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Volume 3

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IS POLYCULTURE FORWARD TO A SUSTAINABLE AQUACULTURE SYSTEM? A CASE STUDY IN TAM GIANG - CAU HAI LAGOON, VIETNAM

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Abstract

Tam Giang - Cau Hai (TG-CH) is the largest lagoon ecosystem in Southeast Asia. Shrimp aquaculture in this lagoon has improved livelihoods and alleviated local communities' poverty. However, emerging environmental issues and disease outbreaks have become critical challenges for shrimp farmers in recent decades. While transitioning from shrimp monoculture to polyculture in shrimp aquaculture is considered a trending model toward sustainable development, more evidence of comparative economic analysis and sustainability evaluation must be given. Therefore, by applying the propensity score matching method for original household survey data, this paper evaluates the comparative economic proficiency of two aquaculture models and then measures their sustainability through the Sustainability Index. Results show that shrimp polyculture gains more outstanding features than shrimp monoculture in terms of economic, environmental, and social aspects, mainly thanks to the reduced variable feed cost and lower waste density. Policymakers may refer to supporting instruments to broaden the scale of polyculture to enhance lagoon communities' livelihoods and life quality.

Keywords: *Polyculture, shrimp monoculture, Propensity Score Matching (PSM), Aquaculture Sustainability Index (ASI), Tam Giang - Cau Hai lagoon.*

1. INTRODUCTION

Aquaculture is the world's fastest-growing food production sector and a key driver of growth in the fisheries sector. Over the years, record-capture fisheries and aquaculture production have contributed to global food security (FAO, 2022). For Vietnam, the fisheries sector is now one of the key economic sectors, playing an important role in developing the economy on an ever-expanding scale. Many countries worldwide affirm and receive Vietnam's seafood brand (MOIT, 2022). In 2021, the total seafood production of the country will reach about 8.8 million tons of products, of which aquaculture accounts for 55% (GSO). In addition, aquaculture accounts for about 65% of Vietnam's total seafood export value, with frozen shrimp, mainly black tiger shrimp, accounting for nearly half of the total export value (VASEP, 2022). The Government of Vietnam has targeted developing effective and sustainable aquaculture, proactively adapting to climate change. By 2030, aquaculture production will reach 7.0 million tons/year, creating jobs and raising worker incomes (Government of Vietnam, 2022).

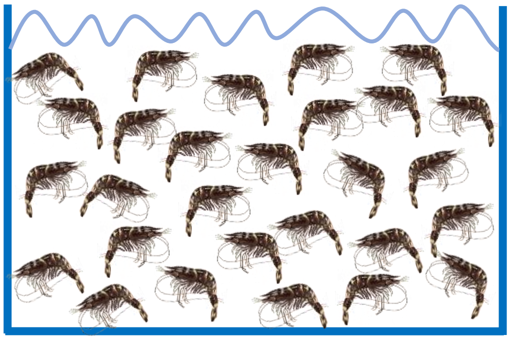
Thua Thien Hue (TTH) is a province in Vietnam's North Central Coast region. Thanks to its long coastline and large lagoon area, the fisheries sector is vital to the province's socio-economic development. While capture fisheries production seems to have reached the production threshold, the aquaculture industry has grown significantly on a production area of 7.7 thousand hectares and an output of 18,442 tons in 2021 (shrimp contribute approximately approx. 38% to total aquaculture production) (GSO). With a water surface area of 21,600 hectares and a length of 70km, TG-CH in Thua Thien Hue (TTH) province is Southeast Asia's largest lagoon ecosystem. Aquaculture in this lagoon is not merely an economic activity; it significantly reduces poverty and improves the quality of life for more than 300,000 people living in and around the lagoon (accounting for about 30% of the province's population) (Ha & Chau, 2016). Nonetheless, these aquaculture activities exert considerable pressure on the TG-CH lagoon system and its natural resources. Environmental pollution and diseases have become enormous challenges that aquaculture has been facing in the past decades.

