys_1 + 1.674 scale_1^{**} + 1.761 ownershp_1 + 1.003 pHdec_1 \\
&- 2.013 pHinc_1^{*} - 1.014 tempdec_1 + 1.871 tempinc_1 + 1.178 disolvO2_1^{**} \\
&+ 0.619 rain_1 - 0.335 highwave_1 - 0.715 pdisease_1 \\
&+ 0.256 npdisease_1 \qquad (4.12)
\end{aligned}
$$

Where,

Z	= ln (odds of non-poor income probability)
$aqsys_1$	= $aqsys$ (1): cage aquaculture system
$scale_1$	= $scale$(1): medium production scale
$ownershp_1$	= $ownershp$(1): aquaculture land ownership-Temporary Occupation License (TOL) land
$pHdec_1$	=$pHdec$(1): pH water decrease effect
$pHinc_1$	= $pHinc$(1): pH water increase effect
$tempdec_1$	= $tempdec$(1): water temperature decrease effect
$tempinc_1$	= $tempinc$(1): water temperature increase effect
$disolvO2_1$	= $disolvO2$(1): Dissolved oxygen effect
$rain_1$	= $rain$(1): raining or precipitation effect
$highwave_1$	= $highwave$(1): strong highwave effect
$pdisease_1$	=$pandemic$(1): pandemic diseases effect
$npdisease_1$	= $npandemic$(1): non pandemic disease effect

Notes: * significant at 5% and ** significant at 1%

The significant influences of natural resources and environmental factors on farmers' income level are highlighted in Table 4.14. The interpretation of results focuses on the marginal effects results. For a continuous variable, the marginal effects value was interpreted as how much the level of income is expected to increase or decrease for a unit change in natural resource or climate change risks factors, holding all other variables are constant. Meanwhile, for categorical variable, the marginal effect value was interpreted as how P(Y=1) is predicted to change as the categorical variable changes from 0 to 1, holding all other variables equal.

Table 4.14: Logistic regression analysis results of natural resources and environmental assets effects on aquaculture farmers' income level

Variables	Marginal effects (dy/dx)	Estimated Coefficient	Standard error	Odds ratio	95% C.I.	P-value
Aquaculture System (cage)	-0.3500*	-1.939	1.133	0.144	0.017, 1.325	0.087
Scale (medium)	0.3141**	1.674**	0.485	5.336	2.062, 13.806	0.001
Land ownership (T.O.L land)	0.3046*	1.761	1.102	5.821	0.671, 50.516	0.110
pH decrease effect	0.1931	1.003	0.740	2.726	0.640, 11.615	0.175
pH increase effect	-0.3659*	-2.013	1.277	0.134	0.011, 1.631	0.115
Temperature decrease effect	-0.2042	-1.014	1.904	0.363	0.009, 15.136	0.594
Temperature increase effect	0.3077	1.872	1.874	6.499	0.165, 256.064	0.318
Dissolved oxygen effect	0.2424**	1.178**	0.333	3.248	1.691, 6.238	0.000
Raining effect	0.1237	0.619	0.592	1.857	0.582, 5.923	0.295
High wave effect	-0.0693	-0.335	0.659	0.715	0.197, 2.601	0.611
Pandemic disease effect	-0.1474	-0.715	0.423	0.489	0.214, 1.122	0.091
Non-pandemic disease effect	0.0523	0.256	0.692	1.292	0.332, 5.017	0.712
Constant	-	-0.287	0.212	-	-	0.176
Likelihood Ratio χ^2 (12)		42.89				
p-value		0.000				
Hosmer-Lemeshow χ^2 (6)		6.80				
p-value		0.339				
Pseudo R^2		0.126				

Notes:* significant at 5%; ** significant at 1%.

The marginal effects results showed that the predicted probability of obtaining non-poor income level is 35% significantly lower for cage aquaculture than for the pond aquaculture activities. Regardless of the aquaculture system, the predicted probability of obtaining non-poor income level is 31.4% significantly greater for medium scale aquaculture production than for small scale aquaculture production. In the case of the aquaculture land ownership factor, the predicted probability of obtaining non-poor income level is 30.5% significantly greater for aquaculture activities operating at T.O.L land as compared to self-owned land, holding all other variables equal.

The climate change risks factors effects show that, by holding all other variables equal, the predicted probability of water pH effects in a pond or cage activities to non-poor income farmers is 36.6% significantly lower than no water pH effects, whilst the probability of dissolved oxygen depletion in water effect to the non-poor income level is 24.2% greater than no dissolved oxygen depletion effects. In contrast, the coefficient and odds ratio results show a different outcome where only production scale and dissolved oxygen had a significant influence on the income level in the pond and cage aquaculture activities in Sarawak. The results reveal that the increase in contributions in medium scale aquaculture production in pond or cage activities is more likely to increase 1.67 of farmers' income to the above poor income level. The odds ratio results support that the involvement of farmers in medium scale aquaculture production (either pond or cage aquaculture) is 5.34 times more likely to result in income above the poor-income level. Meanwhile, the coefficient of odds ratio indicates that dissolved oxygen depletion was 1.18 more likely to affect the non-poor income farmers. The odds ratio of aquaculture activities being affected by dissolved oxygen depletion is 3.25 times more likely for the non-poor income farmers.

The diagnostic test for the model showed that a value of Likelihood Ratio (LR) χ^2, with 12 degrees of freedom, is 42.89, and this has a p-value of less than 0.01. Thus, the null hypothesis can be rejected, which indicates that the current regression model fits the data well. The model specification results show that there is no specification error in the model since the variable _hatsq is insignificant (p=0.103). The Pseudo R^2 value of the model is 0.13 and the Hosmer and Lemeshow's Goodness-of-Fit test with six degrees of freedom is 6.80 and p=0.34, that is, greater than 0.05. The model also has no multicollinearity problem as the values of VIF for most of variables are less than 10.

4.6.7 Assets Associated with the Socio-economic Vulnerability of Aquaculture Farmers in Sarawak

The fourth analysis model (model 4.13) was developed to indicate the aquaculture farmers' socio-economic vulnerability towards climate change risks. The model of association factors to the income level was developed from the combination of significant variables that had been identified from the logistic regression analysis results of each of the capital assets (physical, human, financial, and natural resources and environmental capital) and demographic factors. The dichotomous dependent variable represents 0 as poor income level and 1 as non-poor income level. The fourth analysis model of socio-economic vulnerability assessment had been estimated as:

$$
\begin{aligned}
Z &= -2.668 + 1.464aqsys_1^{**} + 1.462scale_1^{**} - 0.054eduyr - 0.477pHinc_1 \\
&+ 2.221tempinc_1 + 0.890disolvO2_1^{*} - 1.402pdisease_1^{**} + 0.843loan_1 \\
&+ 0.004offinc^{**} + 1.566aptech_1^{**}1.914ethnic_1^{**} + 1.062mstatus_1 \\
&- 0.085family
\end{aligned}
\qquad (4.13)
$$

where,

Z	= ln (odds of non-poor income probability)
$aqsys_1$	= $aqsys$ (1): cage aquaculture system
$scale_1$	= $scale(1)$: medium production scale
$eduyr$	=education years
$pHinc_1$	= $pHinc(1)$: pH increase effect
$tempinc_1$	= $tempinc$ (1): temperature increase effect
$disolvO2_1$	= $disolvO2(1)$: dissolved oxygen effect
$pdisease_1$	= $pdisease(1)$: pandemic disease effects
$loan_1$	= $loan$ (1): having loan
$offinc$	= off-farm income (in RM)
$aptech_1$	= $aptech$ (1): apply technology
$ethnic_1$	= $ethnic$ (1): Chinese
$mstatus_1$	= $Mstatus$ (1): married
$family$	= number of family members

Notes: * significant at 5% and ** significant at 1%

Table 4.15 shows the results of regression analysis for selected capital assets that associate with farmers' income level in the aquaculture sector in Sarawak. Under demographic factors, aquaculture systems, production scale, and ethnicity had significant association with level of income as the measurement of socio-economic vulnerability. The odds that the farmers gained income above the poor-income level is 4.32 by being involved in cage aquaculture activities as opposed to being involved in pond aquaculture activities and the coefficient of odds ratio indicates that involvement in cage aquaculture activities were 1.46 more likely increase a farmer's income above the poor-income level. The marginal effects of the analysis indicated that the predicted probability of obtaining a non-poor income is 17.7% significantly greater for cage aquaculture than the pond aquaculture activities.

Regardless of the aquaculture system, upgrading from small scale production to a medium production scale of aquaculture activities will more likely increase 1.46 of farmers' income above the poor income level. The odds of the farmer who becomes involved in medium scale aquaculture production gaining income above the poor income level are 4.31 compared to farmers who are involved in small scale aquaculture production. The marginal effects results show that the predicted probability of obtaining non-poor income is 19.6% significantly greater for medium scale production farmers than the small scale production farmers.

Table 4.15: Logistic regression analysis result of selected capital assets effects on aquaculture farmers' income level

Variables	Marginal effects (dy/dx)	Estimated coefficient	Standard error	Odds ratio	95% C.I.	P-value
Cage aquaculture	0.1767**	1.464**	0.458	4.322	1.761, 10.605	0.001
Medium scale	0.1959**	1.462**	0.537	4.313	1.504, 12.366	0.007
Education year	-0.0068	-0.054	0.058	0.947	0.845, 1.062	0.354
pH increase effect	-0.0591	-0.477	1.198	0.621	0.059, 6.495	0.691
Temperature increase effect	0.2666	2.221	1.449	9.213	0.538, 157.79	0.125
Dissolved oxygen effect	0.1169*	0.890*	0.420	2.436	1.067, 5.554	0.034
Pandemic disease effect	-0.1691**	-1.402**	0.529	0.246	0.087, 0.694	0.008
Loan	0.1108	0.843	0.466	2.323	0.932, 5.786	0.070
Off- farm income	0.0005**	0.004**	0.001	1.004	1.002, 1.005	0.000
Apply technology	0.2176**	1.566**	0.539	4.785	1.663, 13.774	0.004
Chinese	0.2676**	1.914**	0.520	6.778	2.448, 18.766	0.000
Married	0.1281	1.062	0.812	2.893	0.589, 14.210	0.191
Family	-0.0108	-0.085	0.047	0.918	0.838, 1.006	0.068
Constant	-	-2.668	1.112	-	-	0.016
Likelihood Ratio χ^2 (13)		145.05				
p-value		0.000				
Hosmer-Lemeshowχ^2 (8)		6.06				
p-value		0.640				
Pseudo R^2		0.427				

Notes:* significant at 5%; ** significant at 1%.

Meanwhile, in terms of ethnicity, the study indicates that Chinese farmersare1.91% more likely to increase their income above the poor income level with an odds ratio of 6.78 compared to non-Chinese farmers. The marginal effects results show that the predicted probability of a Chinese farmer gaining a non-poor income level is 26.8% significantly greater than for non-Chinese farmers in the aquaculture sector.

In terms of physical assets, farmers' application of technology in their farm management was an important factor in lessening their socio-economic vulnerability as well as increasing their production. Farmers who use technology in their farm management are 1.57% more likely to obtain income above the poor-income level compared to those who not use any technologies in their farm. The odds ratio of use, compared to the non-use of technology factors affecting income above the poor-income level is 4.79. Meanwhile, the marginal effects indicated that the predicted probability of farmers who apply technology in managing their farm gain a non-poor income level is 21.8% significantly greater than for farmers who did not apply technology in farm.

In terms of financial assets in aquaculture, the diversification of income, either from other farm activities or off-farm jobs, is 0.004 more likely to increase the farmers' income above the poor income level, with an odds ratio of 1.00 compared to farmers who are fully dependent on their aquaculture activities income. The marginal effects showed that the predicted probability of aquaculture farmers gain a non-poor income level is 0.05% significantly greater by becoming involved in an off-farm job or diversifying their income than farmers and their households who do not becoming involved in off-farm job.

In terms of natural and environmental assets in aquaculture, dissolved oxygen depletion and pandemic disease outbreaks were important significant factors to farmers' income levels in assessing their socio-economic vulnerability due to climate change risks. Dissolved oxygen depletion and the incidence of pandemic disease were among the crucial problems for in sustainable aquaculture activities in Sarawak. Most of the farmers experienced these uncontrolled risk factors which were influenced by variation in the climate and hydrological events. The farmers' feedback on environmental risks types revealed that the odds of dissolved oxygen effects increases to non-poor income farmers' was 2.44. The coefficient of odds ratio reveals that the dissolved oxygen depletion risks were more likely to increase 0.89 to non-poor income farmers rather than to show no effect of dissolved oxygen. The marginal effects showed that the predicted probability of dissolved oxygen depletion affecting non-poor income farmers is 11.7% greater than of having no effects of dissolved oxygen depletion.

Pandemic disease risks factors show a contrast. Pandemic disease outbreaks were more likely to decrease 1.40 for non-poor income farmers. The odds of pandemic disease outbreaks decrease on non-poor income farmers was 0.25 rather than no occurrence of the pandemic disease threats. The results also suggest that the predicted probability of pandemic disease outbreaks occurring in the non-poor income farmers is 16.9% lower than no occurrence of pandemic disease threats at all.

The diagnostic test of the model showed that the value of Likelihood Ratio (LR) χ^2, with 13 degrees of freedom, is 145.05, which has a p-value of less than 0.01. Thus, the null hypothesis can be rejected, which indicates that the current regression model fits the data well. The model specification results showed that the variable _hatsq is insignificant (with p-value =0.147), which suggests that the model has no specification error but is in a linear combination of predictor variables.

The Pseudo R^2 value of the final model is acceptable at 0.43. The positive value of Pseudo R^2 shows the likelihood that income category probability happens will increase as the predictor in the model increases. The Hosmer and Lemeshow's χ^2 value with 8 degrees of freedom is 6.06 (p=0.64) and this indicates that the model fits the data well. The model also has no multicollinearity problem as the value of the Variance Inflation Factor (VIF) of each variable is less than 10.

4.7 Discussion

4.7.1 Biophysical Effects on Socio-economic Vulnerability in Sarawak's Aquaculture Sector

The impacts of climate change are a major concern of this study. The results recognized the occurrence, and negative effects of, climate change hazards on aquaculture production sustainability in Sarawak and also on aspects of the farmers' socio-economic vulnerability. The great environmental challenges and crucial factors for the aquaculture sector's survival were access to the required natural resources and the short supply of good quality water (Bates et al., 2008; Vorosmarty et al., 2000) that are important for fish production ecosystems.

The study indicated that water quality, changes in precipitation, drought events, and hydrological events were the greatest challenges and crucial factors impacting aquaculture farmers' climate change risks. The results were consistent with those of Bates et al. (2008), who showed that the extreme change in water quality factors was mainly in terms of changes in water temperature and pH as well as many other factors. The main challenges and threat factors to Sarawak's aquaculture farmers are to maintain the water quality such that it is suitable for aquaculture production. Increased water temperature, if not managed efficiently, will increase the frequency and intensity of red tides, especially in pond aquaculture. Moreover, the increased temperature results in changes in chemical processes and the depletion of dissolved oxygen in water that could affect fish physiology and, in the worst-case scenario, cause the massive death of fish in the ponds (Kundzewicz et al., 2008).

The logistic regression of the capital assets results highlighted two types of significant climate change risks affecting aquaculture farmers. The dissolved oxygen depletion risks were increased more in non-poor income farmers due to the size of the farm activities. The high volume of cultured fish in a single pond or cage can lower the oxygen contents in ponds or cage water. Therefore, the use of equipment such as a water aeration system was important, depending on farm size and production scale. With high production volumes, close monitoring and good farm management practices were important to reduce any extended risks to the water quality, such as an increase in pH or change in salinity. Fish mortality was less in large and medium-sized farms as there was high volume production and the farms were well equipped. Pandemic disease outbreaks were less likely to affect high income farmers due to the close monitoring and technology used. Consistent, good monitoring and control of water quality and farm management aspects reduce the risks of disease outbreaks on farms and thus help avoid production losses.

Dissolved oxygen depletion in water was the main climate change threat for fish growth and sustainable aquaculture production. This occurred as a reaction to changes in the earth's climatological and hydrological processes. World Fish (2007) indicated that the water quality effects on fish ecosystems and the level of effects affected the quality of fish life. Most of the Sarawak farmers interviewed during this study had experienced massive deaths of fish due to the dissolved oxygen depletion impact.

Higher inland water temperatures and changes in sea surface temperature are two climate change effects that contribute to the dissolved oxygen depletion. A decrease in water salinity might also contribute. The sudden and heavy precipitation when the air temperature increases in the afternoons, and also the long hot, dry seasons, exposed aquaculture site water bodies to water stratification due to the reduction of dissolved oxygen in water containing high levels of organic waste. Water under such conditions (low dissolved oxygen, high levels of organic waste) immediately facilitates the spread of diseases and threatens the fish physiology and ecosystem (Sriyasak, Chitmanat, Whangchai, Promya, & Lebel, 2015).

The oxygen concentration depends on the water depth and oxygen depletion usually occurs during the dry seasons when the water is warmer and holds less oxygen. During the dry months pond water usually becomes stratified due to water of different temperatures having different densities - the cooler water with more oxygen sinks and the warmer water rises where the microbial decomposition of organic materials in the water depleting oxygen at the bottom layer of pond's water. The temperature increase will increase the need for oxygen due to the increase in the fish's metabolic rate. When sudden precipitation occurs during the hot season it worsens the water stratification.

The decrease in dissolved oxygen in pond or river water over a longer period of time will cause massive fish deaths and result in great losses in aquaculture yield and farmers' profit and income. The decrease in dissolved oxygen in pond water to levels below the normal range will cause the fish to stop feeding, become stressed, and begin to die. Therefore, careful and consistent monitoring of the oxygen level in the water is important to maintain an adequate level of oxygen and other water quality parameters in ponds and at the same time prevent the breakdown of waste products in the system. The level of oxygen in older ponds that have become shallow through silting may easily decrease with little capacity for restoration and effects such as an increased feed conversion ratio and reduced fish productivity (Engle, 2010).

High capital investment is needed to purchase equipment (such as aerators and blowers) to maintain water oxygen concentrations and skilled workers are needed to ensure the equipment functions efficiently and to avoid breakdowns. A high aeration capacity may help maintain high levels of dissolved oxygen in ponds. However, pumps and aerators to maintain oxygen levels are not necessary for cage aquaculture. The disadvantage of aerators in aquaculture activities is that they require additional electricity. The problem of low dissolved oxygen levels in ponds usually occurred during the evening hours and, without close monitoring, would result in massive fish kill and cause farmers greater production and financial losses (Engle, 2010).

Changing precipitation patterns over the long term affects pond and cage water salinity, especially in brackish water systems, and this factor influenced disease outbreaks in aquaculture production. The climate change effects on the hydrological cycle have changed the balance of the precipitation pattern and caused vegetation imbalance due to temperature and precipitation changes. Intense precipitation events cause water quality changes and water dilution due to pollutant loads being flushed from inland areas and river headwaters. This causes diseases to spread and threatens fish growth (Kundzewicz et al., 2008).

Floods, drought and high waves were not the major climatic risks or the main hazards to aquaculture production in Sarawak. However the occurrence of such events results in greater loss to farms if they are not monitored. Drought, flood, and storm surge events risks were manageable in Sarawak's aquaculture production because these had specific effects on aquaculture production (over a certain time period and at a specific area). Change in precipitation patterns also increased seasonal flood events that affected water body systems (Ficke et al., 2007).

4.7.2 Other Factors Affecting Socio-economic Vulnerability in Sarawak's Aquaculture Sector

The severity of climate change impacts on aquaculture farmers' livelihoods were not well enough determined through the direct relationship of climate change hazards with aquaculture production in the socio-economic vulnerability assessment. The wide means of socio-economic factors demand a wider context of assessment, including natural ecosystem resilience, degree of socio-economic development, social inequalities, human adaptive capacities, health status and services, demographic characteristics and economic livelihood alternatives. This study adapted an assets-based approach by investigating four different capital assets (human, financial, physical, and natural capital) and their effects on aquaculture farmers' income levels (poor and not-poor income) in order to assess socio-economic vulnerability. Some demographic characteristics were included to enhance the assessment.

The findings on the comparison between the relationships of demographic factors and productive assets to poor and non-poor income farmers supported the postulation and assumption that the lesser productive assets owned and good demographic factors support the farmers' livelihoods, the farmers will be more affected by the vulnerability which had been made in the socio-economic vulnerability assessment. A difference in terms of farmers' vulnerability levels was related to different income levels and it is accepted that in aquaculture sector poor farmers or those owning fewer assets, were more vulnerable to the impacts of climate change. Furthermore, they are less able to respond to, cope with or adapt to the vulnerability due to limited alternative income or income diversification in their livelihood and less resilience in adapting in the face of risks.

The factor analysis results posit that financial and technical factors were two important dimensions of the socio-economic effects on aquaculture production. In terms of climate change risks effects, four (4) important dimensions of climate change risks effects on aquaculture production were identified: water quality risks, changes in precipitation, drought event risks, and hydrological event risks. These findings are congruent with the development theory of production wherein addition to labor and capital as basic factors of production, under climate change uncertainties environmental factors which are uncontrolled by the producer cause the modification of inputs and change in production output (Mcconnell & Bockstael, 2005). Furthermore, the multivariate logistic regression results further support that cage aquaculture system activities and ethnicity (i.e. being Chinese) were two (2) demographic factors that had a significant positive influence on farmers' income levels, reducing the vulnerability of farmers' livelihoods.

Aquaculture farmers' productive assets (level of income, scale of production, off-farm income, and technology usage) help to improve the farmers' income level. Dissolved oxygen depletion was more likely to affect non-poor income farmers than poor-income farmers, whereas pandemic disease outbreaks were less likely to affect the non-poor income farmers than the poor-income farmers.

Pond aquaculture activities were determined to be the reference or baseline of the assessment on aquaculture system factors. This was because pond aquaculture was identified as growing rapidly and dominating aquaculture production in Sarawak. Active involvement in pond aquaculture may result in positive or negative competition for the other aquaculture systems, especially cage aquaculture, in terms of the market, price and access to resources.

Pond aquaculture made a major contribution to Sarawak's aquaculture production, but cage aquaculture made a significant positive contribution in reducing poverty and socio-economic vulnerability. Cage aquaculture production had the potential to provide farmers with huge incomes due to the high production volume (Jhingran, 1987) as well as to help improve the livelihood of the poor, impoverished and landless farmers, who were provided with opportunities to access the natural capital and join in the water-based culture system to obtain income (Edwards, 2000). Furthermore, Sarawak's geographical factors, i.e. having a lot of rivers and streams, may indicate a bright potential for the development of cage aquaculture activities in the state now and in future.

The advantages of cage aquaculture as compared to pond aquaculture are that cage activities produce 10 to 12 times higher yields in term of inputs and area, there is less probability of stock loss when faced with major climate events such as flooding, less concern over the problem of water replacement, seepage and evaporation losses, less utilization of artificial foods, reduced competition for land with other agricultural sectors, and finally, ease in handling, harvesting, and marketing the fish. Operating directly on a water body and in a natural ecosystem, known as a water-based system, cage aquaculture involves low capital inputs and opportunity costs of entry and consumes minimal time. Furthermore, the activities are easy to manage compared to those in the pond aquaculture system, and attracted households who live near public access water bodies to become involved in production for additional income and to improve their livelihoods (Bolton et al., 2009). These advantages mean that the cage aquaculture in Southeast Asian countries is developing rapidly, advanced, and involves the culture of many species.

Operating in a natural ecosystem of fish and in running water, cage aquaculture is believed to have less environmental impact. A variety of aquaculture species can be cultured in a cage and help to increase farmers' income. Farmers can rear fish and seaweed in the same cage. The sustainability of cage aquaculture can be enhanced through better knowledge of the reasons for fish mortality and the appropriate number of fish to keep in cages, good feeding management practices that can reduce feed waste and ethical practices that fulfill local concerns on *halal* (permissible) food production. Further benefits of cage management are that it takes into consideration the continuous cycle process of aquaculture, it is a safe type of culture practice and results in low environmental impacts and improved management of coastal zones, access rights, and ownership.

Another significant demographic aspect of socio-economic vulnerability is the ethnicity factor. The study found that Chinese farmers were more likely to achieve higher income, or in other words, were less vulnerable in terms of socio-economic aspects than non-Chinese farmers. The Chinese ethnic group is the second largest (32.1%) to the Bumiputera group (41.8%) in Sarawak's aquaculture sector. Aquaculture activities give Chinese farmers a high return due to the assets owned, risk preference, and location factors that influenced the attainment of high returns from aquaculture activities. Furthermore, scale of production, networking factors, a risk taker's attitude and diversification of income are factors that supported their success. Historical factors influence the success of the Chinese in the economics sectors - Chinese have been actively involved in such activities over the centuries and have converted from traditional to modern fisheries techniques and inherited the skills within the community (AFSPAN, 2014).

The successful achievements and contribution of non-Chinese farmers in this sector are also remarkable - the Bumiputera farmers have great potential too. However, obstacles to their further success in the sector and their less remarkable performance compared to the Chinese included operating in rural and remote areas (ADB, 2014; AFSPAN, 2015). One's own interest and experience were the main factors influencing success in this sector. The high numbers of Bumiputera farmers in this sector were due to their involvement in government development programs such as those for low income households who are less experienced or knowledgeable about the sector, especially in rural areas. The low achievements were due to constraints and weaknesses in assets in terms of financial, physical, and knowledge factors; location factors that limit accessibility to potential markets; involvement in high cost, low scale aquaculture production more for self-consumption and less for the market; rising production costs, especially due to costs of fish feed, fertilizers, and maintenance; and the use of unproductive land for aquaculture activities and dependency on subsidies. These limitations are also mentioned in the study of CARE PECCN (2011) and ADB (2014).

The influence of marital status and number of family members on aquaculture farmers' level of income in Sarawak were low and insignificant. However, the findings do not mean that marital status and number of family members does not reflect at all on aquaculture farmers' success. As Cutter et al.'s (2003) and Dwyer et al.'s (2004) findings emphasized, the contribution of family towards climate change risks resilience in Sarawak's aquaculture farmers was not due to the farmer's marital status or number of family members in the household but more on members' roles in improving the livelihood through contributions of farm income and income diversification through off-farm income for household consumption and financial assistance for expanding farms (Afolabi, 2008).

This study revealed that sales, revenue and profits contributed to the aquaculture farmers' financial sustainability. Financial sustainability was important in providing livelihood options and improves the farmers' livelihood as well as reducing his socio-economic vulnerability. The assessment of the socio-economic consequences indicated that the farmers' income distribution was a factor with social impacts and the measurement and comparison of incomes will help to identify the farmers' level of vulnerability to production risks (Kam & Leung, 2008). Kam and Leung's (2008) and Pomeroy (2003) work supported the significance of financial factors in determining the success of aquaculture activities by showing that production and financial management capabilities, resource availability, and financial conditions in farm activities as well as marketing management were the aspects that farmers need to evaluate in their farm decision making.

The sales factor had the highest score in the factor analysis, which showed that the production activities depended on the performance of aquaculture sales in the market. Increased sales means there is increased demand for Sarawak's aquaculture products and this will affect their market price and promote high quality production and supply.

Sales would be able increase the farmers' revenue as well as increase their income from the profits.

The limiting factors for aquaculture sales in Sarawak's aquaculture sector were due to poor marketing of aquaculture products, especially in rural areas or small towns. Location, distance, and transportation constraints limited farmers' access to large markets. For instance, this study found that aquaculture farmers in Limbang and Lawas districts were faced with market constraints due to their location between Brunei and near the border of Sabah. The farmers were able to produce large scale aquaculture production but were limited in their ability to market the products due to the small size of the market in the local area. Furthermore, Brunei and Sabah's stringent agriculture laws and regulations meant that the aquaculture products from Limbang and Lawas were unable to be distributed to these regional markets (or had limited penetration). Thus, the farmers had to limit their scale of production according to local market demands and personal consumption.

Dynamic aquaculture production activities in Sarawak can be seen mostly in Kuching, Samarahan, and Sarikei divisions, where local demand for aquaculture products was high and there was also a demand from neighboring Indonesia. Good market networking, production inputs, access and transportation facilities influenced the demand for, and supply of aquaculture products. Furthermore, quality aquaculture products such as Red Tilapia (*Oreochromis* sp. Red Tilapia) fish from Batang Ai, Sri Aman have been developed and promoted to the market, meeting specific demands. Thus, these farmers' revenue gains were high compared to those of farmers whose access to markets was limited and this increased the farmers' economic viability together with the expansion in production and product diversification.

Farm revenue determined the profitability of the farms that farmers' used to expand farm activities to further increase the farm's profitability in the next production (FAO, 1984). However, the farmers' revenue depended on the market price and would decrease if the price and the sales decreased (Kam & Leung, 2008). Other problems that the aquaculture farmers' (especially pond farmers in Sarawak) needed to face were price volatility due to competition between aquaculture products and fish landed from the sea or rivers. The price volatility and increases in input price had the effect of decreasing revenue and in the long run will decrease aquaculture production due to production cost minimization.

Farmers believe that farm diversification activities are the best solution to reduce farm risk. The farmers diversified their income through off-farm jobs in order to sustain a more stable income for their livelihood and at the same time for the capital to cover the input costs of their aquaculture activities and also risks protection. Badjeck et al. (2010), Johnston et al. (2009), and Slater et al. (2013) highlighted the benefits of income diversification to farmers in adapting to environmental risks --this strategy would help improve the farmers' adaptive capacity and resilience in the face of production loss and poverty as well as breaking the specialization trap among farmers due to involvement in single activities, and thus reduce income vulnerability. This finding was also congruent with that of King et al. (2009) which revealed that income diversification also comes from the contributions and role of family members such as wife and children who are working outside the farm or in activities other than aquaculture. Further benefits of the diversification of income to farmers were supported in studies by Afolabi (2010), Dixon et al. (2001), and King et al. (2009).

Although many researchers remarked on the contribution of loans to growth in the aquaculture sector, in the case of Sarawak's aquaculture sector, loans or credit was not preferred as a farm financing source due to the high number of small scale farmers in Sarawak. The limitation of access to loan for aquaculture activities (Hishamunda & Ridler, 2006) and repayment risk factors, were among the reasons for the lack of interest in applying for loans for aquaculture farm activities in Sarawak. Besides the fact that savings and extra income from off-farm activities assist in financing the aquaculture activities, the high value of assets owned by farmers or the higher scale production farmers, make farmers able to get the financing resource for their farm expansion through personal bank loans or loans from family members or relatives.

From the point of view of physical capital the study indicates that aquaculture farm production scales had a positive significance to farmers' socio-economic vulnerability. The medium scale production farmers were less vulnerable to climate change risks as compared to the small scale production farmers, as they were more efficient due to the size economies of production (Bolton et al., 2009; Kam & Leung, 2008). By expanding the size of production land or structure, the farmers are able to manage their livelihood assets and increase their income. The change of a pond or cage production size determined the return on production. Farmers' aquaculture returns due to expansion of farm production scale assisted farmers to effectively plan farm operations, allocation, and cost management.

The significance of the relationship between farm production size and income and financial stability in this study were in line with the results of Davis's (2003) study where the large scale aquaculture farmers had the most stable finances and were able to sustain their social capital. Meanwhile, the small scale aquaculture farmers were prone to the problem of poverty. It was very hard for them to ensure the availability of the essential financial capital that most farm components require (Bosma, Udo, Verreth, Visser, & Nam, 2005; Engle, 2010). However, farmers faced major problems in terms of land quality, water constraints and maintaining good infrastructure for aquaculture activities and these sometimes became an obstacle to plans to expand (Bosma & Verdegam, 2011; FAO, 1984; Holmer et al., 2008; Lichtkoppler, 1993).

Unexceptionally, the majority of Sarawak's aquaculture farmers were involved in small size production. This provided additional evidence with reference to Malaysia that small scale production was the chief contributor to aquaculture production in Southeast Asia, as well as in the world (Belton, Little, & Xuan-Sinh, 2011; Bosma & Verdegam, 2001; Sheriff, Little, & Tantikamton, 2008). Although small size production seems ineffective with diseconomies of scale in production, it would be able help reduce the pressure of demand on the reef fisheries and, in the long term, maintain aquaculture production sustainability (Islam et al., 2005; Sheriff et al., 2008). Jhingran (1987) considers that small-scale farmers aim to maximize income at the achievable difference between revenue and production costs. Meanwhile, the large scale farmers are aiming to maximize returns on investment. Thus, the largest production scale and large farm size were commonly believed to be able to return high profits and increase farmers 'income. The scale of economic activities, such as aquaculture activities, was very subjective as was explained under the theory of the firm, where the farm size was determined by the value of cost parameters efficiency and availability of space (Rizov & Mathijs, 2003).

Small size aquaculture production in Sarawak made achievements even though dogged by thought unprofitability, capital difficulties, and difficult income generation. Some small size aquaculture production farmers were able to return high production and profits. Aquaculture activities are able to promise high production if operating at lower capital and with less technological assistance, and with consistent and effective better farm management. Islam et al. (2005) support this contradictory finding, reporting that small size production achieved the highest production returns as compared to medium and large size production due to the species' high percentage survival rate in the long run. Although large farms were well equipped with high technology, they still need skilled laborers to monitor and control the effectiveness process. Perhaps, practicing natural techniques in production activities in small and medium size aquaculture operations, frequent water exchange combined with the assistance of external output would be more effective and yield higher production.

The results also showed the significance of the technology used in managing aquaculture production. This finding supports Peters et al.'s (1999) argument in the discussion on the theory of production where technological change is a rational choice in coping with climate change. The farmers believed that the capability of acquiring the technology in farm management would help to save their time in preparing ponds and the cages in the earlier phase of the production cycle, preparing for cultured fingerlings, controlling the water quality and in the harvesting, and marketing process. The significant role of technology in Sarawak's aquaculture sector was similar to benefits that had been highlighted in previous studies, which include intensive farm transformation (Lebel et al., 2002), ensuring and supporting sustainable farm practices (McCausland et al., 2006; Naylor et al., 2000) and contribution to higher income generation (Prein & Otori, 1996a). However, the capability of allocating and applying technology in farm management depended on the size of the production and financial capacity and most investment was by the large and medium scale farmers. Acquiring the technology means the farmers and workers must know how to handle the equipment effectively to avoid further costs and high losses due to mishandling of the equipment. The adoption of technology in farms would have impacts on farmers' financial status and farm labor allocation (Pemsl et al., 2006).

The role of information, training and extension service activities was important for good management and effective technology use (Edwards, 2000; Prein & Ofori, 1996b; Srinath et al., 2000; Subangsihe, 2003). Technological modification to adapt to climate change risks involves farm intensification that depends on the local and farmers' conditions (Pemsl et al., 2006). Various training schemes and intensive dissemination of information on various technologies to farmers are able to increase the number of fishponds due to farmers' increased awareness and their adoption of improved aquaculture technology in their farms. With limited technology options and constraints in resources such as species combinations, stocking density and feeding, poor and subsistence-oriented households were also able to demonstrate their ability to manage the technology and benefit from its returns (Ahmad & Lorica, 2002).

The majority of aquaculture farmers in Sarawak is involved in medium to small scale aquaculture operations and adopt low technology in managing their farms. Edwards (2000) found a similar situation where, in Asia, the majority of the aquaculture farmers was poor and practiced traditional fish farming techniques using the participatory approach by gathering people to collaborate on preparing ponds or cages before breeding or harvesting fish. Although the farmers were confident of the advantages of technology to increase production, only a few had access to the technology-driven approach while small scale aquaculture farmers with poor socio-economic conditions had very low levels of adoption and practice of technological approaches in their farm activities (Srinath et al., 2000). Technological advances enable the farmers to reduce the cost of aquaculture production, ensure environmental friendly practices and develop the research on species diversification and product differentiation (McCausland et al., 2006).

The aquaculture sector in Sarawak contributes to the creation of employment and also reduces the incidence of poverty, especially in rural communities. Farm jobs offer individuals with basic technical knowledge on how to manage the farm but low (or no) academic qualifications the opportunity to develop their knowledge and skills in managing aquaculture activities. Scientific knowledge on aspects of water quality and the cultured species would admittedly help farmers manage aquaculture farms, but with skill, experience, common sense and observation farmers and laborers can overcome the environmental challenges. Sarawak's aquaculture projects had also successfully developed entrepreneurial skills, especially in the young people, who have been able to transform their aquaculture activities from low stream to high stream production. This finding is consistent with that of Kam and Leung (2008) who stated that the aim of the farm was not only to maximize profits but also maximize employment.

Labor capabilities and the skilled workers' contribution in managing farms were important human assets for farmers in managing production risks. With farm expansion, the numbers of laborers that will be hired also increases. However, most farmers preferred to use family labor in managing their farms, especially in the case of small and medium scale farms. Although aquaculture offered employment to the communities, there were issues of low wages and labor rights in the aquaculture sector in Sarawak as well as the difficulty of finding skilled workers (Bostick, 2008). This contradicts the results reported in the World Bank (2002) study that revealed that the aquaculture sector pays better wages than other sectors.

The results also revealed no significant association between farmers' education and their income level as a factor of human physical in the final model results. This finding contradicts those of Badjeck et al. (2010) and Cutter et al. (2003). Admittedly, education plays an important role in any aspect of human or community development. Education and training were two important human capital assets that can strengthen skills in managing sustainable aquaculture production and reducing socio-economic vulnerability. Sarawak's aquaculture case study showed that non-formal educational activities, such as self-experience and the sharing of knowledge in the family and with other farmers, were more helpful and beneficial to farmers in managing their farms effectively than formal educational qualifications and training. This might be because the majority of farmers involved in the sector was from the older generation and as such, had not undergone formal education. Thus, the study showed that skills and experience were more important in farmers' capacity to adapt to climate change in Sarawak than the benefits of education, as Badjeck et al. (2010), Cutter et al. (2003), and Johnson et al. (2009) had suggested.

4.8 Conclusion

This assessment of the impacts of climate change on Sarawak's aquaculture sector covered vulnerability in terms of both its biophysical and its socio-economic effects. This essay on the socio-economic vulnerability assessment in the aquaculture sector establishes the occurrence of climate change risks which affect production and farmers' livelihoods. It can be concluded that as far as environmental aspects are concerned the main risk to, and impact on aquaculture production is the scarcity of good quality water (i.e. deterioration in water quality). This is the crucial problem for, and great challenge facing aquaculture production sustainability, which has negative effects on farmers' socio-economic situations. The factors that contribute to water quality deterioration were depletion of dissolved oxygen, increase in pH, and increase in temperature. The unpredictable variation in seasonal climatic events, such as precipitation and drought, made it more complicated for farmers to take initiatives for early prevention and protection from the climate change risks. However, the situation in Sarawak is still manageable.

The assets farmers own will be useful in coping with the risks and impacts from climate change vulnerability. The study found that financial and physical capital assets as well as human capital assets, had contributed towards reducing the impacts on farmers' livelihoods in Sarawak's aquaculture sector. The most important assets for aquaculture farms were the usage of technology in farm activities. The use of modern equipment, machines, genetic modification of fingerlings and new formulations of fish feed, and monitoring systems was effective to observe control and reduce the impacts and risks as well as boost aquaculture production growth. Farm production size expansion is one of the determinants that helps increase farmers' income levels as well as reduce their socio-economic vulnerability. The diversification of farmers' livelihoods through off-farm aquaculture activities or jobs also benefitted farmers as a safe strategy in facing the issues of loss due to natural and technical factors. The most important human capital assets in coping with the vulnerability of climate change were farmers who were skilled, well-trained and experienced in managing farms and technology and also skilled laborers.

Assessing the socio-economic vulnerability due to climate change impacts was a complex task and results from other region and cultural boundaries may differ. However, the findings of this assessment are important and significant as a reference in improving Sarawak's, as well as Malaysia's, climate change adaptation and mitigation policies and help develop future economic plans for the sector. Control and prevention of climate change vulnerability risks might be beyond our capabilities. However, effective and dynamic actions to empower and strengthen the potential of other capital assets (i.e. social capital) pertinent to aquaculture sustainability and growth may enhance the sector's growth and help it to resist climate change risks and also improve farmers' livelihoods in the future.

CHAPTER 5: POTENTIAL CLIMATE CHANGE ADAPTATION STRATEGIES OPTIONS THROUGH THE AQUACULTURE FARM MODEL ASSESSMENT AND ADAPTATION COST EVALUATION IN SARAWAK

5.1 Introduction

The study of vulnerability is important in helping us identify the perils of global warming (Kelly & Adger, 1999). A vulnerability study enables us to determine useful practices to address climate change impacts, deal with the issues and assist adaptation. The two main strategies to reduce the impacts of climate change are known as mitigation and adaptation (Cannon, 1994) and a combination of these two strategies in coping with climate change risks can maximize social welfare. Compared to mitigation, adaptation seem applicable to the community, especially lower income farmers, due to its lower implementation costs. Adaptation is an ongoing process that is performed as a complementary solution until the mitigation responses increase. However, it is impossible to integrate adaptation and mitigation (Howden et al., 2007).

This study will be limited to investigating aspects of farmers' adaptation strategies in coping with vulnerability and risk, because there is limited information on mitigation aspects and also because of the large scope of both strategies in coping with climate change. Furthermore, the European Environment Agency [EEA] (2007) identified that gaps in adaptation strategy assessment studies still exist at the local, national, and global level. Smit and Pilifosova (2003) reported that the developed, wealthy countries had a greater adaptive capacity, such as technology and economic resources, and were better-prepared to bear the costs of adaptation than developing countries. EEA (2007) agreed that adaptation is more efficient in high-income groups and richer countries than in poorer ones and that distribution of the costs and benefits of adaptation among sectors, socio-economic groups and countries was uneven. For instance, under some conditions, rich countries adapted to the marginal impacts of climate change as a result of economic activities by paying the costs of damage that poor countries incurred under the Kyoto Protocol to the United Nations Framework Convention on Climate Change [UNFCCC] (Pielke, Prins, Rayner, & Sarewitz, 2007) whereas Smit and Pilifosova (2003) found that in Asia community resilience to climate change is very weak due to limited resources for adaptation, lack of infrastructure, income disparities and poverty, weak institutions, and limited technology. Adaptive capacity varied and was influenced by the social structure, culture, economic capacity, and level of environmental disturbances. Therefore, the climate change impacts caused economic and social stresses because stakeholders had not taken adaptation to climate risks seriously.

The survey identified individuals' interaction in response to adaptation strategies and measurement while identifying potential adaptation strategies to climate change impacts and vulnerability. Cannon (1994) considered that most people were vulnerable due to deficiencies in preparedness measures (the level of income and resilience that results the lack of protection). Thus, this study aims to identify the potential adaptation strategies by assessing the costs of adaptation based on Sarawak aquaculture farmers' farm management options in coping with, and reducing, the risks and vulnerability. Hence, this chapter will focus on identifying potential adaptation strategies from the perspective of planned and autonomous adaptation to reduce climate change risks. Indicating the expected adaptation is crucial to the assessment of impact and vulnerability as well as important in the estimation of the costs or risks of climate change (Smit & Pilifosova, 2003). Adaptation strategy identification was based on aquaculture farm management planning that is in line with government targets for greenhouse gasses [GHGs] reduction and farmers' preferences for farm practices that may help them to reduce the risks.

Thus, this chapter will identify and discuss the potential planned and autonomous adaptation in farm management level by:

1) assessing the profit maximization value on farms; feed waste run-off as a risk of climate change; the marginal abatement cost of reducing the emissions; and optimal farm resource allocation under different farm adaptation strategy models,
2) formulating and projecting the farm based adaptive measures based on farm optimization models and risk reduction strategies options,
3) comparing and indicating the best potential adaptation strategies for aquaculture activities in Sarawak based on the profit, adaptation cost, marginal abatement cost and resource allocation in the farm.

5.2 Potential Adaptation Strategies to Reduce Climate Change Vulnerability in the Aquaculture Sector

The adaptation study's purpose in the context of impact analysis was threefold: 1) to observe society's adaptive capacity that helps measure the rising costs of climate change (Fankhauser et al., 1999); 2) to increase individuals', groups' or organizations' ability to adapt to changes, implement adaptation decisions and then transform the capacity into action (Adger, Arnell, & Tompkins, 2005); and 3) to reduce the adverse effects due to changes in climate variables and benefit society or individuals (Ndamani & Watanabe, 2016). Many factors, including protection of economic well-being or safety improvements, can motivate adaptation and adaptation can be implemented in many ways, for example through market exchange, extension of social networks or through individuals', and organizations' actions to meet their own individual or collective goals (Adger, Arnell, & Tompkins, 2005).

McCarthy et al. (2001) explained that the role of adaptation is to select options to adapt to climate change through evaluating their availability, benefits, costs, effectiveness, efficiency, and feasibility. Vulnerability or susceptibility to climate change impacts can be reduced by further identification of the responses and collective actions by individuals, groups, and government to the climate change stimuli (Adger, Arnell, & Tompkins, 2005; Bradshaw, Dolan, & Smit, 2004). Adaptation assists in reducing harm due to climate change impacts because it is a continuous action that starts by addressing harm under normal, as well as under extreme conditions. However, adaptation does not eliminate the severity of climate change events (Fankhauser et al., 1999).