There are many types of aquaculture methods and systems in the TG-CH lagoon. However, the most popular models include monoculture of Black Tiger shrimp and White-leg shrimp, polyculture, and cage fish farming. Shrimp farming was first introduced to manufacturers and farmers in the 1985s, which has developed and become one of the most profitable industries in this lagoon (Phap et al., 2002; Hirai, 2013; Chi & Yabe, 2014). Shrimp farming areas in the lagoon soared from just 100 ha in 1995 to nearly 4,000 ha in 2004, according to the Fisheries Department of TTH Province. The trigger for this rapid growth was considerable profits in shrimp culture and the uncontrolled privatization of lagoon resources (Truong et al., 2013). Large mangrove areas in TG-CH lagoon, a vital habitat and nursery for many species of marine life, have been cut down by the local people to make room for shrimp aquaculture. Semi-intensive and intensive aquaculture practices have contributed to environmental degradation and contamination from excessive feed, organic waste, and untreated wastewater. 2005 Southeast Asia's largest lagoon ecosystem had environmental, social, and economic disarray (FAO; Fisheries Department of TTH province, 2006; Hieu Truong et al., 2014). The widespread outbreaks of disease in the TG-CH lagoon have resulted in contamination of the environment, which - in turn - has been linked to the rapid growth of shrimp production.

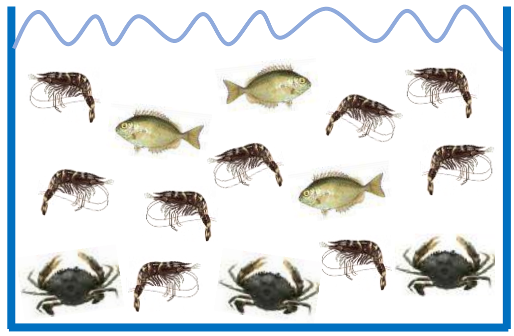
Consequently, the sustainable livelihoods of local people have been dramatically affected. Therefore, there is a need for developing aquaculture towards efficiency and sustainability based on harmonizing the relationship between added value enhancement with quality assurance, food safety, and environmental protection. The conversion of shrimp monoculture into polyculture has been implemented by TTH province's Fisheries Department and Integrated Management of Lagoon Activities Program (IMOLA) since 2004. By 2008, polyculture started as a common practice among farmers in TG-CH lagoon (TTH's Agricultural Extension Center, 2010). The area of polyculture accounted for around 86% of the total aquaculture area in the TG-CH lagoon in 2014 (Fisheries Department of TTH province, 2015). Although shrimp culture in the TG-CH lagoon has seen a thriving contribution to improving the local socio-economic development over the past decades, polyculture is the most popular model in the lagoon nowadays. An important question is what is a sustainable solution for people whose livelihood depends on the TG-CH lagoon.

2. LITERATURE REVIEW

Figure 1. Modelling of shrimp monoculture and polyculture mode



Shrimp monoculture



Polyculture

Polyculture is considered an approach toward sustainable aquaculture in the context of emerging environmental and disease challenges (Medeiros M.V. et al., 2017; Thomas M. et al., 2021; Kim D.-Y. et al., 2022). In the monoculture model, farmers cultivate only one species in their ponds. In contrast, farmers add one or more subordinate species with low density to the culture system of the main species in the polyculture model. These two models differ regarding stocking density, industrial feed utilization, investment level in infrastructure and aquaculture machinery, and environmental impact. Improving water quality and diminution of the environmental impact of effluent discharges are shrimp polyculture's main benefits. Polyculture can minimize farm effluents' environmental impact because some subordinate species can feed on and assimilate most of the wastes generated from shrimp aquaculture (Martinez-Porchas et al., 2010).