Adaptation strategies must be planned and designed for take into consideration four criteria: climate and related stimuli, system, types, and evaluation. Specifying each of these criteria can address the following questions; Adaptation to what? Who or what adapts? How does adaptation occur? How good is adaptation? (Smit et al., 1999). Fussel (2007b) clarified that adaptation is diversity in the context of there being no single approach to assess, plan, and implement adaptation measures. Adaptation includes several steps. It involves the adjustment of practices, processes, and capital reaction to the existence of the perils of climate change as well as reaction in the decision environment, including social, institutional structures, and modification of technical options that can affect the potential or capacity for adaptation implementation. Thus, knowledge of adaptation will be important to effectively handle climate change risks in the future. It helps deliver feedback from related agents and policy makers making adaptation decisions for short- and long-term durations. Adaptation also helps to show the clear relationship between the short-term and long-term alternatives so that management and policy decisions will be able to prepare for any consequences of future risks (Howden et al., 2007).

Smit et al. (1999) noted that adaptation activities were diverse, depending on criteria such as climate-sensitive domain, the types of hazards, the predictability of climate changes, the non-climatic conditions, purposefulness, timing, and planning horizon. Climate-sensitive domain means that adaptation is pertinent to all economic sectors that are climate sensitive. The types of hazards relate to where adaptation was influenced by a diverse set of current and future climate hazards measured by either observed or expected changes in average climate, climate variability, or climate extremes. The non-climatic conditions refer to the existence of adaptation from the environmental, economic, political, and cultural conditions perspective, which varies substantially across regions. Purposefulness distinguishes autonomous and planned adaptations. Timing means planned adaptations can be reactive (after the impacts occurred) or proactive or anticipatory (before the major damage occurs). Meanwhile, the planning horizon means that the planned adaptation can vary substantially or over the long term as well as in form, where adaptation involves a broad range of measures including technical, institutional, legal, education, and behavioral measures.

Ecosystem-based adaptations include ecosystem conservation, restoration, and management. This type of adaptation was targeted to amplify the resilience to, as well as diminish the risks of, climate change. The events that occur due to climate change hazards and environmental pressure will tend to surpass the resilience of many ecosystems (World Bank, 2010). Thus, efficient management and good practices help to outline adaptation options (Oguntuga et al., 2009).

Several studies have focused on both macro-level and micro-level adaptation to climate change impacts. The focus included assessing the returns of financial investment from adaptation options by comparison with the baseline situation (Halsness & Traerup, 2009; Kirschke & Noleppa, 2008); farmers' adaptation to climate change based on indigenous and local knowledge in coping with risks (Mbilinyi et al., 2005; Siedenburg, 2008); national level sector economic adaptation practices (Adger et al., 2007); and classification and characterization of adaptation options (Smit & Skinner, 2002). Artner, Siebert, and Sieber (2010) erected five separate categories in the area of adaptation practices, including farm management and technology, farm financial management, farm diversification, government interventions in infrastructure, health and risk reduction, and knowledge management, networks and governance.

Singh, Byjesh, and Bantilan (2015) revealed an imbalance in understanding adaptation with more studies focused on the macro or regional level. Therefore, understanding micro-level adaptation strategies from the socio-economic perspective can assist in identifying gaps and limitations and has potential in improving vulnerable individuals' or farmers' resilience. Furthermore this can assist policy makers to make more effective plans, programs and targets to cope with the impacts as well as enhance society's resilience.

Previous adaptation studies have mainly concentrated on the wider context - the regional, country, and communities level, so there are concerns about looking at adaptation from the individual perspective or focusing on small scale and farm level farmers (Below, Artner, Siebert & Sieber, 2010; Bradshaw, Dolan & Smit, 2004; Oluwole, Shuaib & Dasgupta, 2016; Reidsma et al., 2015; Sima et al., 2015). The farm level is important in impact and adaptation assessment as farmers take decisions in response to the impacts on their production, management and adaptation (Reidsma et al., 2015). Farmers with low subsistence or family-run farms had low adaptive capacity and were the most vulnerable to climate change and socio-economic impacts, as indicated by the theory of entitlement and theory of resilience and supported by Sima et al. (2015), whilst the wealthier farmers were much better able to apply adaptation practices in response to climate change (Ndamani & Watanabe, 2016). Farmers were found to lack awareness of climate change impacts and the best adaptation strategies because climate change is still not very apparent.

Farm level or local level adaptation was influenced by several micro and macro level factors such as climate variations, the production system, socio-economic factors, the government, non-government organizations or the private sector. However, farm level adaptation is dynamic and as such, challenging to determine as it depends on the farmer's decisions on farm activities and also includes long-term and planned adaptation rather than just coping responses to short-term effects. Farm adaptation practices vary in terms of context, the different constraints, biophysical features and differences in climate change effects. Below, Artner, Siebert, and Sieber (2010) recorded a wide range of adjustments in land use and livelihood strategies in farm management in order to cope with the biophysical and socio-economic situations and these varied from changing farm management practices to developing investment schemes and infrastructure improvement (Sima et al., 2015). Furthermore, the social response to climate change impacts can be facilitated by identifying a farmer's adaptation behavior in both generic and climate specific terms. In addition the adaptation policies may be supported if they were designed according to the farmers' understanding and response to the impacts and this is undertaken by the government (Bradshaw et al., 2004). Successful adaptations must be economically efficient, effective and flexible or institutional-compatible (Bradshaw et al., 2004; Carter et al., 1994; Smith & Lenhart, 1996). Society's specific adaptation practices counterbalance the adverse impacts of climate change (Fussel, 2007b). The effectiveness of adaptation refers to the capacity to achieve the objective, reduce impacts and exposure to them, reduce risk, avoid danger and promote security. The economic efficiency of adaptation requires a consideration of the distribution of the costs and benefits of the actions, the costs and benefits of changes in those goods that cannot be expressed through market values and the timing of adaptation actions (Adger, Arnell, & Tompkins, 2005).

Sima et al. (2015) revealed the three best ways to analyze farm level adaptation: i.e. 1) to understand the farm activities' contextual factors in order to understand the adaptation; 2) to understand the future impacts of climate change in biophysical and socio-economic terms; and 3) to analyze the context for farm adaptation measures by communicating with the farmers as the key actors to assess their knowledge, understanding and actions to identify adaptation options. However, the great challenge in practicing these steps was in terms of understanding the farmers' adaptive capacity due to the heterogeneity of human decision making and behavior, whereby the farmers' perception, sensitivity, and response to the impact stimuli were influenced by the individual farms, farm operators, and also families (Kandlikar & Risbey, 2000; Smit, McNabb, & Smithers, 1996). Thus, transparent information about the farmers' and related stakeholders' responses and action is crucial for the design of adaptation strategies (Reidsma et al., 2015).

Adaptation is the adjustment process whereby farmers can change the options through learning by doing, until the cost of current and future farm emission abatements can be reduced subject to the timing and costs required in order to meet a given concentration target (Manne & Richels, 2002). A start on the evaluation of the potential adaptation strategy at farm level requires identifying the farm's production risks. Farm level risk assessments were conducted by assessing information from farmers with limited resources. For instance, such a study in Mississippi clearly identified the limited resources that influenced farmers' vulnerability to risks (Coble et al., 2001). Bard and Barry (2000) added that economic decisions on risk management were influenced by the producer's attitudes to risks (whether he was a risk taker or risk averse) which was highlighted in the utility theory, to the producer's attitude (progressive versus conservative) and whether the future generations are optimistic or pessimistic about their adaptive capacity (Adger et al., 2007). The producer as the economic agent will make a judgment based on his/her risk attitude towards the preference mechanisms or tools used to manage risk. If producers are risk averse the demand for specification strategies in reducing risk can be identified.

Mendelsohn et al. (1996) in the United States conducted a study that assessed risk in identifying potential adaptations. The study applied the Ricardian Model to analyze the long-term effects of environmental change on farm profitability. The Ricardian Model holds the actual response to the environmental change. The Ricardian Model approaches focus on the farm profit and help farmers to develop their adaptation strategies. This model was implemented to value the impacts of climate on the total farm value using as variables environmental and natural resources information (such as salinity, clay content, sand content, soil permeability, available water capacity, flood probability, soil erosion, slope length, precipitation, and temperature). Actual farm value per hectare was the study's dependent variable. The results indicated that farm value responded more to temperature than to precipitation. The environmental changes were very significant in reducing the farm's value. Another almost identical recent farm level adaptation study is that of Oluwole et al. (2016) who focus on assessing the climate change adaptations made by arable crop farmers in Oyo and Ekiti States, Nigeria, by evaluating the farmers' socio-economic characteristics, examining the farmers' adaptation strategies and the level of use of various adaptation strategies, and examining the constraints associated with the adaptation strategies. This study found that the farmers had practiced a combination of adaptation strategies and the variation of strategies was due to the differences in farmers' access to capital and information on the strategies and the type of crop plant. The study also revealed that information on climate change forecasting, adaptation options, and diversification of agricultural activities was significant in determining the application of various adaptation strategies.

Reidsma et al. (2015) noted that farms have their own production objectives, the main objective being to maximize profit, whilst farms' activities are subject to a variety in available resources and constraints which influence the adaptation to changes of drivers. Farm performance was indicated by farm income, farm plans and management, input and output prices, farm size, technological developments, markets, and policies. Thus, the farm impact assessment for adaptation design will allow or enable farmers to maximize profits under conditions of climate change. Furthermore, identifying the perception of risk may help in effective risk assessment as the level of risk and vulnerability is identified both in terms of environmental changes and also socio-economic changes. For example, Meuwissen, Huirne, and Hardaker's (2001) study to identify the production risk among Dutch livestock farmers identified that influential factors, such as animal disease and pests and price risks were the most important source of risks. In addition, several studies identified factors that influenced perception, such as geographic areas and farm types (Patrick, Wilson, Barry, Boggess, & Young, 1985) and institutional and other factors that influence the farmers' environments (Patrick & Musser, 1997).

5.3 Costs of Adaptation Assessment in Indicating Potential Adaptation Strategies for Aquaculture Farms

The main goal of the economics of climate change research is to achieve cost effectiveness in climate change policies' structure. The cost effectiveness in adaptation can benefit the people by reducing current and future damage in the right balance on the margin of cost of actions. Another goal is to deliberate on the climate change risks and impacts through action to maximally reduce the harmful climatic change for a given level of expenditure (Nordhaus, 1993). The cost effectiveness analysis gives an overview of the economic and climatic complexities by taking a global view of economic activity and simple dynamic specification of emissions, concentrations, and economic growth (Nordhaus, 1991). Stavins (1997) added that the instrument assessment should be capable of maximizing net benefits and be relatively efficient, which means it should be based on the best knowledge of both abatement costs and benefits and understanding both physical consequences and economic valuation of climate change consequences.

The costs of climate change would be considerably higher without adaptation. According to Smit and Pilifosova (2003) and EEA (2007) the best adaptation strategy can be identified through an assessment of the costs and benefits of adaptation where the adaptation option was valued in monetary measures for every strategy taken. The main aim of the decision making in adaptation is to focus on reducing the cumulative climate change impacts and ensure that adaptive measures taken do not adversely impact upon other measures, avoiding anticipated adverse climate change impacts, and ensuring that the distributional impacts of adaptation are minimized (Adger, Arnell, & Tompkins, 2005). Adaptation actions to reduce the climate change impacts incurred the adjustment of costs and these impact costs were calculated by totaling the adaptation costs and residual damage costs. At the scale of the individual the cost of adaptation action consists of transaction costs and costs of inaccurate prediction, whilst the adaptive benefits are those reduced impacts or enhanced opportunities (Adger, Arnell, and Tompkins, 2005). Adaptation is possible in any economic sector and occurred with transition costs and equilibrium or residual costs. In buffering the climate change effects the reactive action of aspects of the ecological, social, and economic costs was important in adaptation options (Smit & Pilifosova, 2003).

The advantage of costing the adaptation was that this provides guidelines on the decision making context in choosing and practicing the best adaptation option to mitigate and cope with the climate change risks (Metroeconomica, 2004). Burton (1997) revealed in a case study that assessed the costs of adapting to the normal variability of climate and extreme climate in Canada in 1995 showed that Canada had obtained many advantages by spending for improving adaptation to normal changes in climate from the extreme events and huge losses due to the major events.

The EEA (2007), in identifying the cost of adaptation, identified several knowledge gaps in the extension of methodologies where the full costs of climate change and solving the issues raised in terms of economic costs and benefits of biodiversity needed to be properly addressed. Furthermore, the non-market damage, indirect effects, horizontal inter-linkages, and socio-political implications of change in adaptation studies are also unclear. Adaptation cost assessments for the world or a region that covers different time horizons need to be carried out and compared, adopting alternative weights. Studies also needed to be expanded to cover different sectors and including additional types of climate change, after which the non-market damage needs to be studied along with the market damage aspects and the major catastrophic events and shocks.

The potential adaptation strategies were identified by assessing the damages costs and benefits costs - known as the impact costs. These include market and non-market adaptation aspects (Howden et al., 2007; Hurd, Callaway, Kirshen, & Smith, 1997). The imbalance assessment, which was biased to market proxies, will only affect the serious costs and benefit underestimates (Adger, Arnell, & Tompkins, 2005). Tol (2005) discovered that the market impacts could be significant under some conditions of adaptation, such as large losses over adaptation cost due to the increased severity of extreme events. Meanwhile, non-market impacts and benefits assist in the adaptation efficiency. Nevertheless, adequate assessment of cost and benefit adaptation required a consideration of the viability and cost of concurrently lessening greenhouse gas emissions and adapting to climate change, the outcome of capital and other resource constraints and the adoption level in seriously affected areas as the impacts of climate change are present (Howden et al., 2007). Furthermore, Fankhauser (1996) revealed that the adaptation activities are acceptable and optimal in the sense of economic efficiency if the additional costs of adaptation are lower than the additional benefits in reduced damage or the total of adaptation costs and residual damage costs is minimized.

Tol and Fankhauser (1997) pointed out that there were different opinions on the process of defining and calculating adaptation costs. The researcher considers equilibrium adaptation costs but disregards the transition cost of adaptation. The cost of adaptation is minimal compared to other management or development costs (Smit &

Pilifosova, 2003) and was limited to the specific measures of well-being (Brown, 1998). However, the cost of adaptation kept growing due to the gradual increase in damage costs due to extreme climatic events (Smit & Pilifosova, 2003).

Although the measurement of economic costs and benefits of adapting to climate change is not necessarily adequate as the determinant factor in indicating the accuracy of adaptation (Smit & Pilifosova, 2003), it is important in evaluating the response options as well as the motivation of the autonomous adaptation (Grothmann & Patt, 2003). The alternative adaptation options can be prioritized based on the costs and benefits identified by policy analysts and economists (Fussel, 2007b). In addition to costs and benefits, the elements of equity, efficiency, and implement ability need to be investigated to evaluate the adaptation performance.

The potential adaptation was considered successful if it was flexible and effective in meeting the stated objectives under a range of future climate scenarios and had the potential to create more than just financial, physical, and human benefits. An effective adaptation must include non-climatic stresses and be consistent with current policy aspects, development objectives and the structural management (Smit & Pilifosova, 2003). In contrast, Adger, Arnell, and Tompkins (2005) argued that the success of adaptation cannot be simply identified through the effectiveness of meeting objectives due to two reasons. First, the action may be successful in terms of one stated objective but may impose externalities at other spatial and temporal scales. Second, the adaptation may be successful over the short term but less successful over the long term and the action may cause negative externalities and spatial spillovers, increasing impacts on others or reducing their capacity to adapt although the action of the adapting agent is effective.

To facilitate the adaptation, macroeconomic or development goals, socio-economic trends, the adaptive capacity increases with development, and the degree and type of adaptation needed to be linked. This will make economies less vulnerable to both climatic and a range of other economic and natural pressures (Adger, Arnell, & Tompkins, 2005; EEA, 2007). Furthermore, the valuation approach and indirect effects were other influencing factors which can cause potential direct and indirect costs in adaptation. Various approaches were used to model adaptation, including spatial analogies and micro-economic optimization, and these approaches may sometimes underestimate or overestimate the effectiveness and costs of adaptation. Thus, to reduce the estimation faults, adaptation costs assessment must include the combination of economic, social welfare, and equity criteria (Tol, 2005) as well as the capacity of natural and socio-economic systems to adapt (EEA, 2007). Nevertheless, the study must also emphasize individuals', communities', corporations', private and public institutions', governments' and international organizations' roles, and responsibilities in adaptation because the adaptive measures were constrained by other priorities, limited resources and economic or institutional barriers (Smit & Pilifosova, 2003).

Smit and Pilifosova (2003) distinguished the different cost assessment advantages of autonomous adaptation *versus* planned adaptation. Their study revealed that cost estimation in autonomous adaptation is not only important for impact assessment, but also as a reference for the baseline scenario in evaluating policy initiatives in both adaptation and mitigation. EEA (2007) added that adaptation is important in assessing the baseline of inaction costs. However, autonomous adaptation is limited in terms of information access and includes the resource adaptation costs and residual damages. Thus, anticipatory and precautionary adaptation through planned adaptation strategies by public agencies is more effective than autonomous adaptation because it requires fewer costs than emergency adaptation. The study also confirmed that it was difficult to capture adaptation adequately in impact assessment. The degree and type of adaptation included influencing the estimation of adaptation and many studies focus on autonomous adaptation as compared to planned adaptation.

Notwithstanding all the positive aspects of adaptation, Tol (2005) showed that adaptation was lacking in several respects. It was difficult to capture in impact assessment due to different goals in economic activities which affect differences in adaptation costs and residual impacts. It has a strong relationship with other socio-economic trends where, without explicit adaptation, impact assessment will vary depending on the type of socio-economic development expected in the future. In addition, the abatement costs should be balanced against the avoided costs of climate change when targeting for emissions reduction. EEA (2007) posited that uncertainty affects the reliability of the adaptation cost assessment which reduces the rate and speed of adaptation. Therefore, the role of the decision making process in local and sector-specific case studies need to be studied in order to solve the problems. Adger et al. (2007) verified that there were three dimensions of limitations to adaptation, namely the ecological and physical limits, economic limits, and technological limits. These dimensions have various analytical capabilities for study adaptation and allow adaptation to be present in various aspects of policy assessment. The ecological and physical limits to adaptation are about indicating the limits through physical modeling under the changing climate. The limits of adaptation are similar to a state in sensitive ecological or physical systems beyond which change becomes irreversible. The economic limit to adaptation is about assessing its cost effectiveness and cost benefits and the adaptation limits may arise from analyses of the economic costs of adaptation.

Meanwhile, technological limits are about the various types of technology mapping and innovation analysis.

The physical and economic impacts of climate change were difficult to measure. EEA (2007) verified that, based on the theory of adaptation, the adaptation measures need to be considered across all climate parameters across all sectors and the entire risk matrix. Two cost valuation approaches were proposed to tackle the issue of climate change: the cost of inaction (impacts of climate change) and the cost of adaptation. Furthermore, there were different types of costs linking with different adaptation actions, such as direct costs of implementing a specific adaptation measure (that is the general costs of enhancing the broad adaptive capacity of an impacted system, known as cost of facilitative adaptation) and transition costs (which link with the adjustment process triggered by adaptive responses). Transition cost is relevant for cost assessments of both planned and autonomous adaptation processes but is the most difficult cost to assess.

The anticipatory adaptation policies are the best choice if they fulfill at least two criteria: flexibility, and a potential for benefits to exceed costs in which net benefits are greater than zero. Compilation of information on various practices may be a cost effective way to identify feasible adaptation options because those that require long-term decisions should be identified and analyzed for implementation (Smith & Lenhart, 1996). The feasibility and costs of adaptation determined by the rate of climate change, especially when major adjustment was needed in physical infrastructure or land use, was influenced by technical, socio-economic and political change over time. Thus, resources need to be allocated efficiently among adaptation strategies and between adaptation and mitigation strategies. This can be achieved if the costs and benefits of the different options are clearly determined (EEA, 2007).

In indicating the potential strategies to cope with climate change risks, Pindyck (2013) posited that the integrated assessment models (IAMs) are a good guide for the selection of adaptation strategies. De Bruin, Delink, and Agrawala (2009) agree that the IAMs have the advantage in terms of suggesting the efficient allocation of abatement burdens and accepted damages, by specifying the costs and benefits of various abatement strategies. The IAMs combined the economic models and climate science models in the analysis. This combination integrates the projection of abatement costs and describes how changes in climate affect output, consumption and other economic variables with the description of emissions and their impact on temperature. The analysis preference parameters affect the benefits. The situation where the benefits are sufficiently large and robust to reasonable ranges of those parameters would support a stringent abatement policy. The IAMs analysis calculates the present value of the benefits of preventing climate change consequences or reducing the probabilities of the incidence of climate change impacts. This method is acceptable to many economists and climate scientists because it presents the rational outcomes and acceptable ranges of probabilities.

Formulation of the farms' optimization model in this study involved concentrating on the valuation of the costs of adaptation. Five series of integrated steps were applied, starting with identification of the baseline scenario that links the climate (level of impacts or change in vulnerability and level of adaptive capacity) with socio-economic trends. Then the direct and indirect cost of adaptation was identified through the valuation approach and the discount rate determined as the measurement of temporal variation of adaptation. The next step that needs to be considered concerns the equity or distributional effects of geographical variation. Then, the uncertainty, irreversibility and coverage of adaptation were considered. Adaptation is not an independent process but needs to be combined with other decisions in the context of demographic, cultural and economic change, transformation in information technologies, global governance, social conventions, and globalizing flows of capital and labor (Adger, Arnell, & Tompkins, 2005).

5.3.1 Marginal Abatement Costs Estimation for Determining the Potential Adaptation Options

The marginal abatement cost curve (MACC) has been applied in research in many sectors of economics since the 1970s to assess the abatement potential and costs related to air pollution, water availability and carbon dioxide and greenhouse gas emissions in the case of global warming (Bockel, Sutter, Touchemoulin, & Jonsson, 2012). In the agriculture sector, MACC assessment was first applied in 2000. However, Manne, and Richels (2002) indicate that there was less interest in studies on assessing the abatement costs as a method for cost effective assessment in farm level studies in choosing the adaptation strategies that at the same time meet the farm production targets. The importance of MACC in policy makers' policy creation rose after 2008 to demonstrate an affordable quantity of an economy's abatement and identify the area of focus with respect to policies to reduce emissions (Bockel, Sutter, Touchemoulin, & Jonsson, 2012).

The marginal cost curve of emissions reductions illustrates the costs that the economy undertakes to reduce a unit of greenhouse emission (or equivalent in other policies that would deliberate greenhouse warming) (Nordhaus, 1991, 1993). The

MACC is effective in illustrating the technical and economic arguments for cost effectiveness and abatement potential of strategies to cope with climate change. The MACC is able to indicate an appropriate and applicable climate policy, indicating the impacts of policy options without unearned costs but contribute to the abatement exertion, suggesting for the adoption of newer technologies, promote economically and cost-effectiveness of measures supports the need for financial incentives (Ibrahim & Kennedy, 2016). Thus, the MACC is one of the appropriate methods that can be used to assess the best decision option through the comparison of the marginal costs and marginal benefits of each option.

The MACC shows the relationship between the cost effectiveness of different abatement options and the total emissions abated, which reflects the additional cost of reducing the last unit of emissions. The MACC is an upward-sloping curve which shows the efficient marginal cost of abatement function (Nordhaus, 1991) and reveals that the marginal costs rise with the increase of abatement efforts by one unit (Bockel, Sutter, Touchemoulin, & Jonsson, 2012). Minimizing the abatement cost is a complex process because it requires all the foundations towards a clean environment to be equated to the marginal cost of abatement (McKibbin & Wilcoxen, 2002). Nevertheless, an efficient level of abatement can be achieved at which the difference between benefits and costs is maximized. If the benefit and cost function are shaped as they are typically believed to be, then this efficient level occurs at the point where the marginal benefits equal marginal costs (Baumol & Oates, 1988).

Nordhaus (1991) revealed that three conditions will be in existence when there are no externalities and when efficient controls are designed in MACC functions assessment. First, the market price on emissions is zero when a unit of emission is virtually free.

Second, if the level of abatement increases, the cost function will also increase. Third, society will act contrary to the abatement cost function if the regulations are inefficiently designed. Stavins (1997) posited that the choice of strategy in reducing target level emissions was affected by the function of marginal abatement cost, but not the uncertainty about the benefits of abatement.

Kesicki and Ekins (2012) indicated that MACC has several limitations. Where the method of generating the cost curve omits the ancillary benefit of emissions abatement, the uncertainty was treated in a limited way, inter-temporal dynamics is excluded, and there is an absence of clarity behind the model's assumptions. However, the limitations in generating MACC can be treated by insertion of ancillary benefits, improvement of the depiction of uncertainties, and representation of cumulative emission abatement to address time related interactions (Kesicki & Strachan, 2011)

5.4 Methodology

This study analyzes the potential adaptation strategy based on the farm management model with the consideration of target emissions in order to meet the third study objective. Generally, planned adaptation by the Malaysian government involves setting reduction. The setting target of emission reduction by the government is adapted in the farm management model as one of the constraints. The setting of emissions reduction in the model will affect adjustment to farm management activities and suggest the autonomous adaptation options of aquaculture production in coping with climate change risks and vulnerability.

5.4.1 Data Description

Two hundred and fifty five (255) aquaculture farmers at Kuching, Samarahan, Sri Aman, Betong, Sarikei and Limbang divisions underwent semi-structured interviews to elucidate their potential adaptation options to cope with vulnerability and climate change risks. The semi-structured interviews were conducted to ensure no information was missed using the questionnaires alone. Furthermore, such interviews help the researcher obtain additional qualitative information not covered by the questionnaires. Only 110 of the 249 qualified respondents were selected as representatives of each of the aquaculture systems to forecast the potential adaptation models. Then, the respondents were categorized into three groups based on their production scale. Seventy four (74) pond farmers and 36 cage farmers were selected as representative of aquaculture farmers in Sarawak. The numbers of farmers were reduced in analyzing the Chance Constrained Programming (CCP) model to minimize inaccuracy in the results and simplify the comparison between farm based management decision models in identifying the best options to adapt to climate change risks.

5.4.2 Indicating Potential Planned Adaptation through Farm Optimization Model Using Chance Constrained Programming (CCP)

Chance constraint optimization is one of the methods used in assessing the risk management in the random variations scenario, especially in natural resources systems (Bevers, 2007; Eshragi, 2008). Bhat et al. (1999) indicated application of chance constraint optimization in assessing environmental risk in river contamination assessments; Zhu, Taylor, and Kramer (1990) and Zhu, Taylor, Sarin, and Kramer (1994) focused on soil conservation; and Moghaddam and DePuy (2011), focused on farm management optimization. In the case of climate change effects studies Spring and Kennedy (2005) have applied this analysis in studies in assessing catchment management for water, timber production and carbon sequestration; and Kirchner, Strauss, Heumesser, and Schmid (2012) used it to focus on farm adaptation to a warmer and drier climate.

Chance constrained programming (CCP) is a modification model analysis of the linear programming (LP) presented as follows:

$$Maximize\ Z = CX \tag{5.1}$$

$$Subject\ to: AX \ \leq b \tag{5.2}$$

$$X \geq 0 \tag{5.3}$$

where Z is the objective function that is being maximized, C is a vector of costs and returns, X is a vector of decision making variables, A is a matrix of technical coefficients, and b is a vector of constraint coefficients.

CCP is employed as the key approach that engages in random parameters in optimization problems. It is usually applied to the areas that deal with uncertainty conditions, like product demand, meteorological or demographic conditions, current exchange, and other areas (Henrion, 2004). Many factors, such as temperature, precipitation, relative humidity, water quality, anthropogenic gases and substances, and production management influence climate change (climate variability and extreme events). The strategy to reduce climate change impacts can be a long-term or short-term strategy. Thus, the effectiveness of this strategy depends on the probability distribution of annual climate variability. A high probability of satisfying tolerance level will lead to a climate change impacts reduction strategy being effective. This would mean that the strategy practice was very restrictive. It is important to identify the relationship between changes in tolerance levels of climate variability, probability levels, and the producers' economic impacts for risk based economic and policy analysis for climate change (Zhu et al., 1994).

Chance constraint analysis was a potential option that could be used for risk-based decision making and it was widely applied in the 1960s and 1970s. The CCP model maximizes the objective function subject to constraints and held up at a fixed level of probability. The general CCP model as shown as:

Maximize f(c, X) (5.4)

Subject to: $\Pr[AX \leq b] \geq \alpha$, $X \geq 0$ (5.5)

where f(c, X) is the objective function, X is the decision variable vector; A is a matrix of technical coefficients; b and c are vectors of coefficients and α is the prescribed level of probability. Not all of the coefficients in A or b are necessarily random in empirical CCP models. Assuming that climate variability is the only random variable in the model, then climate variability constraint is the only chance constraint in the model. If the ith row of the A matrix represents the climate variability constraint in this study, the model can be written as:

maximize $f(c, X) = \sum_j c_j X_j$ (5.6)

subject to: $\Pr\left[\sum_j a_{ij} X_j \leq b_i\right] \geq \alpha_i$ (5.7)

$\sum a_{ij} X_j \leq b_k \qquad \forall k \neq i$ (5.8)

$X \geq 0$ (5.9)

where the objective function coefficient, $c_{j,}$ is net returns, X_j is the decision variable, production rotation, $1-\alpha_i$ represents the acceptable risk of not meeting the climate variability constraint and a_{ij} represent soil loss coefficients, which are functions of random variables.

5.4.2.1 Formulation of farm management chance constrained optimization model

Chance constrained programming was applied to address complex farm management problems in aquaculture activities by developing an optimization model to find the realistic decision of farmers in adjusting farm management practices and coping with climate change risks. The optimization models were useful to capture the probabilistic nature inherent in aquaculture products as compared to deterministic decision models. Additionally, the optimization models can explain the influence of variability factors such as weather, water quality, market and non-market prices, farm management policies, and seasonal factors over time in aquaculture activities (Moghaddam & DePuy, 2011). The results may give a guideline on efficient management and good practices in managing farms (Oguntuga et al., 2009) as well as give farmers the information they need in order to plan practical adaptations in the long run and short run. A few aspects of the adequacy of adaptation will be considered. These include cost and benefits adaptation (such as market and non-market values, the capability to, and concurrent cost of, lessening greenhouse gases emissions) and adapting to climate change that is the outcome of capital and other resource constraints and adoption levels in very badly affected areas as the impacts of climate change is positive (Howden et al., 2007).

This study will analyze two optimization models: the optimization models for pond aquaculture and cage aquaculture farms, which combine fresh water and brackish water activities. The analysis included biophysical and economic simulation models to gather the heterogeneity in production and environmental factors. These models will consider the cycle of production in a year, estimated aquaculture yield according to production zone, output price, feed cost, random variables of total production over aquaculture area size, labor resource used and endowment, total feed waste effluent produced by the farm, and land endowment. Pond and cage aquaculture activities were classified under 15 and eight zones respectively (details presented in Table 5.1).

Assuming that climate change risks on aquaculture production in Sarawak exist, a CCP model was developed to determine the best strategy to maximize farm profit as well as cope with the climate change risks. Therefore, the economic and environmental factors were analyzed by developing three different management options for aquaculture farm production activities. The costs and benefits of different options need to be clearly determined in order to suggest effective farm management options based on the resource allocation (EEA, 2007).

Table 5.1: Classification of pond and cage aquaculture farm zones

Ponds		Cages	
Zone	Location	Zone	Location
1	Betong-Saratok	1	Kuching
2	Kuching	2	Kuching-Paroh Sejijak
3	Kuching-Bau	3	Kuching-Lundu
4	Kuching-Lundu	4	Sri Aman-Batang Ai
5	Kuching-Siburan	5	Sarikei-Selalang
6	Lawas	6	Limbang
7	Limbang	7	Lawas-Sungai Punang
8	Samarahan	8	Lawas-Awat-Awat
9	Samarahan-Asajaya		
10	Samarahan-Serian		
11	Sarikei		
12	Sarikei-Maradong		
13	Sri Aman-Batang Lupar		
14	Sri Aman-Lubok Antu		
15	Sri Aman-Pantu		

In the first farm management option, the researcher assumed that there is no uncertainty about the average output prices and aquaculture yields. These models are known as baseline models and labeled Scenario A. The original set of data on factors of farm production was used in the analysis. The second management option models were simulated by considering the condition where the aquaculture production increases by 10% (as targeted by the government) with a 5% increase in output price. The third management option models were simulated by assuming a 10% increase in aquaculture production with a 5% decrease in output price.

The simulations also considered the environmental risk aspects contributed by the factor of production. Under the climate change risk, the aquaculture feed waste may cause bad water quality in the aquaculture area and nearby community areas. The main environmental problems related to aquaculture effluents are water pollution. The chemical pollutants, metabolic products pollutants, and feed waste and metabolic waste pollutants were the three major contributors to poor water quality in aquaculture areas. This study considers feed waste as an environmental constraint on aquaculture production due to data constraints for chemical and metabolic products measurement at the observed farms. The feed wastes of each farm were estimated using the food conversion ratio (FCR) formula in water quality guidelines for aquaculture as suggested by Mugg, Serrano, Liberti, and Rice (2000).

The direct discharge of feed waste to watercourses will increase the concentration of suspended solids in water and thereby reduce the biodiversity. The suspended solids from waste water organic particles have biochemical, chemical and physical effects, such as the problem of sedimentation, dissolved oxygen utilization, and nutrient sources. From the biological point of view the suspended solids affect the dissolved oxygen in, and eutrophication of water (Bash, Berman, & Bolton, 2001). The variability in temperature and precipitation due to climate change events will cause extreme additional water quality problems.

The current condition of aquaculture activities, without any change to management plans and without an emissions reduction target and environmental restrictions, is the study baseline model known as Scenario A. Burton (1997) verified that a practical adaptation was to adapt to current and future climate variability and reduce the hazards that may cause the conditions to become more critical. This concept of adaptation has motivated the setting up of scenario B that includes the setting of environmental regulations. Thus, we set and compare the results of different scenarios, with 10%, 20%, and 40% reduction of total feed waste effluent by each farm, in order to minimize the water quality problems. The optimal allocation of production factors in the different scenarios will be compared. The other consideration that applies in this optimization analysis is the imposition of acceptable emissions constraints with a 90% probability in Scenario B (which is known as environmental restriction) that develops Scenario C.

The comparative static analysis was conducted based on the results of farm optimal land use and management portfolios. The proposed adaptation options available to aquaculture farmers in Sarawak are based on farm management decision of the Chance Constrained Programming mathematical model of this study, which can be expressed as,

$$Max\ f(P.X) = \sum_c (P_c X_c) \tag{5.10}$$

$$subject\ to \quad \sum_c (a_{ic} X_{c)} \leq b_c \forall_j \tag{5.11}$$

$$Pr(\sum_c (l_c X_c) \leq L) \geq \alpha_i \tag{5.12}$$

$$Pr(\sum_c (w_c X_c) \leq W) \geq \alpha_i \tag{5.13}$$

$$Pr(\sum_c (e_c X_c) \leq E) \geq \alpha_i \tag{5.14}$$

$$Pr(\sum_c (s_c X_c) \leq S) \geq \alpha_i \tag{5.15}$$

$$\sum_m (\theta_m M_{cm}) \leq X_c \forall_c \tag{5.16}$$

$$\sum_c (X_c) \leq \sum_m (\theta_m \sum_c M_{cm}) \tag{5.17}$$

$$X_c \geq 0 \tag{5.18}$$

The objective function (5.10) maximizes the average aquaculture profit where X_c is the quantity of aquaculture products (fish) and P_c is the price parameter. The index $_c$ represents production choice such as farm (F), aquaculture system (S), aquaculture rotation or cycle (R), and aquaculture zone (Z). Inequality (5.11) constrains the choices of variables to available resource endowment (*b*) such as land, labor and fish feed and in the environmental regulation (ER) model includes feed waste runoff that is denoted as $_i$. Eshraghi (2008) considers that the total used resources in inequality must be equal or less than the average resource availability less the standard deviation times a critical value which arises from the probability level. The Leontief fish technology matrix to convert resources into fish production is represented by a. The parameters for land (*l*), labor (*w*), fish feed (*e*), and sewage (*s*) are subject to uncertainties. Inequalities (5.12), (5.13), (5.14) and (5.15) represent such probabilistic constraints for land, labor, fish feed and sewage effluent. These constraints shall not be violated at a given probability denoted by α=90%. The allocation of land for farm activities, labor working hours and fish feed consumption and sewage effluent as results of aquaculture activities must not exceed the maxima of L, W, E, and S respectively.

The chance constrained programming deals with an uncertain right-hand-side value based on the normal distribution that can be transformed to an equivalent deterministic constraint. McCarl and Spreen (1997) mentioned that in this condition, the decision maker was assumed to determine a probabilistic statement about the frequency with which constraints need to be satisfied, as follows:

$$P(\sum_c a_{ic} X_c \leq b_i) \geq \alpha_i \tag{5.19}$$

$$p\left(\frac{\sum_c a_{ic}-\bar{b}_i}{\sigma_{b_i}} \leq \frac{(b_i-\bar{b}_i)}{\sigma_{b_i}}\right) \geq \alpha_i \tag{5.20}$$

Where $\overline{b_\iota}$ is average value of the right hand side (RHS) or b, and σ_{bi} is the standard deviation of b. Then the standard error of b_i is $\frac{(b_i-\bar{b}_i)}{\sigma_{b_i}}$.

Chance constraint was also evaluated using inequality deterministic constraints having higher right hand side values than in the original. The $Z_\forall$ value was estimated with a particular probability limit (∀) and the constraint becomes:

$$P\left(\frac{\sum_c a_{ic}X_c-b_i}{\sigma_{b_i}} \leq Z_\alpha\right) \geq \alpha_i \tag{5.21}$$

restated as $\sum_c a_{ic}X_c \leq \bar{b}_i - Z_\alpha \sigma_{bi}$ where resource use ($Ea_{ic}X_c$) must be less than or equal to average resource availability less the standard deviation times a critical value which is indicated from the probability level. McCarl and Spreen (1997) and Eshraghi (2008) added that Z_α can be identified by:

a) assuming normality and using values for the lower tail from the standard normal probability table for the form of probability distribution of b_i, or,

b) estimation using Chebyshev's inequality.

The chance constrained programming with a normal distribution (Segarra, Kramer, & Taylor, 1985) can be presented as,

$$\sum_c \bar{a}_{ic} X_c + K_a\left(\sum_k \sum_c X_k X_c \sigma_{ikc}\right)^{1/2} \leq b_i \tag{5.22}$$

$$\sum_c \bar{a}_{ic} X_c + K_a\left(\sum_c X_c^2 \sigma_{ic}^2\right)^{1/2} \geq b_i \tag{5.23}$$

where $\bar{a}_{ic}$ is the mean value of a_{ic}, $\bar{\sigma}_{ikc}$ is the variance covariance matrix of a_{ic}, σ_{ic}^2 is the variance a_{ic} and parameter K_a depends on the distributional assumption of random variable and level of probability. According to Zhu et al. (1994), $(\sum_c X_c^2 \sigma_{ic}^2)^{1/2}$ is the standard deviation of $\sum_c \overline{a}_{ic} X_c$. Constraints (5.16) and (5.17) ensure a convex set of alternative aquaculture rotation system cycles, where θ is the choice variable for the aquaculture rotation cycle and M the parameter for available cycles denoted by *m*.

The findings of farm decisions under certain and uncertain climate variability conditions were presented by Scenarios A, B and C with three different management options models. The results for representative farms were solved using the General Algebraic Modeling System (GAMS) software with large-scale nonlinear optimization [CONOPT] solver.

5.5 Findings of the Chance Constrained Programming (CCP) Analysis

The results of using the CCP analysis showed the potential adaptation strategy that Sarawak aquaculture farmers can use to cope with climate change risks. This strategy was selected based on the comparison of three different environmental regulations under three different farm management options. Assuming production certainty, the model is estimated using chance constrained models without including the probabilistic constraint into a deterministic equivalent in objective function.

Scenario A or the baseline model is a certainty model that omits environmental constraints and presents the typical maximization procedure. The Scenario B model is a certainty model that estimates the optimal allocation of farms with three different percentages of feed waste reduction. The Scenario C models evaluate the farms' decisions that are under uncertain climate change risk with the assumption that the feed waste constraint imposed will be satisfied with a probability of 90%. Table 5.2 summarizes the development of a scenario based study using Chance Constrained

Programming. The findings for the optimal mix of management measures to a changing climate are elaborated in the next section.

Table 5.2: Summary of Chance Constrained Programming analysis

MANAGEMENT OPTION / SCENARIO	MGMT OPT I: BASELINE		MGMT OPT II: 10 % PRODUCTION INCREASE + 5% PRICE INCREASE		MGMT OPT III: 10% PRODUCTION INCREASE + 5% PRICE DECREASE	
SCENARIO A: BASELINE	CURRENT CONDITION		CURRENT CONDITION		CURRENT CONDITION	
SCENARIO B: EMISSIONS REDUCTION TARGET	10 %, 20% & 40% REDUCTION		10 %, 20% & 40% REDUCTION		10 %, 20% & 40% REDUCTION	
SCENARIO C: EMISSION REDUCTION + ENV RESTRICTION	NORMALITY DISTRIBUT'N •10 %, 20% & 40% REDUCTION •90% ENV RESTRICTION	CHEBYSHEV'S INEQUALITY •10 %, 20% & 40% REDUCTION •90% ENV RESTRICTION	NORMALITY DISTRIBUT'N •10 %, 20% & 40% REDUCTION •90% ENV RESTRICTION	CHEBYSHEV'S INEQUALITY •10 %, 20% & 40% REDUCTION •90% ENV RESTRICTION	NORMALITY DISTRIBUT'N •10 %, 20% & 40% REDUCTION •90% ENV RESTRICTION	CHEBYSHEV'S INEQUALITY •10 %, 20% & 40% REDUCTION •90% ENV RESTRICTION

5.5.1 Total Profit Maximization under Different Pond Aquaculture Farms' Objectives

Using the chance constrained programming analysis, the third analysis showed a potential adaptation strategy for Sarawak aquaculture farmers to use to cope with climate change risks. This strategy was selected based on the comparison of three different environmental regulations under three different farm management options. Table 5.3 and Table 5.5 illustrate the comparison of profit maximizing plans or total profits of pond aquaculture and cage aquaculture in Sarawak under the different scenarios. The total profit values under Scenarios B and C were compared with the total profit value of the baseline Scenario A and were distinguished based on the different management options.

Table 5.3: Summary of potential adaptation strategies to climate change risks based on farm management decision options for pond aquaculture in Sarawak

	Management option & Scenario		I: Baseline management						II: 10% production increase & 5% price increase						III: 10% production increase & 5% price decrease					
Objective value (Profit) (RM/farm)	A: Baseline scenario	Baseline	2050.48						2694.32						2235.55					
	B: Environmental constraint reduction	10%	2049.93						2693.66						2234.97					
		20%	2049.39						2693.00						2234.40					
		40%	2048.31						2691.68						2233.24					
		Prob. constraint	Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality		
	C: Environmental restriction	10%	2047.69			2049.02			2692.56			2690.95			2234.01			2232.59		
		20%	2047.15			2048.48			2691.90			2690.29			2233.43			2232.02		
		40%	2045.49			2047.40			2690.58			2688.51			2232.28			2230.50		
Production scale			High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low
Avg. feed waste runoff (kg/hectare(ha))	A: Baseline scenario	Baseline	14.08	9.26	104.48				12.55	9.31	73.93				14.08	9.78	104.48			
	B: Environmental constraint reduction	10%, 20% & 40%	14.08	9.26	104.48				12.55	9.31	73.93				14.08	9.78	104.48			
		Prob. constraint	Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality		
	C: Environmental restriction	10%, 20% & 40%	14.08	9.26	104.48	14.08	9.26	104.48	12.55	9.31	73.93	12.55	9.31	73.93	14.08	9.78	104.48	14.08	9.78	104.48
Marginal cost for feed waste emissions (RM/ha)	A: Baseline scenario	Baseline		-						-						-				
	B: Environmental constraint reduction	10%, 20% & 40%		0.03						0.03						0.03				
		Prob. constraint	Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality		
	C: Environmental restriction	10% & 20%		0.84			0.84			1.02			1.02			0.89			0.89	
		40%		0.84			7.32			1.02			9.65			0.89			8.40	
Avg. land surplus (ha/pond)	A: Baseline scenario	Baseline	1401.05	33.37	0				2048.22	99.57	0				1589.60	52.68	0			
	B: Environmental constraint reduction	10%, 20% & 40%	1401.03	33.23	0				2048.2	99.39	0				1589.58	52.53	0			
		Prob. constraint	Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality		
	C: Environmental restriction	10%, 20%	1400.69	32.61	0	1400.69	32.61	0	2047.79	98.66	0	2047.79	98.66	0	1589.22	51.88	0	1589.22	51.88	0
		& 40%	0	0	0	1397.96	26.81	0	0	0	0	2044.15	90.92	0	0	0	0	1586.06	45.16	0
Avg. labor surplus (hours/pond)	A: Baseline scenario	Baseline	1.22	2.65	0.16				1.64	3.23	0.25				1.34	2.81	0.19			
	B: Environmental constraint reduction	10%, 20% & 40%	1.21	2.64	0.31				1.63	3.23	0.47				0.72	2.81	0.36			
		Prob. constraint	Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality		
	C: Environmental restriction	10% & 20%	1.21	2.64	0.29	1.21	2.64	0.14	1.63	3.22	0.45	1.63	3.22	0.45	1.33	2.80	0.34	1.33	2.80	0.34
		40%	0	0	0	1.15	2.56	0	0	0	0	1.55	3.11	0.06	0	0	0	1.26	2.71	0
Avg. fish feed surplus (RM/pond)	A: Baseline scenario	Baseline	1.83	0.38	0				2.55	0.51	0				2.04	0.42	0			
	B: Environmental constraint reduction	10%, 20% & 40%	1.83	0.39	0				2.55	0.52	0				2.04	0.43	0			
		Prob. constraint	Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality			Normal distribution			Chebyshev Inequality		
	C: Environmental restriction	10% & 20%	1.83	0.21	0	1.83	0.21	0	2.55	0.33	0	2.55	0.33	0	2.04	0.25	0	2.04	0.25	0
		40%	0	0	0	5.42	0.62	0	0	0	0	2.54	0.32	0	0	0	0	2.03	0.24	0

Notes: Avg. = average; Prob. = probability.