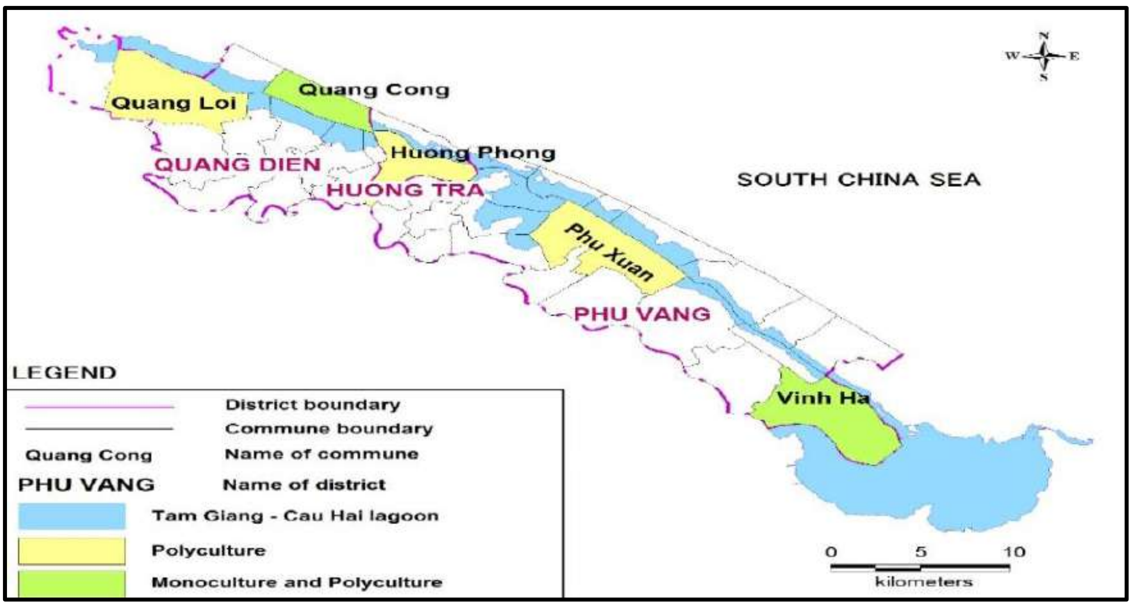
There is extensive previous research evaluating the production performance of aquaculture models with a focus on polyculture and monoculture in the TG-CH lagoon (Phuc & Hung, 2009; Linh, 2010; Au & The, 2013; Chi & Yabe, 2014; Hieu et al., 2020; Minh et al., 2022). A piece of consistent evidence of the polyculture model's economic performance is given in the research scope of a commune or a district (Phuc & Hung, 2009; Binh et al., 2014; Ha, 2022). However, very few researches address the complex issue of sustainability from an economic, environmental, and social point of view. Mac Nhu Binh et al. (2014) reviewed the sustainability of the polyculture model in Phu Vang district, Thua Thien Hue province. However, this study needs to be more comprehensive when it mainly evaluates the environmental aspect (water quality parameters, temperature, salinity, DO, BOD, COD, TDS, NH3...) and economic aspects (average weight, survival, and yield). As economics is always a vital decision-making factor in aquaculture production, this study aims to identify the factors that affect the choice of shrimp aquaculture model and then examine economic changes when farmers transition from shrimp monoculture to polyculture in the TG-CH lagoon. Such information would be critical in ensuring financial viability and enhancing the quality of life for farmers and society. In addition, to fill the research gap and further contribute to the development of a set of criteria for assessing sustainability in aquaculture in Vietnam, this study evaluates and compares the sustainability of shrimp monoculture and polyculture based on sustainability assessment criteria in aquaculture, thereby finding opportunities and challenges in the sustainable development of aquaculture in TG-CH lagoon. It is important to find out how sustainable the aquaculture model is and what challenges it faces. Considering a sustainable development perspective for assessing the effect of the aquaculture model, that is, the connections and interactions between the economic, environmental, and social dimensions. The research results will reflect the level of sustainability in aquaculture in the TG-CH lagoon and provide scientific evidence for policymakers to find strategies for sustainable aquaculture development in the TG-CH lagoon system.