However, under management option II, a very small value change in total profit was indicated between Scenario B, which was estimated by basic optimization, with Scenario C - results that were indicated by normal probability and Chebyshev's inequality estimation. Hence, the environmental regulation model (Scenario C) with probability constraints based on the normality assumption and Chebyshev's inequality, shows greater decrement of farms' total profit than Scenarios A and B. The different deterministic values were obtained due to incorporation in the model of the uncertainty of the parameter at a certain level of confidence, known as a safety term (Moghaddam & DePuy, 2011; Kirchner et al., 2012). This posited that the more stringent the environmental regulation in farms, the less the profit the farmers gained, as indicated in Scenarios B and C under different management options.

5.5.2 Water Quality Runoff and Marginal Cost of Pond Aquaculture

Climate change had significant effects on the pattern of fish feed in aquaculture production, with the temperature, precipitation, humidity, sunlight intensity and water quality of an area influencing the fishes' food consumption. The analysis of the biophysical effects of climate change on the aquaculture sector in chapter 3 indicates that climate change uncertainty affects aquaculture production. Unfortunately, farmers had not generated consistent monitoring data on the climatic factors and water quality. Thus, the feed waste from each pond and cage farm was calculated by kg/ha (ponds) or kg/m^2 (cages) and the estimation value was used as a proxy to represent the effects of climate change on aquaculture production. Assuming that a farm management is efficient and if climate change occurs, the value of feed waste will be high.

Table 5.4: Feed waste runoff and mean runoff (kg/ha) for pond aquaculture farms

Management option		I : Baseline		II : 10% prod increase and 5 % price increase		III : 10% prod increase and 5% price decrease	
Representative farm	Production scale	Runoff (kg/ha)	Mean of runoff (kg/ha)	Runoff (kg/ha)	Mean of runoff (kg/ha)	Runoff (kg/ha)	Mean of runoff (kg/ha)
F1.Z1	FWPH	0	0	0.72	0.36	0	0
F2.Z1	FWPH	3.44	1.72	3.44	1.72	3.44	1.72
F5.Z2	FWPH	4.74	2.37	4.74	2.37	4.74	2.37
F6.Z2	FWPH	51.66	25.83	51.66	25.83	51.66	25.83
F8.Z3	FWPH	1.24	0.62	1.24	0.62	1.24	0.62
F9.Z3	FWPH	42.40	21.20	42.40	21.20	42.40	21.20
F11.Z4	FWPH	3.43	1.72	3.43	1.72	3.43	1.72
F15.Z5	FWPH	6.85	3.43	6.85	3.43	6.85	3.43
F24.Z7	FWPH	3.60	1.80	3.60	1.80	3.6	1.80
F33.Z9	FWPH	0.45	0.23	0.45	0.23	0.45	0.23
F34.Z9	FWPH	0	0	5.93	2.97	0	0
F37.Z10	FWPH	0.78	0.39	0.78	0.39	0.78	0.39
F43.Z11	FWPH	11.76	5.88	11.76	5.88	11.76	5.88
F48.Z12	FWPH	38.65	19.32	38.65	19.32	38.65	19.32
F3.Z1	FWPM	5.04	2.52	5.04	2.52	5.04	2.52
F4.Z1	FWPM	0	0	4.20	2.10	0	0
F10.Z3	FWPM	3.78	1.89	3.78	1.89	3.78	1.89
F17.Z5	FWPM	15.82	7.91	15.82	7.91	15.82	7.91
F18.Z5	FWPM	0	0	14.96	7.48	14.96	7.48
F26.Z7	FWPM	10.59	5.29	10.59	5.29	10.59	5.29
F39.Z10	FWPM	5.75	2.88	5.75	2.88	5.75	2.88
F45.Z11	FWPM	5.32	2.66	5.32	2.66	5.32	2.66
F50.Z12	FWPM	16.38	8.19	16.38	8.19	16.38	8.19
F51.Z12	FWPM	26.02	13.01	26.02	13.01	26.02	13.01
F56.Z14	FWPM	2.49	1.25	2.49	1.25	2.49	1.25
F60.Z15	FWPM	1.40	0.70	1.40	0.70	1.40	0.70
F19.Z5	FWPL	182.87	91.43	182.87	91.43	182.87	91.43
F22.Z6	FWPL	26.09	13.05	26.09	13.05	26.09	13.05
F54.Z13	FWPL	0	0	12.84	6.42	0	0
Average Runoff (kg/ha)	High	14.08	7.04	12.55	6.27	14.08	7.04
	Medium	9.26	4.63	9.31	4.66	9.78	4.89
	Low	104.48	52.24	73.93	36.97	104.48	52.24

Notes: F1.Z1 (for example) means Farmer (F) 1 at the Zone (Z) 1 (specific name of zones can be found in Table 5.1); FWPH is high scale fresh water pond; FWPM is a medium scale fresh water pond; FWPL is low scale fresh water pond.

Table 5.4 indicates that the average feed waste runoff values differed according to the management option and production scale implemented by the farmers. Interestingly, there was no difference in values in terms of the percentage reduction of fish feed between scenarios. The results also showed that management option II resulted in the lowest value of average feed waste runoff, with values of 12.55 kg/hectare (ha) for high scale production farms, 9.31 kg/ha for medium scale production farms, and 73.93 kg/ha for low scale production farms. Higher values for the average feed waste runoff for management option III were recorded than for management option II, i.e. 14.08 kg/hectare for high scale production, 9.78 kg/hectare for medium scale production, and 104.48 kg/hectare for low scale production.

Considering that the marginal cost for feed waste emissions abatement was influenced by Scenario B (environmental constraint reduction) and Scenario C (environmental restriction), the results showed that the changing value of marginal cost occurred between management options under the Chebyshev's inequality assumption under Scenario C. The changing values of marginal cost in Chebyshev's inequality estimation were high, between 10% and 20% to 40% reduction in feed waste under management option II. The marginal cost for 10% and 20% feed waste reduction was similar in value, i.e. RM1.02 per hectare, while the 40% feed waste reduction showed an increment of marginal cost values at RM9.65 per hectare. The estimation of marginal cost under Scenario B (feed waste reduction) and Scenario C (normal distribution) showed that the marginal cost was fixed at a certain value in all percentage reductions of feed waste, i.e. RM 1.02 per hectare.

The results showed that if Scenario B were implemented as an adaptation strategy to cope with climate change in pond aquaculture activities in Sarawak, each management option at each percentage of feed waste reduction had a fixed marginal cost at RM 0.03 per hectare. The estimated marginal costs using the normal distribution assumption in Scenario

C were RM 1.02 per hectare in management option II, RM 0.89 per hectare in management option III and RM 0.84 per hectare in management option I and were similar for every percentage of reduction.

If the government plan to impose 90% environmental restriction (Scenario C) with a 10% to 20% feed waste reduction target, under the Chebyshev's inequality estimation of CCP, the marginal cost for feed waste abatement would be RM 1.02 kg/hectare in management option II, RM0.89 kg/hectare in management option III, and RM0.84 kg/hectare in the baseline option. However, under the same environmental restriction, if the government targeted to increase the reduction of feed waste by about 40%, the marginal cost for feed waste abatement increases to RM9.65 kg/hectare in management option II, RM 8.40 kg/hectare in management option III, and RM 7.32 kg/hectare in the baseline option.

The estimation of marginal cost by the normal distribution assumption under Scenario C with environmental restriction shows the same value at all percentages of feed waste reduction, i.e. RM 1.02 kg/hectare in management option II, RM0.89 kg/hectare in management option III, and RM0.84 kg/hectare in the baseline option. The marginal cost estimation under Scenario B revealed that any increment of percentage reduction target of feed waste under any management option would be fixed and lowest at RM0.03 kg/hectare.

Table 5.4 shows results that indicate that brackish water aquaculture ponds contribute no feed waste runoff since the number of participants was small. Few representatives were free from feed waste runoff under management options I and III. In the high production scale group, one representative from Saratok, Betong zone (F1.Z1) and Asajaya, Samarahan zone (F34.29) showed no feed waste runoff in their activities under management options I and III. Meanwhile, at the medium scale production level, one representative in the Saratok, Betong zone (F4.Z1) did not experienced runoff in management options I and III while a representative from a farm in Siburan, Kuching zone (F18.Z5) was free from runoff under management option I. The low scale representative farms in Siburan, Kuching (F19.Z5) produced the highest total feed waste runoff, at 182.87 kg/hectare. Only a low production scale representative in Batang Lupar, Sri Aman was free from feed waste runoff under management options I and III.

5.5.3 Total Profit Maximization under Different Cage Aquaculture Farm Objectives

Table 5.5 shows the variation of total profits of each cage aquaculture farm in Sarawak based on three different scenarios and farm management options. In the comparison of the baseline profit in each farm management option, if the government target is to increase the cage aquaculture production by 10% in the future, the cage aquaculture production will be able to increase the profit by about 15.6%[1] with a 5% increase of output price (management option II). However, if the production remains increased by 10% while the output price decreases by 5% from the baseline output price, the profit will be decreased by 4.5%[2].

[1] Profit change = ((2727.03-2359.23)/23659.23)*100%=15.6%

[2] Profit change = ((2465.49-2359.23)/2359.23)*100%=4.5%

Table 5.5: Summary of potential adaptation strategies to climate change risks based on farm management decision options for cage aquaculture in Sarawak

	Management option & Scenario		I: Baseline management						II: 10% production increase & 5% percent increase						III: 10% prod increase & 5% decrease					
Objective value	A: Baseline scenario	Baseline	2359.23						2727.03						2465.49					
(Profit)	B: Environmental	10%	2359.23						2727.03						2465.48					
(RM/farm)	constraint reduction	20%	2359.23						2727.02						2465.48					
		40%	2359.21						2727.01						2465.47					
		Prob. constraint	Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility		
	C: Environmental	10%	2359.23			2359.23			2727.03			2727.03			2465.48			2465.48		
	restriction	20%	2359.23			2359.23			2727.02			2727.02			2465.48			2465.48		
		40%	2359.21			2359.21			2727.01			2727.01			2465.47			2465.47		
Production scale			High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low
Avg. feed	A: Baseline scenario	Baseline	1.970	22.45	22.39				1.970	22.45	22.39				1.970	22.45	22.39			
waste runoff	B: Environmental	10%, 20% & 40%	1.970	22.45	22.39				1.970	22.45	22.39				1.970	22.45	22.39			
(kg/msq)	constraint reduction																			
		Prob. constraint	Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility		
	C: Environmental	10%, 20% & 40%	1.970	22.45	22.39	1.970	22.45	22.39	1.970	22.45	22.39	1.970	22.45	22.39	1.970	22.45	22.39	1.970	22.45	22.39
	restriction																			
Marginal cost	A: Baseline scenario	Baseline	-						-						-					
for feed waste	B: Environmental	10%	0.22						0.26						0.23					
emissions	constraint reduction	20% & 40%	0.76						0.87						0.79					
(RM/msq)		Prob. constraint	Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility		
	C: Environmental	10%, 20% & 40%	0.51			0.51			0.59			0.59			0.53			0.53		
	restriction																			
Avg. land	A: Baseline scenario	Baseline	FWC						FWC						FWC					
surplus			0	14.49	0.36				0	16.79	0.42				0	15.16	0.38			
(msq/cage)			BWC						BWC						BWC					
			144.19	27.39	0				166.75	34.76	0				150.74	28.63	0			
	B: Environmental		FWC						FWC						FWCH	FWCM	FWCL			
	constraint reduction	10%, 20% & 40%	0	14.46	0.36				0	16.76	0.42				0	15.13	0.38			
			BWC						BWC						BWC					
		10%, 20% & 40%	144.19	27.39	0				166.75	34.76	0.00				150.74	28.63	0			
		Prob. constraint	Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility		
	C: Environmental		FWC			FWC			FWC			FWC			FWC			FWC		
	restriction	10%, 20% & 40%	0	18.01	0.35	0	14.39	0.35	0	16.68	0.41	0	16.68	0.41	0	15.06	0.37	0	15.06	0.37
			BWC			BWC			BWC			BWC			BWC			BWC		
		10%, 20% & 40%	144.18	27.38	0	144.18	27.38	0	166.75	34.75	0	166.75	34.75	0	150.74	28.62	0	150.74	28.62	0

Notes: 1 cage = 9msq; Avg. = average; Prob. = probability; msq = square meters; FWC = freshwater cage production; BWC = brackish water cage production.

'Table 5.5, Continued'

	Management option & Scenario		I: Baseline management						II: 10% production increase & 5% percent increase						III: 10% prod increase & 5% decrease					
Production scale			High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low
Avg. labor surplus (hours/cage)	A: Baseline scenario	Baseline		FWC						FWC						FWC				
			6.41	7.25	0.11				7.43	8.38	0.13				6.71	7.58	0.12			
				BWC						BWC						BWC				
			0	10.19	1.12				0	12.93	1.29				0	10.65	1.17			
	B: Environmental constraint reduction			FWC						FWC						FWC				
		10%, 20% & 40%	6.41	7.25	0.11				7.43	8.38	0.13				6.71	7.58	0.12			
				BWC						BWC						BWC				
		10%, 20% & 40%	0	10.19	1.12				0	12.93	1.29				0	10.65	1.17			
	C: Environmental restriction	Prob. constraint	Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility		
				FWC			FWC			FWC			FWC			FWC			FWC	
		10%, 20% & 40%	6.41	7.23	0.11	6.41	7.23	0.11	7.43	8.36	0.13	7.42	8.36	0.13	6.71	7.56	0.12	6.71	7.56	0.12
				BWC			BWC			BWC			BWC			BWC			BWC	
		10%, 20% & 40%	0	10.18	1.11	0	10.18	1.11	0	12.92	1.29	0	12.92	1.29	0	10.64	1.16	0	10.64	1.16
Avg. fish feed surplus (RM/cage)	A: Baseline scenario	Baseline		FWC						FWC						FWC				
			69.15	0.21	0.01				79.88	0.25	0.02				72.27	0.22	0.01			
				BWC						BWC						BWC				
			19.83	4.9	4.41				22.92	6.22	5.10				20.72	5.12	4.61			
	B: Environmental constraint reduction			FWC						FWC						FWC				
		10%, 20% & 40%	69.15	0.64	0.01				79.88	0.74	0.01				72.27	0.67	0.01			
				BWC						BWC						BWC				
		10%	19.83	4.9	5.74				22.92	6.22	6.64				20.72	5.12	6.00			
		20% & 40%	19.83	4.9	5.74				22.92	6.22	6.63				20.72	5.12	6.00			
	C: Environmental restriction	Prob. constraint	Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility			Normal distribution			Chebyshev Inequility		
				FWC			FWC			FWC			FWC			FWC			FWC	
		10%, 20% & 40%	69.15	0.21	0.02	69.15	0.21	0.02	79.88	0.25	0.03	79.88	0.25	0.03	72.27	0.22	0.02	72.27	0.22	0.02
				BWC			BWC			BWC			BWC			BWC			BWC	
		10%, 20% & 40%	19.83	4.9	5.74	19.83	4.9	5.74	22.92	6.22	6.63	22.92	7.46	6.63	20.72	5.12	6.00	20.72	5.12	6.00

Notes: 1 cage = 9msq; Avg. = average; Prob. = probability; msq = square meters; FWC = freshwater cage production; BWC = brackish water cage production.

Considering that the feed waste reduction option was important as an adaptation strategy, the results revealed that farm management option II, with a 10% target of feed waste reduction (Scenario B), offered the highest profit compared to all other options. The total profit of each farm under management option II and scenario B showed that the average total profit of each cage farm was RM 2,727.02 and the profit of each percentage of feed waste reduced very slightly with the increase in percentage feed waste reduction target from 10% to 40%.

The decision on the potential adaptation strategy for cage aquaculture was similar to that for pond aquaculture, where the increase in aquaculture production and price under management option II is able to generate more profit to cage aquaculture farmers than under management option III or the baseline option. This option was proposed because it may result in a realistic outcome in order to maximize the farmer's profit and at the same time assist farmers to make their aquaculture farm practices efficient and adaptable to climate change risks.

5.5.4 Water Quality Runoff and Marginal Cost of Cage Aquaculture

The results of the total average feed waste runoff at each production scale in Table 5.5 were similar under all farm management options and scenarios. The results showed that high scale production farmers practicing each management option contributed the least, at 1.970 kg/m^2 of feed waste in cage aquaculture production, meanwhile the low scale farmers showed the gradual high increment of feed waste run-off, i.e. 22.39 kg/m^2. The average total feed waste runoff was slightly higher in the medium production scale farms than in the low production scale farms, which were also indicated as the highest contributors to feed waste run-off in cage aquaculture activities, at 22.45 kg/m^2.

The value of average total of feed waste run-off according to production scale shows that medium scale production cage aquaculture farms were the majority operators in Sarawak's cage aquaculture production. Furthermore, the average total of feed waste runoff for the three different scales of production groups in cage aquaculture farms was higher than that in pond aquaculture farms due to the high volume of cage production as compared to pond production in Sarawak.

When cage production was compared to pond aquaculture, although the production volume was high in cage production the marginal cost value for feed waste emission shown in Table 5.5 was low as the estimation was per square meter. Similar to what happens in pond aquaculture, the increment value of marginal cost for feed waste reduction occurs with the increment of feed waste reduction percentage target. The marginal cost estimation also showed results that contradicted those from the pond cage activities. The gradual change of marginal cost occurred under Scenario B (feed waste reduction strategy) while the value of marginal cost remained the same according to the management options at all percentage of feed waste reduction under Scenario C (environmental regulation), either under a normal distribution assumption or Chebyshev's inequality assumption, according to the management option. The results on marginal cost for feed waste emissions under Scenario C are not impressive but contrast with those from Scenario B. As a marginal cost value was quite high, this condition indicated that environmental restriction could not be an appropriate strategy and was also too stringent for cage aquaculture activities. If the government imposed a 90% environmental restriction and at the same time targeted for a 10% to 40% reduction of feed wastes in aquaculture farm activities, the marginal cost would be highest under management option II, at RM0.59 per m^2, followed by RM0.53 per m^2 and RM0.51 per m^2 in management under option II and the baseline management option respectively.

The lowest value of marginal cost for each management option was shown under Scenario B at the 10% feed waste reduction target. If the government were only to concentrate on reducing the feed waste without the environmental restriction, the marginal cost for feed waste emission at a 10% reduction would be RM0.26 per m^2 under management option II, RM0.23 per m^2 under management option III and RM 0.51 per m^2 under the baseline management option. However, if the government were to target to reduce the feed waste by about 20% to 40%, the marginal cost for feed waste emissions abatement would increase to RM0.87 per m^2 under management option II, RM0.79 per m^2 under management option III and RM0.76 per m^2 under the baseline management option. The results revealed that the decision to increase feed waste reduction from 20% to 40% in cage aquaculture was unrealistic since the marginal cost involved was too high.

Table 5.6 showed that in cage aquaculture production, 28 out of 36 representative farms had feed waste runoff in their farm operations. Nine of them were freshwater cage aquaculture farms and the remainder brackish water aquaculture farms. The representative farm from the medium production scale group in Kuching (F3.Z1) produced the highest runoff (129.5 kg/m^2) followed by the low production scale representative in Batang Ai, Sri Aman (F21.Z4) (104.5 kg/ m^2).

The medium scale representative farm from the brackish water cage production in Sungai Punang, Lawas (F29.Z7) showed that a 10% increment of aquaculture production with a 5% increase or decrease in price will reduce the feed waste emissions to zero as compared to the baseline farm management. Meanwhile the other representative from the same zone (F30.Z7) showed that the increment of production and changes in price would contribute to the increment of feed waste emissions under both management options II and III, from zero emission under the baseline option.

Table 5.6: Feed waste runoff and mean of runoff (kg/m2) for cage aquaculture farms

Management option		I : Baseline		II : 10% prod increase and 5 % price increase		III : 10% prod increase and 5% price decrease	
Representative farm	Production scale	Runoff (kg/m^2)	Mean runoff (kg/m^2)	Runoff (kg/m^2)	Mean runoff (kg/m^2)	Runoff (kg/m^2)	Mean runoff (kg/m^2)
F1.Z1	BWCH	1.39	0.70	1.39	0.70	1.39	0.70
F2.Z1	BWCH	4.07	2.03	4.07	2.03	4.07	2.03
F10.Z3	BWCH	1.12	0.56	1.12	0.56	1.12	0.56
F17.Z4	FWCH	1.29	0.64	1.29	0.64	1.29	0.64
F3.Z1	BWCM	129.50	64.75	129.50	64.75	129.50	64.75
F4.Z1	BWCM	7.43	3.72	7.43	3.72	7.43	3.72
F13.Z3	BWCM	1.94	0.97	1.94	0.97	1.94	0.97
F23.Z5	BWCM	16.71	8.36	16.71	8.36	16.71	8.36
F24.Z5	BWCM	24	12.00	24.00	12.00	24.00	12.00
F29.Z7	BWCM	2.97	1.49	0	0	0	0
F30.Z7	BWCM	0	0	2.97	1.49	2.97	1.49
F33.Z8	BWCM	2.97	1.49	2.97	1.49	2.97	1.49
F34.Z8	BWCM	6.32	3.16	6.32	3.16	6.32	3.16
F8.Z2	FWCM	56.48	28.24	56.48	28.24	56.48	28.22
F9.Z2	FWCM	9.29	4.65	9.29	4.65	9.29	4.65
F18.Z4	FWCM	4.83	2.42	4.83	2.42	4.83	2.42
F19.Z4	FWCM	4.50	2.25	4.50	2.25	4.50	2.25
F5.Z1	BWCL	41.80	20.90	41.80	20.90	41.80	20.90
F14.Z3	BWCL	2.00	1.00	2.00	1.00	2.00	1.00
F15.Z3	BWCL	4.08	2.04	4.08	2.04	4.08	2.04
F31.Z7	BWCL	2.77	1.39	2.77	1.39	2.77	1.39
F32.Z7	BWCL	6.43	3.21	6.43	3.21	6.43	3.21
F35.Z8	BWCL	3.90	1.95	3.90	1.95	3.90	1.95
F36.Z8	BWCL	68.89	34.44	68.89	34.44	68.89	34.44
F20.Z4	FWCL	9.29	4.65	9.29	4.65	9.29	4.65
F21.Z4	FWCL	104.50	52.25	104.50	52.25	104.50	52.25
F27.Z6	FWCL	0.46	0.23	0.46	0.23	0.46	0.23
F28.Z6	FWCL	2.23	1.12	2.23	1.12	2.23	1.12
Average Runoff (kg/m^2)	High	1.97	0.98	1.97	0.98	1.97	0.98
	Medium	22.45	11.12	22.45	11.12	22.45	11.12
	Low	22.39	11.2	22.39	11.2	22.39	11.2

Notes: F1.Z1 (for example) means Farmer (F) 1 at the Zone (Z) 1 (specific name of zones can be obtained from Table 5.1); BWCH is high scale brackish water cage; FWCH is high scale freshwater cage; BWCM is a medium scale brackish water cage; FWCM is medium scale freshwater cage; BWCL is low scale brackish water cage; FWCL is low scale fresh water pond.