3. METHODOLOGY

3.1. Data collection

The research was carried out on 5 communes in TG-CH lagoon with large aquaculture areas in polyculture and monoculture. 113 farms applying polyculture model and 67 shrimp monoculture farms were interviewed face-to-face through questionnaires. They contain detailed information on various aspects of aquaculture farming, such as farmers' demographic and production characteristics, production costs, production revenues, difficulties, and challenges in the sector. Economic performance from two aquaculture models is calculated in the main crop 2018 (3 months from February to May for monoculture and 4-5 months for polyculture).

Figure 2. Survey sites in Tam Giang - Cau Hai



3.2. Data analysis

3.2.1. Propensity Score Matching (PSM)

Propensity Score Matching (PSM) was used to evaluate the economic impact of aquaculture model transformation from shrimp monoculture to polyculture. Let T be an indicator variable denoting the treatment received (T = 0 for control group - shrimp monoculture farm and T = 1 for treatment group - polyculture farm). The potential outcomes (income) are defined as Yi(Ti) for each farm i. If one could observe the income of farm i with both polyculture participation and non-participation, then the change in the income of farmer i would be Yi(1) –

Yi(0). The Average Treatment Effect (ATE) is defined to be: **ATE = E[Yi(1) – Yi(0)]**. This estimation is ideal when we can compare the income of a farm when polyculture model is applied to when it is not applied. Nonetheless, each farmer only has one outcome of observing: the outcome under the actual treatment received. For a farm that applies polyculture model, we observe Yi(1); thus Yi(0) is an unobserved outcome (counterfactual outcome). To solve the missing-data problem, counterfactual outcomes are constructed using control group (shrimp monoculture farms) through the PSM method. The propensity score in our case is defined as the conditional probability of polyculture participation given its observed variables X (called covariates), that is, **Prob (Polyculture = 1) = F (X, α)**

In which:

+ Polyculture = binary variable equal to 1 when the respondent has participated in the polyculture model and 0 otherwise;

+ X = set of individual variables, including gender, age, educational background, cultivation experience, production areas, salinity, attended training course;

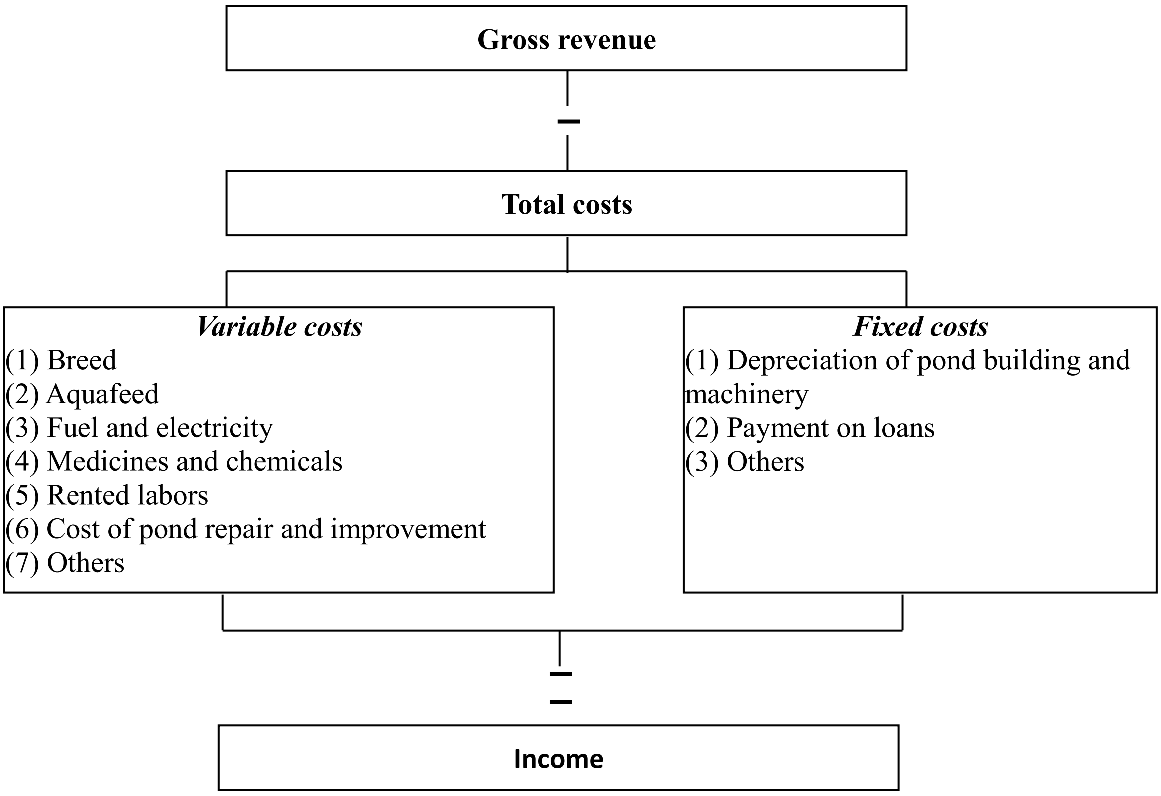
+ α = parameter typically estimated by maximum likelihood.

The probit model aims to calculate the propensity score based on the likelihood of the association of some observed individual factors (variables X) with the probability of polyculture model participation. The similarity in observed individual characteristics (common support) is the basis for matching. Formally, one needs to check if P(X |T= 1) = P(X |T= 0). A related measure of treatment effect is the Average Treatment Effect on the Treated (ATT), defined as: **ATT = E [Y(1) – Y(0)|T = 1] = E[Y(1)|T = 1] – E[Y(0)|T = 1]**

There are some different matching algorithms used to estimate the ATT. Different matching criteria can be used to assign participants to non-participants based on the propensity score. In this study, Nearest-neighbor (NN) matching is the estimator used.

The essential elements of economic performance are briefly defined in Figure 3.

Figure 3. Economic performance indicators



3.2.2. Aquaculture Sustainability Index (ASI)

Figure 4. Sustainable development

The term “sustainable development” emerged in 1987, appearing for the first time in the Brundtland Report. Sustainable development means (1) Development that meets the needs of the present, without compromising the ability of future generations to meet their own needs (2) Working towards a safe and stable future for people and the planet, now and in the future (3) Thinking about economic, social and environmental conditions. These three cannot exist separately from each other. They are harmonious and interconnected. The three pillars supporting sustainability are satisfying economic viability, social fairness, and environmental conservation.

United Nations Conference on Environment and Development in Rio de Janeiro in June 1992 recognized the critical role of indicators in helping countries make informed decisions regarding sustainable development. The United Nations Sustainable Development Commission released three editions of "Sustainable Development Indicators" in 1996, 2001, and 2007. In this context, some studies worldwide have developed a set of indicators to assess sustainability for the aquaculture sector in general from an economic, environmental, and social perspective (Fischer & Larsen, 2006; P. Trujillo, 2007; Valenti, W.C. et al., 2011; Fezzardi D. et al., 2013; K.-H. Ting, 2014; Valenti, W.C. et al., 2018). Some studies in Vietnam have also proposed a system of criteria to evaluate the sustainable development of aquaculture (Boi & Tem, 2013; Thao & Tung, 2020). Economic sustainability indicators reflect the efficiency level in using financial resources, economic feasibility, and ability to generate capital for reinvestment. Environmental sustainability indicators measure natural resource use and its efficiency, pollutant emissions, and the risk of biodiversity loss. Social sustainability indicators show the ability to generate benefits for local communities, including employment and food security, equitable income distribution, equality of opportunity, and inclusion of vulnerable populations. The sustainability index in this study has been imitated by Aquaculture Sustainability Index (ASI) from Pablo Trujillo (2007). In addition, the criteria have rebuilt to suit the actual situation in the lagoon, based on two important references are:

(1) Circular No. 45/2010/TT-BNNPTNT dated July 22, 2010 of the Ministry of Agriculture and Rural Development on regulations on base conditions, intensive farming zones of Penaeus monodon (Black Tiger shrimp) and Litopenaeus vannamei (White-leg shrimp), ensure hygiene and food safety.