5.5.5 Optimal Allocation of Farms' Resources in Adapting to Climate Change Risks

The cost of adaptation estimation using the farm optimization models helped to indicate how effective resource allocation can be achieved and managed in a farm where it is important in both adaptation and mitigation strategies (EEA, 2007). In coping with the climate change risks, effective resources allocation was the basic adaptation plan that farmers can practice to adjust their activities to the production risks and at the same time reduce the possibility of production losses.

Table 5.7 shows the results of resource allocation in pond aquaculture. The results indicate that the optimal land use and fish feed were found in the low scale pond production farms where both these resources were fully utilized in the aquaculture activities. However, the pond aquaculture activities need to utilize the labor surplus in order to achieve 100% allocative efficiency. Furthermore, the high and medium production scale farms conducting pond activities would be able to increase production by efficiently utilizing their labor and fish feed surplus to maximize their profit.

These resource allocation results referred to freshwater pond aquaculture, representing the majority of pond aquaculture activities in Sarawak. No resource allocation value was indicated in brackish water pond activities as the number of farmers involved in this aquaculture system was minimal. Subject to the land resources, if the government were to impose a feed waste reduction regulation with a 90% environmental restriction, using Chebyshev's inequality estimation, the high scale pond farmers would be able to achieve farm land allocation efficiency if they managed to utilize 2,047.79 hectares to increase the production as well as to maximize their profits from the 10% to 20% reduction of feed waste in aquaculture production.

Table 5.7: Summary of potential adaptation strategies to climate change risks based on farm management decision options for pond and cage aquaculture in Sarawak

Aquaculture system		Pond			Cage		
Scenario		C (Feed waste reduction + environmental regulation)			B (Feed waste reduction)		
Probabilistic constraint		CCP (Chebyshev's Inequality)			Basic Optimization		
Management Option		II: 10% production increase and 5 % price increase			II: 10% production increase and 5 % price increase		
Profit (RM/farm)	Baseline	2,694.32			2,727.03		
	10%	2,690.95			2,727.03		
	20%	2,690.29			2,727.02		
	40%	2,688.51			2,727.01		
Production scale		High	Medium	Low	High	Medium	Low
Average land surplus (ha/pond or m^2/cage)	Baseline	FWP			FWC		
		2048.22	99.57	0	0	16.79	0.42
		BWP			BWC		
		-	-	-	166.75	34.76	0
	% Emission reduction	FWP			FWC		
	10% and 20%	2047.79	98.66	0	0	16.76	0.42
	40%	2044.15	90.92	0			
	% Emission reduction	BWP			BWC		
	10%, 20% and 40%	-	-	-	166.75	34.76	0
Average labor surplus (hrs/pond) or hrs/cage)	Baseline	FWP			FWC		
		1.64	3.23	0.25	7.43	8.38	0.13
		BWP			BWC		
		-	-	-	0	12.93	1.29
	% Emission reduction	FWP			FWC		
	10% and 20%	1.63	3.22	0.45	7.43	8.38	0.13
	40%	1.55	3.11	0.06			
	% Emission reduction	BWP			BWC		
	10%, 20% and 40%	-	-	-	0	12.92	1.29
Average fish feed surplus (RM/pond or RM/cage)	Baseline	FWP			FWC		
		2.55	0.51	0	79.88	0.25	0.02
		BWP			BWC		
		-	-	-	22.92	6.22	5.1
	% Emission reduction	FWP			FWC		
	10% and 20%	2.55	0.33	0	79.88	0.74	0.01
	40%	2.54	0.32	0			
	% Emission reduction	BWP			BWC		
	10%, 20% and 40%	-	-	-	22.92	6.22	6.64

Notes: FWP is freshwater pond; FWC is freshwater cage; BWP is brackish water pond; BWC is brackish water cage.

With the same percentage reduction, medium scale farmers need to utilize 98.66 hectares to maximize their profits. However, the increment of emissions reduction target to the 40% effect slightly decreased the land size utilization in high and medium scale farms, i.e. by 2,044.15 and 90.92 hectares respectively. Meanwhile, under the same emissions reduction target percentage, the small scale aquaculture farmers were efficient and fully utilized their land allocation - there was no land surplus for this group of farmers.

In terms of labor allocation, medium scale farms showed the least effective labor management, i.e. 3.22 hours/pond, followed by high scale farms at 1.63 hours/pond and low scale farms at 0.45 hours/pond when 10% to 20% reduction of feed waste and environmental restriction was imposed on pond aquaculture activities. The 40% target reduction of feed waste in farms under the same scenario and the farm's management option results in small changes on the results of labor utilization, i.e. 3.11 hours/pond for medium scale production, 1.55 hours/pond for high scale production and 0.06 hours/pond for low scale production.

In terms of fish feed allocation, the farm had to utilize RM 2.55 per pond of fish feed surplus in high scale productions and RM 0.33 per pond in medium scale productions if the farms implemented a 10% to 20% reduction of feed waste emission target and environmental restriction. There was a slight difference in terms of fish feed utilization in farms when the percentage of fish feed reduction targeted increased to 40%, i.e. about RM2.54 per pond in high scale productions and RM0.32 per pond in medium scale productions. As in the case for land utilization, the low scale aquaculture farmers fully utilized the fish feed in their activities.

The different probabilistic constraints estimation practiced in the chance constrained model showed a slight difference between each of the findings values in Chebyshev's inequality cases in the setting of a 40% feed waste reduction under all management options as compared to those in the normal distribution method in CCP. The results also indicated that the small scale farms have fully utilized their land and fish feed allocation. The results from each farm showed that out of 74 selected farms (representatives) in this study, 49 were found optimally allocated while the other 25 were recommended to improve and minimize one of the constraint factors, either land, labor or fish feed.

The resource allocation results in cage aquaculture activities based on the basic optimization estimation depicted specific results for freshwater and brackish water cage aquaculture activities. The results indicated that the optimal 100% allocative efficient land use was found in the high scale freshwater aquaculture farmers and the low scale brackish water aquaculture farmers. Furthermore, the optimal allocation of labor was indicated in the high scale brackish water aquaculture farmers. The resource allocation for cage aquaculture also showed that the resource value of land, labor and fish feed were not affected by the percentage of feed waste reduction and shared the same value for all percentages of reduction.

Subject to farm land allocation referring to all percentage changes (10%, 20%, and 40%) of feed waste reduction, the high scale brackish water cage farmers had to expand the size of cages by as much as 166.75m^2/cage in their activities. Meanwhile, the medium scale farmers were recommended to expand the size of cages by about 16.76m^2/cage for freshwater cage activities as well as 34.76 m^2/cage in the case of brackish water cage activities. To achieve 100% land allocative efficient, the low scale freshwater cage farmers were recommended to expand their cages by $0.42m^2$/cage in their activities.

In terms of labor allocation, the high scale freshwater cage farmers had to increase their labor working hour allocations efficiently at 7.43 hours/cage. The less effective labor hours were found at about 8.38 hours/cage and 12.93 hours/cage in freshwater and brackish water cage operations respectively. The brackish water cage operations showed the least efficient utilization of labor hours in managing their farms. Meanwhile, the low scale cage farmers had to efficiently utilize labor hours at 0.13 hours/cage and 1.29 hours/cage in freshwater and brackish water cage activities respectively.

In terms of farms' fish feed allocation, the least efficient utilization of fish feed was found among the high scale freshwater and brackish water cage farmers. The results show a fish feed surplus of RM 79.88 per cage in the higher scale freshwater farms and RM 22.92 per cage in high scale brackish water cage activities. The brackish water cage farms also showed poor fish feed utilization or management in medium and low scale farms where the farmers still had to manage the fish feed surplus efficiently at RM 6.22 and RM 6.64 per cage in medium and low scale farms respectively. The medium and low scale freshwater farms showed the gradual difference of fish feed surplus as compared to the high scale farmers. The medium scale freshwater cage farmers had to utilize RM0.74 per cage while the low scale freshwater cage farmers RM 0.01 per cage in the allocation of fish feed in their aquaculture activities.

The different probabilistic constraints estimation practices in the chance constrained model give no difference in values to the constraints in basic optimization cases in the setting of different percentages of feed waste reduction under selected management options for potential adaptation for the cage farms model. The results for each of the farms showed that out of 36 selected cage farms (representatives) in this study, only eight were optimally allocated while another 28 were recommended to improve and minimize one of their constraints factors, either land, labor, or fish feed.

5.6 Discussion

The findings indicate the potential adaptation strategy options in coping with climate change risks in the aquaculture sector in Sarawak. The adaptation strategies are identified based on the aquaculture farm management options, in compliance with the Malaysian government’s target to reduce the impacts of climate change on national economic activities. Thus, different environmental regulations were identified and tested at the selected representative farms to indicate the rigorousness of farm adaptive measures. The adaptation was measured and compared using the basic optimization and chance constrained programming analysis, aiming for profit maximization as the farm objective.

Based on the farms’ activities, the adaptation costs in coping with climate change risk were measured and compared, based on several farm management options, with the baseline case (Scenario A), risk (feed waste) reduction (Scenario B), and risk reduction with environmental regulation (Scenario C). The results demonstrated the potential to maximize farm profits under different scenarios with fish feed run-off measurement as the effect of climate change.

The EEA (2007) considers that using scenarios to measure the cost of adaptation can show a strong relationship between adaptation and socio-economic trends and the degree and type of adaptation were determined by the socio-economic scenario assumed. The advantage of a scenarios-based assessment was that this assessment consisted of planned and autonomous adaptation as well as public and private plans in adaptation.

Table 5.8: Summary of potential adaptation strategies to climate change risks based on farm management decision options for pond and cage aquaculture in Sarawak

<table>
<tr><td colspan="2">Aquaculture system</td><td colspan="3">Pond</td><td colspan="3">Cage</td></tr>
<tr><td colspan="2">Scenario</td><td colspan="3">C
(Feed wasted reduction + environmental regulation)</td><td colspan="3">B
(Feed wasted reduction)</td></tr>
<tr><td colspan="2">Probabilistic constraint</td><td colspan="3">CCP (Chebyshev's Inequality)</td><td colspan="3">Basic Optimization</td></tr>
<tr><td colspan="2">Management Option</td><td colspan="3">II: 10% production increase and 5 % price increase</td><td colspan="3">II: 10% production increase and5 % price increase</td></tr>
<tr><td rowspan="4">Profit (RM/farm)</td><td>Baseline</td><td colspan="3">2,694.32</td><td colspan="3">2,727.03</td></tr>
<tr><td>10%</td><td colspan="3">2,690.95</td><td colspan="3">2,727.03</td></tr>
<tr><td>20%</td><td colspan="3">2,690.29</td><td colspan="3">2,727.02</td></tr>
<tr><td>40%</td><td colspan="3">2,688.51</td><td colspan="3">2,727.01</td></tr>
<tr><td colspan="2">Production scale</td><td>High</td><td>Medium</td><td>Low</td><td>High</td><td>Medium</td><td>Low</td></tr>
<tr><td>Average feed Waste runoff (kg/ha for pond, or kg/m² for cage)</td><td>10%, 20% and 40%</td><td>12.55</td><td>9.31</td><td>73.93</td><td>1.97</td><td>22.45</td><td>22.39</td></tr>
<tr><td rowspan="5">MC for feed wasted emissions (RM/ha for pond, or RM/m² for cage)</td><td rowspan="2"></td><td>Scen. B</td><td colspan="2">Scen. C</td><td>Scen. B</td><td colspan="2">Scen. C</td></tr>
<tr><td>B. O.</td><td>N. D.</td><td>C. I.</td><td>B. O.</td><td>N. D.</td><td>C. I.</td></tr>
<tr><td>10%</td><td rowspan="3">0.03</td><td rowspan="3">1.02</td><td rowspan="2">1.02</td><td>0.26</td><td rowspan="3">0.59</td><td rowspan="3">0.59</td></tr>
<tr><td>20%</td><td rowspan="2">0.87</td></tr>
<tr><td>40%</td><td>9.65</td></tr>
</table>

Notes: Scen. B = Scenario B; Scen. C = Scenario C; B. O. = Basic optimization; N. D. = Normal distribution; C. I. = Chebyshev's Inequality.

The best adaptation strategies for pond and cage aquaculture were decided based on the comparison of farm profit, water quality runoff, and the marginal abatement cost of emissions between three different scenarios and management options. Table 5.8 showed that the best adaptation strategy for ponds was Scenario C (feed waste emission reduction and environmental restriction) under Chebyshev's inequality assumption and that for cages was Scenario B (feed waste reduction target) estimated by basic optimization. The results also showed that the average profit for cage aquaculture was higher than for pond aquaculture because of the high volume of fish production in cage activities.

Management option II was predicted to be the rational adaptation strategy option to select for aquaculture activities in Sarawak due to the high potential of aquaculture in the future. Aquaculture production was projected to increase due to its significance in the future development of the fisheries sector in overcoming reductions in marine fish landings and to satisfy the rising demand for fisheries products as the main protein resource in daily meals. Furthermore, it was believed that the increasing price of farm inputs, especially in terms of fish foods and the future application of technology in farm management, would cause fish price to increase in order to obtain high production returns, as depicted by the profit estimation simulation results.

The results clearly showed the significance of water quality run-off values as justification for selecting the adaptation strategy to cope with climate change risks in Sarawak, which is supported by the results of average feed waste run-off in pond aquaculture. The results revealed that with increasing aquaculture production and output prices in the future, the average feed waste run-off at each production scale was lower than that of the baseline scenario and also if the output price was lower. The output price increase may help farmers to make their farm management more environmentally friendly and efficient.

The marginal abatement cost (MAC) values were the final and most important element that was considered in determining the potential adaptation strategies Sarawak aquaculture sector players could choose in adapting to climate change risks. The different values of MAC according to the different scenarios and farm management options supported the theory and concept of the marginal abatement cost of reducing farms' emissions due to climate change risks. The similar value of MAC under Scenarios B and C (normal distribution) in pond aquaculture and under Scenario C (both in normal distribution and Chebyshev's inequality estimation) in cage aquaculture do not show the benefit of emissions abatement to the farm with the increasing percentage of production and environmental regulations in aquaculture activities since the MAC value was constant at all percentage of feed waste reduction. Thus, the farm management options that showed no change in MAC were assumed to be the least effective options in coping with, and adapting to the climate change risks to be faced by the aquaculture sector in the future.

The results revealed that the values of the MAC under the different management options would be increased along with the change of aquaculture output price and the level of environmental stringency in farm activities regulation and control. As in pond and cage aquaculture, the MAC value of selected potential adaptation strategy options followed the theory of MAC where the increase of the percentage of abatement target will increase the abatement cost of emissions. Moreover, the more stringent environmental regulation imposed by the government will also result in high abatement cost. Although the cost would be high, farmers who gain high profits with high awareness of the importance of natural resources conservation to future aquaculture activities will be willing to pay or contribute to the environmental stewardship to ensure the sustainable growth of their aquaculture production in the long run.

5.6.1 Impacts of Adaptation on Selected Scenarios for Pond and Cage Aquaculture Production in Sarawak

The assessment of costs and benefits of adaptation to climate change provided important information on planning effective adaptation strategies to cope with climate change. A better understanding of the relationship between feed waste reduction strategy (climate change risk reduction) and its contribution to impacts on aquaculture activities (in profits measurement) was sought.

The estimated average profits for a pond farm and for a cage farm were RM 2,691.02 and RM 2,727.02 respectively. However, under Scenario C (pond aquaculture) and Scenario B (cage aquaculture) the profit will gradually decrease with the increment of emission reduction targets and environmental restriction in aquaculture activities. The estimated profit gained by a pond aquaculture farm under climate change risk and without adaptation during the study period is RM 2,050.48 and that for a cage aquaculture farm is RM 2,359.23. The future impacts represent the profit that will be gained in the future, assuming that climate change is occurring. The government has targeted to increase aquaculture production by up to 10% in the future and assuming that if the price of fish is increased by 5%, across time, *t*, the future impact on aquaculture production is to increase profit at RM 2,694.32 for a pond aquaculture and RM 2,727.03 for a cage aquaculture.

The profit of pond aquaculture activities will be increased compared to the baseline scenario if a feed waste reduction strategy is implemented and environmental regulation is imposed on pond aquaculture activities in future. However, the increment of profit will lessen as the percentage of feed reduction increases and the restriction on the emission constraint is implemented. A similar situation happens in cage aquaculture activities, although the proposed adaptation strategy was only to reduce the feed waste. Table 5.9 shows the different outcomes (value of profit) given by the different adaptation strategies.

Table 5.9: Comparison of residuals impacts and gross benefit of adaptation to climate change for pond and cage aquaculture in Sarawak based on different risk

Aquaculture system	Pond aquaculture (RM/ha)		Cage aquaculture (RM/m^2)	
Adaptation strategy	Difference in profit (adaptation vs. baseline or before adaptation) (RM/farm) [A]	Difference in profit (adaptation vs. future impacts with no adaptation) (RM/farm) [B]	Difference in profit (adaptation vs. baseline or before adaptation) (RM/farm) [C]	Difference in profit (adaptation vs. future impacts with no adaptation) (RM/farm) [D]
Future impacts (with climate change) after adaptation (10% reduction)	640.47	-3.37	367.80	0
Future impacts (with climate change) after adaptation (20% reduction)	639.81	-4.03	367.79	-0.01
Future impacts (with climate change) after adaptation (40% reduction)	638.03	-5.81	367.78	-0.02

Note: (-) means profit less than the reference option or future impacts with no adaptation

The different value of profit given by different strategies to adapt to climate change risks implied that in future aquaculture production profits would increase in both aquaculture activities with the increment of price. A farm based adaptation strategy involving implementation of the emission reduction strategy together with stringent environmental regulation will lessen the aquaculture production profits. However, the situation as regards pond aquaculture was revealed as the opposite. Here, if stringent environmental regulations and an emission reduction strategy were implemented, the difference between the profit gained under different adaptation strategies would be larger than that gained in cage aquaculture when only the reduction of feed waste was practiced (refer to columns [A] and [C] in Table 5.9).

A comparison of the profits for each adaptation option also revealed that implementing the adaptation strategy only results in very minimal losses to the farmers and these losses indirectly lead to sustainable aquaculture practices in coping with climate change risks (refer to columns [B] and [D] in Table 5.9). The profit projection based on the feed waste effects due to climate change risks showed that implementation of stringent environmental-friendly aquaculture practices was more important in pond aquaculture activities than in cage aquaculture activities due to the nature of the aquaculture systems. The increment of feed waste will have a worse effect on water quality in pond aquaculture and threaten the fish growth as the pond water is stored whereas cage aquaculture operates in an open water system.

5.6.2 The Benefits of Adaptation Strategy for the Reduction of Feed Waste Emissions

The selected adaptation strategy results for the average feed waste runoff revealed that the average feed waste emissions were high in pond activities compared to cage activities. The low production scale farmers emitted the highest feed waste production in ponds (73.93kg/hectare) due to the use of low technology and ineffective farm management practices. The high production scale farms with high production volumes and huge land areas caused 12.55kg/hectare of feed waste to be emitted. The medium scale farms emitted 9.31 kg/hectare of feed waste. In contrast, in the case of cage farms, medium scale production farms emitted the highest feed waste at 22.45kg/m^2,followed by the small scale farms (22.39kg/m^2) with the least from high scale farms (1.97kg/m^2).

A comparison was made of the contribution of selected adaptation strategies to feed waste runoff reduction based on the difference in results from different management options. In pond aquaculture, practicing the feed waste reduction strategy and imposing environmental restriction on pond activities can reduce feed waste emissions by 10.9% under high scale production when farm management option I and farm management option III are compared. However, the feed waste runoff under medium scale production shows unique results - the reduction in feed waste emissions was slightly higher (0.5%) under farm management option I and decreased by about 4.8% under farm management option III. For low aquaculture production, management option II with a similar adaptation strategy can reduce as much as 29.2% of feed waste runoff compared to the baseline scenario and management option III under a similar adaptation strategy.

The situation in cage aquaculture was completely opposite to the situation in pond aquaculture. The average feed waste runoff values were similar under every management option according to their production scale level. There was no difference in terms of contribution towards feed waste runoff reduction for any farm management option involving reducing feed waste by 10%, 20%, or 40% in cage production activities.

The difference between pond and cage aquaculture activities in terms of feed waste reduction results revealed that it was appropriate to impose the more stringent environmental regulation in the case of pond aquaculture activities as this could contribute to the reduction of feed waste runoff as the climate change risks were realized. Without the environmental restriction, such as are indicated potential adaptation strategy in cage aquaculture, the effective feed waste management in a farm will influence the growth and sustainability of the aquaculture practice in the long run, although the effects of this strategy occur at a slow rate. The choice of potential adaptation strategy depends on the nature of the aquaculture activities and the conformity of the aquaculture system with the climate change risks reduction and adaptation strategy. The more stringent environmental regulation does not promise the best adaptation strategy outcome and the less stringent strategy cannot be considered a less effective adaptation strategy in coping with climate change.

The stringent environmental regulation was suitable as an adaptation strategy in pond aquaculture activities because this activity was not operating in the fishes' natural ecosystem. The negative effects of climate change risks, as well as inefficient farm management, will cause major problems. They will not only have negative effects on the water quality and pollution, but also deplete the physical and natural capital of the aquaculture area surroundings. Strict enforcement and control of pond aquaculture activities should therefore be implemented in pond, as compared to cage, activities. Furthermore, practicing better farm management will be enough to cope with the climate change risk in cage aquaculture as long as external factors, such as river or stream water pollution near the cage area, have no effect. The nature of cage activities (operation in open water bodies and in the fishes' natural ecosystem) was why less stringent adaptation strategies were used in cage activities and modifications concentrated on the farm management practices. Nevertheless, strict enforcement and regulation need to be imposed if aquaculture activities contribute to negative externalities on the water bodies and river ecosystems.

5.6.3 Marginal Abatement Cost of Emissions from Aquaculture Activities

The potential adaptation strategy assessment based on the CCP profit optimization analysis also estimated the MAC on adaptive options. The MAC demonstrated that the adaptation evaluates effectiveness and influence on the increase of adaptation measures from mitigation measures (Gren, 2008). Thus, the shadow price was the direct change per unit of constraint in the objective value of the farm optimal solution, known as marginal utility or the marginal cost of strengthening the constraint. Figure 5.3 and Figure 5.4 showed the trend of the MACC for selected adaptation strategies in pond and aquaculture activities under the different percentage targets of feed waste emissions reduction.

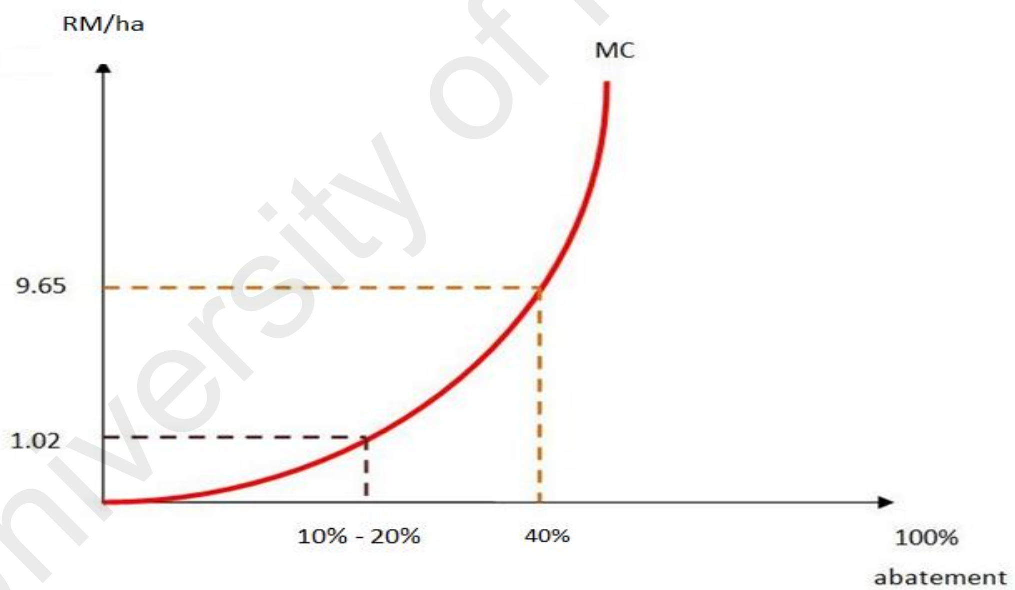

Figure 5.1: Marginal abatement cost curve of adaptation in ponds aquaculture farms

Source: Author

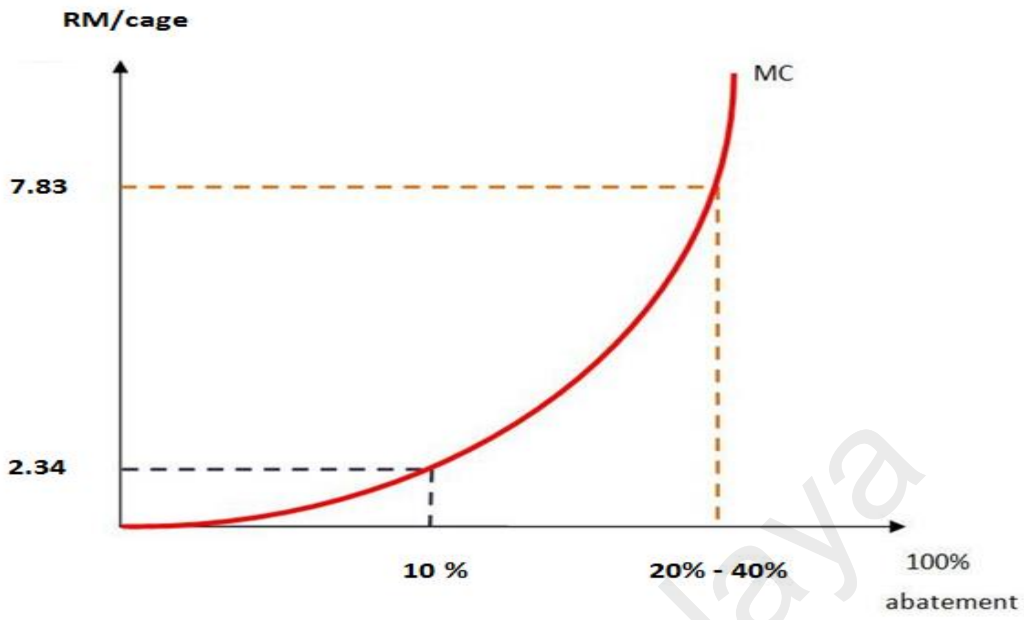

Figure 5.2: Marginal abatement cost curve of adaptation in cage aquaculture farms

Source: Author

The MACC of pond production demonstrated that under Chebyshev's inequality assumption estimation, at 10% and 20% of emissions reduction targeted, the abatement cost of emissions was RM1.02/hectare for ponds. Meanwhile, the 10% emissions reduction target in cage aquaculture will cost of RM 0.26/m^2, equivalent to RM2.34/cage[3], in the basic optimization assumption estimation of MAC cost. The increment of feed waste emissions target of 40% reduction gives different outcomes in pond and cage farms in Sarawak. In pond aquaculture farms, if the government planned to impose a 40% reduction in feed waste emissions and environmental regulations that imposed of satisfied emissions constraint with a 90% probability, the abatement cost value was RM 9.65. However, in the cage aquaculture farms, if the government planned to impose a 20% to 40% emissions reduction in aquaculture activities, the MAC that

[3] Marginal abatement cost (MAC) = RM0.26*9m^2=RM2.34/cage.

would be needed to achieve the targets was constant at RM 0.87/m^2, equivalent to RM7.83/cage, although there was an increase in the percentage of emission reduction.

The abatement costs of pond farms were influenced by the double environmental regulations in the model that force the farmers to practice proper waste management in their farms. The results revealed that the more emissions reduction was targeted under stringent environmental regulations, the more MAC increased to abate the emissions. This MACC trends is consistent with the findings of a study by Bockel, Sutter, Touchemoulin and Jonsson (2012). The consistent monitoring and controlling of water quality and pond structure, efficient management practices with good fish feed management and a technology assistant to help monitor water quality and vaccinate cultured fish, helped to reduce the emissions in pond production.

The abatement cost appeared to be a lower value in the cage farms as compared to pond farms because the estimation was based on ‘per cage’, which is smaller than the measurement of MAC in pond activities. However, as the targeted reduction increased from 10% to 20%, the MAC value gradually increased and became constant at the 40% feed waste reduction target. Furthermore, the high production volume in cage aquaculture will increase MAC more in a farm due to the number of cages owned by farmers and due to the open production system that needs more cost to conserve the river water quality.

5.6.4 Managing Resources Allocation in Aquaculture Activities as the Factors of Adaptation

Adaptation is the process of handling the external factors of change, such as farm size, changes in management practices and environmental regulation, while sustaining the farming objectives in yield, production, profitability and farm sustainability (Risbey, Kandlikar, Dowlatabadi, & Graetz, 1999). At the micro-level sector, the adjustment in farm resource management will help farmers adapt to climate change risks at low cost. The results when using the current situation as a reference and working on future predictions, with the inclusion of the probability of emissions reduction target and environmental restriction, are able to compare the future potential adaptation with the current scenario of farm activities in order to predict the possible outcome. Thus, the advantage of this study is the combination of autonomous adaptation (farm level) with a planned adaptation set by the government (emission reduction targets) using the chance constrained optimization in order to predict the consequences of changing reduction targets to the abatement cost and also the resource farm management.

Focusing on farm level adaptation, the utilization of land or aquaculture size was identified as the crucial problem for aquaculture farmers in Sarawak for both pond and cage aquaculture activities. Ineffective land use for the aquaculture sector had effects on the increment of feed waste runoff as an impact of climate change. To maximize the profit and reduce the ineffective feeding management, the ponds aquaculture farmers were recommended to increase the volume of aquaculture production by increasing the number of fish stocks in ponds and this will ensure that the problem of feed waste can be reduced. The use of unproductive land for ponds will increase the maintenance cost in ensuring good quality water.

Fish feed constraints were identified as crucial problems in the aquaculture sector in Sarawak in terms of the price, quality and management. Thus to manage the feed cost efficiently, the farmers have to balance the land use for fish farming with the pattern of fish feed. The unproductive use of a number of cages effects the increasing of maintenance cost for cage structures. Since cage aquaculture was operating in the open river system, the feed waste runoff was minimal and the feed was channeled to the wild fish or aquatic organisms in the river.

The labor hours also influenced the productivity of pond aquaculture activities. The pond aquaculture activities need extra monitoring compared to cage systems due to the closed operating system with infrequent changes of water. Thus, the working hours or labor for medium scale production farms needs to be increased to monitor the changing water patterns and other environmental threats that may harm aquaculture production.

5.7 Conclusion

Based on the comparison of the simulation results for different farm optimization models and scenarios, the study found that to strengthen the future competitiveness of the aquaculture sector, Sarawak aquaculture production, referring to pond and cage activities, will be expected to increase at least at 10% with a 5%price increase. This will be the best farm management option and target that benefits the farms' management level in adapting to the raised incidence of climate change risks. However, under the same farm management option, different aquaculture systems showed different preferable environmental strategies or scenarios which present the planned adaptation that best achieves the farms' objectives to maximize the profit as well as reduce the impacts of climate change risks.

The study suggested that for the future planned adaptation in the aquaculture sector, the government should implement more stringent regulations on pond aquaculture activities than on cage aquaculture activities. The results revealed that different aquaculture systems responded differently to environmental regulation. For pond aquaculture, with the increase of production and price, stringent environmental regulations with a feed waste reduction target had no effects on farm profit. In contrast, this scenario was not suitable for imposition on to cage aquaculture activities as the strategies would not result in the improvement of farm adaptation.

The average profit per cage is higher than for pond aquaculture due to the volumes of production involved. Furthermore, the cultured fish survived better in cage aquaculture activities which operate in natural fish ecosystems. The estimated average profit of both aquaculture systems decreased from the profit value for normal practices or the baseline scenario when there is an increment in emission reduction targets and environmental restrictions on aquaculture activities.

Of the selected potential scenarios, the stringent environmental regulations and feed reduction strategy imposed in pond aquaculture was able to reduce the feed waste run-off from the pond more than from the opposing management options of pond aquaculture. However, the average feed waste emissions from pond activities were high compared to those from cage activities. The low production scale farmers were found to emit the highest feed waste run-off due to the low level of technology in use and inefficient farm management practices, while the least feed waste run-off was from medium production scale farmers. In contrast, in the case of cage farms the medium scale production farms emitted the highest feed waste emissions and the high production scale farmers the least. The comparison of adaptation cost based on the farms' profit revealed that implementing a suitable adaptation strategy results in very minimal profit losses which counterbalanced the climate change impacts reduction and enhanced the sustainability of future aquaculture activities.

Furthermore, in pond aquaculture, the assessment of MAC showed that the abatement costs were constant at 10% to 20% reduction with a gradual increase at 20% to 40% feed waste emission reduction. The MAC of cage activities showed a difference where the abatement cost increased from 10% to 20% of feed waste emission reduction and was constant at 20% to 40% feed waste emission reduction. The marginal abatement cost of pond aquaculture increased if double environmental regulations were imposed on pond aquaculture to abate the climate change risks. The marginal abatement cost of cage aquaculture increased when the production volume and feed waste reduction target increases due to the open production system that needs more costs to conserve the river water quality.

Effective resource allocation practice was identified as the basic autonomous adaptation that farmers should practice. The land is optimally utilized for aquaculture activities by low scale production fresh water pond farms, high scale production freshwater cage farms and low scale production brackish water cage farms at every percentage of feed waste reduction. The optimal labor hours allocation for aquaculture activities was found in the high scale brackish water cage farms, while the low scale production freshwater pond farms showed efficiency in term of allocating fish feed in their farm activities. The excluded farms needed to better manage their resource allocation in order to increase their production and at the same time reduce the losses due to climate change risks.

CHAPTER 6: CONCLUSIONS

6.1 Conclusions

This study is an assessment of the vulnerability of, and adaptation to climate change risks in the aquaculture sector in Sarawak. The study had three objectives: To assess the impacts of climate change on the biophysical vulnerability of aquaculture production; to identify the relationship between aquaculture farmers' livelihood assets and socio-economic vulnerability to climate change; and to identify the potential adaptation costs and strategies to cope with climate change risks and the vulnerability of the aquaculture sector. Three essays are presented, which address these three objectives, based on the economic approach. A series of analyses, including Multiple Linear Regressions, Factor Analysis, Reliability Analysis, Multivariate Logistic Regression and Chanced Constrained Programming analyses were employed to achieve the study objectives.

The climate change risks and biophysical vulnerability of aquaculture production in Sarawak differ depending on the type of aquaculture - pond or cage. In the case of pond aquaculture systems the macro-level assessment results showed that mean maximum temperature, mean minimum temperature, sunlight intensity and the increase of pond size have a significant positive effect on production. Mean rainfall has a positive relationship while mean relative humidity has a negative relationship with pond production, though neither relationship is statistically significant. In the case of cage aquaculture the results are somewhat contradictory as an increase in mean maximum temperature has a significant negative relationship with production. Meanwhile, mean relative humidity has a significant positive relationship with production. Mean total rainfall and sunlight intensity have a positive relationship, while an increase in cage size had a negative relationship to cage production, though neither relationship is statistically significant.

The farm level study gave further support to the macro findings on the assessment of the biophysical vulnerability of aquaculture production. Water and weather are environmental elements that are important to aquaculture production, so variability in precipitation patterns and temperature were shown to be the critical climate change risks factors that influence production failure and lead to socio-economic vulnerability in Sarawak's aquaculture sector. The other factors not identified in the macro analysis, such as water pH (either increased or decreased) and disease outbreaks, are also climate change risks events that contribute to aquaculture production losses. The water pH influences the toxicity of water in the pond and cage areas, and this causes a crucial problem affecting farmers at all income levels in sustaining their increment of income. However, pandemic disease was less of an issue to non-poor income farmers in Sarawak due to the farmers' immediate action to monitor and control diseases through the lowest cost techniques using natural remedies and without the assistance of any specific equipment or technology. Dissolved oxygen depletion in water was another major threat to aquaculture production in Sarawak caused by the rising impacts of climate change which affects the farmers' livelihoods. Unpredictable variation in temperature and rainfall cause changes in water quality in terms of dissolved oxygen content in both ponds and cages, and is a great challenge for farmers to control without technical support.

The macro and farm level assessment findings of this study indicate that the climate change impacts were quite low in Sarawak's aquaculture sector. Admittedly, these climate change risks will increase in the future as global warming worsens over the years. Without exception, the economic sectors, especially the aquaculture sectors of all countries, have to face the increasing impacts of global warming and climate change. Frequent climate change events have occurred recently and will continue to occur in future, and the socio-economic vulnerability of aquaculture farmers' livelihoods will increase as a result of decreases in production.

The study results suggested that the negative effects on biophysical factors were less in aquaculture ponds than in cages and this may be due to farm management factors. The biophysical vulnerability assessment of the natural capital aspects revealed that pond aquaculture production gives higher income returns than cage aquaculture production in Sarawak. This finding supports the macro assessment findings on the biophysical vulnerability impacts, where pond production activities were found to be less risky than cage activities. Furthermore, in terms of land accessibility, medium scale aquaculture production was more sustainable than small scale production and better ensured farmers' income stability, regardless of the aquaculture system type. Furthermore, farm operations at T.O.L. lands produced more revenue and income compared to operations on farmer-owned land.

Pond aquaculture is an inland aquaculture activity, so farms usually needed closer and more active monitoring and management compared to cage aquaculture activities. Farmers can thereby directly control and minimize the negative effects of biophysical factors on pond production. However, farmers had difficulties in becoming alerted to the effects of humidity on pond aquaculture, as this was volatile and influenced by other climate factors. A direct change in humidity may cause severe fish death, usually at dawn or when rain suddenly occurs after a long sunny period. The other effect of a change in humidity was a change in the volume of fish food due to the change in air moisture.

Cage aquaculture, which operates in open water bodies and involves less equipment, has negatively affected production as a result of an increase in maximum temperature and aquaculture farm size. Farmers found it difficult to directly control cage aquaculture activities, including temperature, due to the nature of cage aquaculture activities, which are directly influenced by the river water quality and the surroundings. An increase of cage size may result in high losses to the farmers when disease outbreaks occur, water quality deteriorates and also when water pollution rises due to effluents from the inland economic activities in the river water, due to the lack of farmers' control.

The socio-economic vulnerability assessment of farm level pond and cage aquaculture in Sarawak revealed that level of income determined the vulnerability level. If a farmer has a low (poor-level) income, he is believed to be vulnerable because he has few capital assets to assist him to sustain his livelihood and thus less resilience in adapting to the risks of climate change. These findings are consistent with Sen's (1981, 1984) theory of entitlement as well Holling's (1973) resilience theory. As the level of assets owned by a household influences the vulnerability level of risks, an assets based approach was used to assess the socio-economic vulnerability factors in Sarawak's aquaculture sector.

The assessment of demographic aspects found that cage aquaculture activities will have potential in the future to contribute to the competitiveness of the aquaculture sector due to the strong human and financial capital support. The future development of human capital will also encourage the growth of cage activities. Furthermore, farmers owning limited land have the opportunity to become involved in aquaculture through cage activities. With the support of other capital assets and with intensive care and good cage management practices, cage aquaculture would, perhaps, be able return high revenues. The future contribution of pond aquaculture activities was not less important than that of cage activities. However, rapid industrialization and growth in commercial activities will limit the availability of suitable land for the expansion of pond aquaculture activities.

Capital assets are important to the sustainable aquaculture sector, and it is important to efficiently utilize the natural capital assets, including land and river or stream, to enhance this sector's competitiveness. Expansion of farm size and aquaculture activities would help improve farmers' livelihoods. The findings show that medium scale production farmers were less vulnerable than low production farmers as the former are able to recover the production costs as well as obtain promising profit returns. The expansion of activities would need financial support to increase production inputs and technical support, such as skill and aquaculture technologies used to manage the farm efficiently.

The socio-economic vulnerability assessment study also indicates that ethnicity plays a role. The study discovered the remarkable contribution and performance of Chinese aquaculture farmers in Sarawak who obtained high profit returns with lower production costs. Reasons for this include historical factors (inheriting skills within the family), strong ownership of capital assets, scale of production, networking factors, a risk-takers' attitudes and income diversification. Admittedly, some Bumiputera and Malay farmers performed on par with Chinese farmers but their performance in this sector was limited due to the weak self-interest and experience of Bumiputera and Malay farmers in aquaculture as well as their operating in rural areas.

Financial and technical factors influenced vulnerability in aquaculture activities. Farmers who owned sufficient financial capital, as rolling capital or maintenance expenditure would be able to support their production over the long run as well as cover losses due to climate change risks. Off-farm income or income diversification is a financial capital asset that is significant in promoting the farmers' livelihood sustainability. Off-farm activities help farmers to increase their income as well as improve and stabilized their livelihoods; increase the contribution and employability of family members of poor income farmers; and prepare backup in terms of savings for their future needs. Off-farm activities also benefit farmers in enhancing their farm management knowledge and skills.

Technology is among the physical capital assets that influence aquaculture productivity. Higher disposable income for farm households can be generated by the use of technology and technological assistance to improve livelihoods. Technology is needed to produce high quality fish fries, prepare fish pellets and monitor pond water quality. Furthermore, high scale production farms need a synergy between financial, knowledge and technology factors to minimize the costs, especially of fish food and chemicals. Low cost efficient technology was still the best option to help low and medium scale farmers manage their farms effectively.

Technology is only a way to help practices become more sustainable, reduce risks and protect aquaculture production that can boost aquaculture production and minimize production loss. The most important factors for managing farms for sustainable aquaculture production are ecological practices and sustainable resource management - strategies that consume the least costs and are the most effective in reducing the production risks and adapting to climate change risks and impacts.

Good technical aquaculture management can assist in reducing the hazards of climate change risks to aquaculture production. Having more skilled farm labor and using technology in managing farm activities can promote sustainable aquaculture and minimize technical failures that would cause great production loss. Regular training on farm management techniques and close monitoring would help strengthen the use of technical factors in aquaculture farms.

Although the climate change risks are considered low and at a level tolerable by aquaculture farmers in Sarawak, it is important to identify farmers' potential adaptation capacity and capability to cope with the risk. The future occurrence of climate change events and level of the associated risks is unpredictable. Thus, this early vulnerability assessment study is important to indicate the possible action that may need to be taken to mitigate potential risks and at the same time put in place adaptation strategies with potential to cope with future climate change risks.

The potential adaptation strategy at farm level in Sarawak had been identified through estimating and comparing the marginal cost of abatement as the cost of adaptation in order to select the best adaptation options. In terms of farm profit optimization, the results show that the profit will gradually decrease if the emissions reduction target and environmental restriction values increase in the farm management model. The study also concluded that the future expansion of aquaculture production must be in step with the increment of output price. Otherwise, the farms will not be able to achieve high profits and will suffer production losses. As output price increases, in the future production inputs in both freshwater and brackish water pond and cage activities will significantly increase. In order to adapt to the climate change impacts and maintain farmers' welfare, the proposed optimal environmental restriction for feed waste emissions in aquaculture activities is 90%. Meanwhile, a rational target emissions reduction was 10% to 20% reduction. The increase of the environmental restriction target in production activities and the higher percentage of target emission reduction will cause farmers extreme profit loss due to the stringency of the regulations.

The comparison between the two models showed that the marginal abatement cost of feed waste emissions was high in pond aquaculture due to government-imposed environmental restriction as well as the emissions reduction target implemented in the activities. The marginal abatement cost was high in the pond system due to the closed water system or water changing operations in the pond that require more conservation cost for water quality treatment and monitoring. In pond aquaculture, the stringent environmental regulations and good feed management practice was able to reduce the amount of emissions due to climate change.

The efforts to reduce feed waste emissions contribute to the abatement of emissions. However, without stringent environmental regulations, this abatement rate was slow, as was indicated for cage aquaculture. The significance and effectiveness of stringent environmental regulations imposed on aquaculture activities depended on the nature of the aquaculture production itself. The results showed that the imposition of stringent environmental regulations successfully reduces the feed waste emissions in pond activities. In contrast, this strategy did not work well in cage aquaculture and is beyond the adaptive capacity of the cage aquaculture farmers. The MAC results support this evidence as, if stringent environmental regulations were imposed on cage aquaculture the MAC will remain constant at a single price and only be effective in abating the emissions by up to 10%. Increased efforts to reduce the emissions will not result in any change to the MAC for cage culture. This ensures that the realistic adaptation options were based on the adaptive capacity and in accordance with the nature of the aquaculture farms. If the adaptation strategy selection is realistic, the increment of feed waste percentage reduction targets or if more stringent environmental regulations are imposed on the activities, the more the MAC needed to reduce the emissions.

The feed waste emissions runoff was high in pond production due to the reservoir of feed waste in ponds, while the feed waste emissions in cage production were discharged directly into the river. The water quality runoff results showed that pond aquaculture activities were more vulnerable to climate change risks than cage aquaculture activities. Low scale farmers' lower capability and use of less technology in both pond and cage activities were identified as the reasons for high discharge of feed waste effluent to river water. Furthermore, the results showed that the majority of aquaculture farmers in Sarawak were involved in low and medium scale production rather than high scale production. Also, the climate change risks and impacts as well as lack of capital and technological assistance in farm management practice and control contributed to the high feed waste effluent levels.

The identification and estimation of potential adaptation scenarios in this study took into account the government's planned targets for national GHG reduction by 2020. The farmers' autonomous adaptation was identified through the farm practice information. All the information was digested and analyzed to portray the possible scenarios that may happen in Sarawak's aquaculture sector in the future.

Both pond and cage farms need to fully utilize all the excess resources (land, labor, and fish feed) in their farms to achieve efficiency in farm management and resource allocation. The competitiveness of the aquaculture sector can be enhanced by developing more high scale production activities in Sarawak's aquaculture sector as the major contributors of aquaculture production are currently the low and medium scale farmers. The optimal allocation results revealed that there were large unproductive ponds and cage areas that farmers need to develop to increase the state's aquaculture production in future. The inefficient use of land for aquaculture activities in Sarawak may be caused by the increasing price of good quality fries that limits the volume of farm production. The cheaper fries were low quality or non-resistant to climate and water quality risks which easily exposed them to mortality. Furthermore, the increasing cost of farm inputs, such as fish foods and cage structure materials, limits the farmers' capability to operate high production activities in order to minimize the cost and potential losses.

The labor contribution was still high in Sarawak's aquaculture sector, as use of technology was low, especially on cage farms. Ineffective labor contribution occurred in low and medium scale aquaculture farms where less time was spent managing the farms and time was spent doing other jobs or earning off-farm income. The labor was mostly family labor and most of the time was spent only feeding the fish. Another labor constraint in Sarawak was the lack of skilled and experienced labor to manage farms that sometimes caused production failure.

Good fish feed management ensures the sustainability of aquaculture production. The difference in cost and type of fish food between pond and cage aquaculture influenced the efficiency and effectiveness of feeding activities. Fish pellets were usually cheaper than the thrashed fish used in cage activities. The consumption of fish food had a significant relationship with the land used for aquaculture activities. As the size of aquaculture farms expanded, the demand for fish food increased and the rate of consumption was also influenced by the stage of fish growth as well as the weather conditions and water quality.

Good and efficient aquaculture practices in farm management will influence the potential growth of this sector and minimize farm production risks and vulnerability. At the farm level, all aspects of aquaculture farm management will influence the sustainable growth of this sector currently and in the future and ensure that aquaculture practices remain sustainable and safe. This will ensure high quality aquaculture production including effective land use management as well as technical factors such as labor, feed management, harvesting, and marketing the products. Admittedly, technological assistance will help enhance the future growth of aquaculture. Thus, the creation and availability of low cost and efficient aquaculture technology may help low and medium scale farmers enhance their production.

6.2 Contribution of the Study

The study has contributed towards the understanding of the effects of climate change risks on aquaculture sector development vulnerability and adaptation to climate change, in Malaysia but especially in Sarawak. The study has updated information in this field and the findings provide baseline information and fill gaps in research on climate change impacts assessment and risk management studies in Malaysia. A limited number of studies had focused on the vulnerability and adaptation to climate change risks in aquaculture development in Malaysia from the biophysical and socio-economic perspectives. This study has thus contributed by gathering and sharing relevant information on the former and the predicted future potential impacts of climate change risks on aquaculture production and potential adaptations from the perspective of farm practices in order to buffer the effects and cope with future risks. The study states the implications of climate change on aquaculture production in Sarawak, makes recommendations for the improvement of related policies, laws and regulations in Malaysia and suggests some improvements to managerial aspects of aquaculture activities. Specifically, this study has made contributions by examining three different types of implications, namely, methodological, theoretical, and policy implications.

6.2.1 Methodological Implications

The study combined both macro and micro level aspects of climate change information, using several quantitative approaches for an in-depth biophysical vulnerability and impacts assessment. The study addressed the details of biophysical risks by collecting data directly from farmers due to the limitations of the analysis in explaining the impacts of biophysical factors to aquaculture production using aggregate data. This micro data enriched the choice of analysis and enabled further assessment of the socio-economic vulnerability and indicated the potential adaptation strategies from the farmers' farm management point of views.

The study extended further the application of multiple linear regression analysis, factor analysis, and multiple logistic regression analysis as applicable analyses for vulnerability assessment in the study of climate change impacts on economics. Thus, the analysis of the impact assessment and adaptation strategy identification was not limited only to assessment using the qualitative data approach. Furthermore, the study also proposed, and enhanced the application of the CCP model that former studies have usually used to assess risk, to estimate adaptation cost, and identify the potential adaptation strategies in farm activities. The basic CCP model was adapted to the aquaculture farm situation combined with information on government GHG and environmental targets, to develop and assess the potential adaptation strategies that may be applicable to cope with climate change impacts.

6.2.2 Theoretical Implications

This study contributed to the theoretical, conceptual and practical development of the study of the economics of climate change with reference to Sarawak's pond and cage aquaculture sector. As the climate impacts study combined explanations from the perspectives of environmental science and economics, the study integrated several main theories and developed a conceptual and analytical framework to understand the interaction and response between climate change risks and aquaculture activities in Sarawak. Scientific and economic knowledge related to the aquaculture sector were combined to model the risks and vulnerability assessment from the biophysical and socio-economic aspects. The study also proposed models for the potential adaptation strategy assessment based on the farm practices in Sarawak.

The study has contributed to the development of knowledge on the economics of climate change focusing on the impacts and adaptation assessment in the context of the Malaysian aquaculture sector as few researchers have explored this area so far. The empirical findings from the study added to the literature and assisted in identifying the significant impacts and relevant adaptation strategy as well as bridging the theoretical and conceptual gaps in climate change studies in Malaysia.

This study posits a few strong points and advantages in terms of climate change economics based on the empirical analysis. The study contributed to the enrichment of vulnerability assessment and adaptation strategy information from the economic perspective, specifically to the aquaculture sector. The study expanded the analysis of several biophysical factors of climate change risks that previous economic studies of climate change in agriculture had not covered. Meteorological factors such as humidity and sunlight intensity variability were shown to affect fish growth in addition to temperature and precipitation. Information on the land used for aquaculture was included as this represented the physical factor of production and enabled the meaningful measurement of aquaculture productivity. The biophysical vulnerability assessment also took into account the farmers' perceptions and experience of climate change risks through the microeconomic analysis approach.

The study then assessed aquaculture farmers' socio-economic vulnerability as the biophysical vulnerability assessment was insufficient to explain the whole system of risks of climate change in aquaculture sector activities. The socio-economic vulnerability assessment was adapted from Chambers and Conway's (1991) SLA model in explaining the connection between the vulnerability level and the capital assets owned as an important socio-economic factor in farmers' production and livelihoods. The four dimensions of the assets-based approach content in SLA were used to evaluate the effects of climate change risks on farmers' socio-economic vulnerability.

Using the farm-based approach, the study proposed several future aquaculture management options derived from baseline information about recent pond and cage aquaculture activities in Sarawak under different scenarios that take into account Malaysia's national emissions target for the agriculture sector. Furthermore, the study pinpointed the limitations of climate change adaptation assessment, which lacked specific information from farmers, limitations that were overcome by projection of estimated feed waste effluent of representative farms using the farm activities data.

The empirical findings contributed to the enhancement of the adaptation evaluation and extended the application of optimization and chance constrained programming analysis in modeling the potential adaptation strategy. The findings from this method contributed not only to the selection of the best adaptation option based on current actual farm practices in Sarawak but also indicated the way forward and proposed solutions to enhance aquaculture in future through farm resource management. The findings empirically support the vulnerability theories of climate change. To escalate the adaptive capacity, the farmers need to adjust the farm operation with the environmental regulations and government targets on GHG reduction. This is to ensure that the future potential adaptation strategies are coherent, sufficient and effective in coping with climate change risks. There must be different levels of adaptation in aquaculture activities depending on the farmers' production scale so that equality among farmers can be achieved and to promote a win-win situation and successful adaptation results. Furthermore, the study indicated the adaptation cost, potential concept and strategies necessary to cope with climate change risks in Sarawak's aquaculture sector that may also be useful as a reference for Malaysian aquaculture as a whole.

6.2.3 Policy Implications

Climate change is a global issue and Malaysia also faces great challenges due to this global risk. Malaysia set up the first NPCCM in 2010 to mitigate and reduce the current and future climate change risks to national economic activities and to contribute at the international level in combating the rising risks and hazards of global warming. This

NPCCM policy further supports the limited national issues of environmental aspects covered in the NEP and other environment-related policies and ordinances.

The significant contributions of aquaculture to development in the agriculture sector were also highlighted in several government policies. The Malaysia National Agro-Food Policy (2011-2010) and the Eleventh Malaysia Plan (2016-2020) have highlighted recent plans for the transformation of the aquaculture sub-sector. The Aquaculture Blueprint, developed by the Ministry of Agriculture Malaysia, underlined several development strategies to strengthen and enhance the future competitiveness of the aquaculture sector through i) increasing supply of high quality and value fries; ii) transforming small-scale aquaculture farmers; iii) increasing the production of high value aquaculture; iv) ensuring a supply of affordable, quality fish feed; and v) enhancing sustainable fish resource management (Malaysia, 2015). The focus on national efforts to mitigate and adapt to the socio-economic effects of climate change in Malaysia was recently highlighted in the Eleventh Malaysia Plan (2016-2020) which discussed in general efforts to reduce climate change impacts on national economic sectors and emphasized the resilience of the aquaculture sub-sector to climate change risks. Policy makers documented related policies in a very systematic and well planned manner.

Several recommendations are made to improve the policies' implementation aspects based on the findings of this study. First, increase the national target for reduction of GHGs emissions intensity of its GDP to 40% by 2020 as a result of the national achievement in reducing the GHG emission by 33% by the end of 2013. The 40% target for GHGs reduction was a general target the government set that required the collaborative efforts of all sectors in Malaysia (Ministry of Natural Resources and

Environment, 2011; Malaysia, 2015). All stakeholders in aquaculture production can achieve effective mitigation and adaptation strategies by co-operating and acting responsibly. Serious actions by the sectors will be needed to ensure the effectiveness of each sector's contribution to this target. The study suggested a specific percentage target of GHG reduction, according to economic sector. The study also suggested that a reduction target below 10% GHG would be the ample for the aquaculture sector since a target above this level would be too stringent and cause inefficiencies in aquaculture productivity. Society will be clearly informed that the national objective to mitigate climate change risks and ensure environmental conditions can be sustainable - the target set for each sector is summed, and this will support the strategic thrust of the NPCCM

The existing national regulations and policies related to aquaculture and environmental protection and conservation are still significant and important to ensure a sustainable environment as well as to control activities that damage the environment and natural resources and to support government efforts to mitigate and adapt to climate change impacts. However, the relevance of regulations to current environmental and natural resource conditions needs to be assessed from time to time to ensure it is the right policy to implement at the current time and to strengthen it. Strict enforcement and penalties must be imposed on farmers who break the rules.

The study suggests that the government should set up and develop a research center or monitoring station for climate change that collects data on meteorological parameters, water quality and disease in the main aquaculture areas such as the AIZ. This would help mitigate future climate change risks and impacts on aquaculture sector development. The development of such a center or monitoring station would help provide and distribute climate information to farmers, provide useful information for dynamic aquaculture research and development (R&D) activities and assist future climate change risk assessment and management on aquaculture farms. Furthermore, the special research center for climate change monitoring in Malaysia would help realize the national target for mitigation of, and adaptation to climate change risks and help achieve the target of reduced GHG emissions as well as ensure that the environment can be sustained for economic activities.

Access to technological assistance in farms in the aquaculture sector was crucial to increase production and minimize the effects of climate change risks. The systems synergy in farm technology, knowledge, information, and marketing will have implications on the environment and livelihoods. Innovations and technology transfer along the farm commodity chain will promote the transformation and development of traditional farms to more intensive systems (Lebel et al., 2002) and promote ecological practices and sustainable resource management in aquaculture farms (Naylor et al., 2000). The farmers' capability to use relevant technology in aquaculture farms would help increase farm productivity and reduce the risks and vulnerability.

Above all, efficient farm management was key to the sustainable growth of aquaculture and was the best and simplest way to adapt to, and cope with climate change risks and vulnerability. It is important to promote and facilitate green technology at reasonable prices for cage and pond aquaculture. Environmentally friendly equipment and safe substances that do no harm to, or have no side effects on the environment, should be used in managing aquaculture activities in order to promote and enhance sustainable aquaculture practices in the future. Sustainable aquaculture practices require the integration of natural resources management and conservation, aquaculture scientific guidance, technological orientation, and financial and institutional change – all important factors in satisfying the human needs of present and future generations (Frankic & Hershner, 2003; Subangsihe, 2003; Valenti, Kimpara, & Preto, 2011) and good knowledge in handling and managing technology (Edwards, 2000; Prein & Ofori, 1996b). Improvements can be made in aspects of water management; environmental friendly feeding strategies; ensuring fingerling stocks are genetically fit; health management; and practicing the integration of aquaculture with agriculture (Subangsihe, 2003). Resource allocation in terms of land used and water quality management, skilled labor and participation as well as technical assistance in operating farm and fish food management and safe harvesting procedures would reduce the impacts of climate change risks on production.

Good knowledge in managing aquaculture farms will help farmers identify the risks and adapt to climate change. Therefore, it is necessary to provide assistance schemes, consistent advice and training, especially to low scale aquaculture farmers. Related agencies can use this platform to share with farmers' knowledge and ideas that will help them to better understand good aquaculture management practices and accurate techniques and keep updated on the current problems, risks, and challenges facing them in managing their farms. Frequent interaction between assistant fisheries officers and practitioners would help identify the current production risks farmers face.

Facilitation of good marketing channels for aquaculture products, enhancement of the local market and also access to international markets are important to enhance the sector's competitiveness and its contribution to economic growth. The government and private related agencies must synergize to outsource aquaculture products both to local and international markets. Farmers should gain exposure and be encouraged to become involved in downstream aquaculture activities such as entrepreneurship and ecotourism to enrich the added value and variety of aquaculture products. This would help them to generate extra income and diversify their economic activities as well as offer local people job opportunities.

The rising price of fish food, such as pellets and trash fish, has burdened farmers and limited their production. Aquaculture produce in the market suffers price volatility due to the cheaper price of imported fish products, and so is unable to promise the aquaculture farmers the highest returns and is not worth the cost incurred in its production. Low and medium scale farmers were unable to expand their activities (in order to limit the farm expenditures) or control the probability of losses due to production risks due to the rising cost of fish food and other aquaculture inputs with the unstable biophysical environment. Farmers with low financial assets were unable to survive and exited the sector. Therefore, the government needs to control and monitor the increasing cost of aquaculture inputs in the market. The other solution is to encourage and fund research to invent substitutes plant-based fish foods of at least equivalent quality to ensure low market prices.

The government should also create a policy to promote off-farm rural development, including wage labor; enhance skills in order to attract members of rural communities, especially the younger generation; and create options to reduce migration to urban areas and increase the safety net for farmers who are exposed to uncertainties in their production (Akram-Lodhi, 2008). Such efforts can help reduce aquaculture farmers', especially those in rural areas, poverty levels due to low production as a result of climate change risks and related factors. On-farm and off-farm income can complement each other and work simultaneously to ensure further growth of the sector (Dixon et al., 2001). Household members, especially those who are female and young, can be empowered through off-farm activities to generate more income to increase the sustainability of their livelihood (King et al., 2009). The government can empower youth through vocational training to prepare them for a career as skilled workers in the higher income labor force market. Education is therefore important to help government objectives to be reached. The young people can gain broader experience and opportunities with after school education extension programs, exposure to life outside agriculture, and encouragement to travel. This will help them in gain a better income and livelihood and help their family escape poverty (King et al., 2009).

Lastly, effective financial assistance schemes can help farmers cope with production risks. A stable financial safety net will lessen the impacts of risks by giving protection and assistance in covering losses and maintaining livelihoods. The farm credit co-operative model can be made available to aquaculture farmers in addition to farm credit programs arranged by government stakeholders such as Amanah Ikhtiar Malaysia (AIM)[4] and Malaysian Administrative Modernisation and Management Planning Unit (MAMPU), which offer microcredit at low interest and through lenient repayment schedules and easy procedures. The credit co-operative is one of the best strategies to support farmers to meet the market's requirement (Davis, 2003). Through co-operatives small farm farmers in Japan were exposed to savings behavior and their financial savings were mobilized to access agriculture loans (Adams, 1978).

6.3 Limitations of the Study

This vulnerability and adaptation study could be improved in several ways. First, the biophysical and socio-economic vulnerability assessment would be more accurate and

[4] Amanah Ikhtiar Malaysia (AIM) is the largest microcredit organization in Malaysia that had been established on 1987. The function of this organization is almost similar with the Grameen Bank in Bangladesh.

meaningful if the impact assessment were based on a comparison of the two periods, that is, before and after the impacts. This would lead to a better understanding of the level of hazards, exposure, resilience and the adaptive capacity of aquaculture production systems to climate change impacts.

Limited resources meant that the study was limited to, and focused on, pond and cage fish aquaculture production only. Other types of aquaculture might differ in terms of exposure to risks. The study used a single data collection period due to limitations in the time available to collect the data on the aquaculture farms. The data collection survey was carried out over one and a half years due to location factors, time constraints and safety issues. During this period data were only collected from 255 farmers. The farms and districts were distant from each other and this resulted in the survey taking a long time. Officers from the Inland Fisheries Unit, Department of Agriculture assisted in data collection (due to the locations, distance and safety issues) so the agriculture officers' schedules had to be taken into account.

The crucial issue in the macro-research approach to study climate change impacts and adaptation in the aquaculture micro-sector was the availability of direct data, both meteorological and relating to water quality monitoring. The biophysical risks and vulnerability assessment for aquaculture production needs monthly records of the pond and cage water quality during the observation years in order to indicate the details of weather variability impacts on climate change risks to aquaculture production. Furthermore, meteorological data from the aquaculture areas will give more accurate results on the biophysical impacts of climate change on aquaculture production in Sarawak. The secondary data for this research was very limited and some important indicators for climate change assessment were not documented or sufficient for in-depth study. Some data, such as water quality data, were not included due to this constraint. This information could also not be collected during the survey due to farmers' failure to document information, or their inconsistency in documenting them.

The socio-economic vulnerability assessment faced the problem of difficulty in measuring how social asset capital influences the farmers' level of vulnerability to the impacts of climate change risks on their livelihoods. In addition, the assessment of farms' management risks was mostly based on farmers' perceptions as management systems to collect daily farm activity data were poor and the information recorded by farmers was inconsistent, especially in terms of farms' environmental aspects.

The farm-based adaptation model assessment in this study was designed based on limited farm information and the scenarios were selected based on information on the government's emissions reduction target in official reports. Due to the climate change risks' data constraints, the climate change risks for the model were estimated indirectly from the ratio of fish feed to the production volume in order to get the information on feed waste discharged in pond and cage aquaculture. The estimation was then used as a proxy for climate change risks to the farm. The use of actual data, such as the temperature or rainfall variation, in adaptation modeling may give different and more accurate results as regards farms' selection of potential adaptation models. In terms of farm allocation of resources indicated from the adaptation model, the estimation of allocation on technology usage can be calculated if information on the prices of acquired technology can be found. This would help indicate a holistic strategy to manage aquaculture farm resources more efficiently and for higher productivity.

This study can be used as a reference for further studies on climate change risks assessment and potential adaptation options in national efforts to manage climate change risks in national aquaculture production and activities as well as in other agriculture sectors. However, the results were only specific for Sarawak and only of general application at the national level. As climate change risks differ due to geography and location, the findings might not explain the exact climate change risks and suitable adaptation strategies for other states in Malaysia, especially those in Peninsular Malaysia. The standard research procedures and methods need to be conducted in other states in order to map the vulnerability level and adaptive capacity of the aquaculture sector in each state and in order to identify the effects of climate change on aquaculture activities in Malaysia as a whole.

6.4 Suggestions for Future Research

This study is limited to Sarawak and future studies may involve similar assessments in the aquaculture sector of other states. This would give a clear picture of the vulnerability level of the national aquaculture production to climate change risks and a more accurate adaptation assessment to cope with climate change risks in the Malaysian context. The whole assessment of vulnerability aspects in aquaculture farms would assist mitigation planning for future climate change risks and aid decision-making on assistance schemes for low asset farmers who are the most vulnerable to the risks. Furthermore, the study could be expanded to other aquaculture cultured species and systems other than ponds and cages.

A future in-depth analysis of biophysical vulnerability can be conducted by including water quality data, diseases and production loss data. The mixed method analysis, combining quantitative and qualitative approaches, can be applied for a thorough biophysical and socio-economic assessment. The socio-economic aspects can be further assessed by indicating household income and consumption patterns, including farm and off-farm income, gender vulnerability aspects due to climate change and the farmers' and household's resilience levels in the face of climate change risks and hazards.

Adaptation aspects can be studied further from different adaptation perspectives. This study has concentrated on the individual farmer's farm-based assessment, which is more related to the autonomous adaptation condition. The institutional and aquaculture stakeholders' adaptation for specific planned adaptation options can also be covered. As the scope of adaptation is wide, assessing and covering the different aspects of adaptation assessment will help develop an understanding of the whole adaptive capacity of the aquaculture sector in Malaysia. Furthermore, future studies can focus on the estimation of mitigation and adaptation cost with the benefits to the sector.

Finally, the hazard assessment can be made more comprehensive by comparing impacts in both 'directions', that is, the effects of the aquaculture sector on climate change risks and the climate change risks' impacts on the aquaculture sector. Back-to-back studies that link the hazards and vulnerability assessment with mitigation and adaptation aspects of the study sector will offer a complete assessment and an important explanation of how these aspects are related and interact with each other. The efficiency and effectiveness of the risk assessment as well as adaptation and mitigation strategy assessment valuation will be important as another area of the study of the economics of climate change. The study of climate change from both scientific and social science perspectives will enrich the findings and further exploration in this area.

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