(2) Circular No. 22/2014/TT-BNNPTNT dated July 29, 2014 of the Ministry of Agriculture and Rural Development on National technical regulation of Vietnam on brackish water shrimp culture farm - Conditions for veterinary hygiene, environmental protection and food safety.

In addition, discussions and consultations with experts from the Fisheries Branch and Agricultural Extension Centre of TTH province were carried out to determine the suitability of the proposed sustainability criteria with the general theory and geographical location.

The Aquaculture Sustainability Index provides an overview of how to assess the sustainability of aquaculture models. This study has provided Environmental, Social, and Economic Sustainability Indicators with 15 criteria, of which five are economic, four are social, and six are environmental aspects (see Table A, B, C in Appendix). The criteria with the highest score have the most increased sustainability.

After evaluating and scoring for each criterion, the mean value of each criterion in the indicator is calculated according to the following formula:

$$Sd_i = \frac{\sum_{i=1}^{n} w_i \times n_i}{n}$$

In which:

Sd_i: The value of criteria;

i: The *i*-th case;

w_i: Score of the *i*-th case;

n_i: Number of cases corresponds to wi;

n: The number of survey sample.

The value of indicators (environmental, social and economic) is average calculated according to the score of criteria are in each indicator.

$$Md_j = \frac{\sum_{i=1}^{n'} Sd_i}{n'}$$

In which:

Md_j: The value of indicators according to the corresponding criteria;

n': Number of criteria included in each indicator.

Aquaculture Sustainability Index is calculated by applying the following formula:

$$ASI = \frac{\sum_{j=1}^{3} Md_j}{3}$$

4. RESULTS

4.1. Average treatment effect of aquaculture model transformation from monoculture to polyculture on the economic efficiency

The probability that farmers would be involved in the polyculture model can be estimated based on observed factors. Related variables and their definitions are illustrated in Table 1.

Table 1. Definition of variables

Variables		**Definition**
Demographic characteristics	Gender	= 1 if household head is male and 2 for female
	Age	Age of household head
Educational background	Education	Years of household head's school attendance
Production factors	Area	Production area (hectares)
	Salinity	= 1 if the salinity from 0.5‰ to 5‰ = 2 for 5‰ - 10‰ = 3 for 10‰ - 15‰ = 4 for 15‰ - 20‰
	Experience	Experience of farmer in aquaculture
	Training course	= 3: farmer has participated > 80% training courses. = 2 for 40 – 80%.

Variables		Definition
		= 1 for < 40%.
Polyculture participation	Polyculture	= 1 if respondent has participated in polyculture model, 0 otherwise
Economic performance indicator	Income	Income of the main crop per hectare (million VND) in 2018.

Demographic characteristics describe the gender and age of the household head; years of school attendance measure educational background. Natural resources (production area, salinity of water) and human resources (experience, training course participation of household head) belong to the production factors. To some extent, production factors are essential in choosing an aquaculture model.

Table 2 shows the descriptive statistics on the key factors affecting farmers' behavior in choosing an aquaculture model between polyculture (113 farms) and monoculture (67 farms). As can be seen from the mean value, polyculture farmers have achieved a higher education level, larger production areas, more extended cultivation experience, and total attendance in training courses than those of the monoculture group. However, water salinity in the polyculture model tends to be smaller than in the monoculture.

Table 2. Statistical description of farmer's individual characteristics

Variables	**Polyculture**				**Monoculture**			
	Mean	**Standard Deviation**	**Min**	**Max**	**Mean**	**Standard Deviation**	**Min**	**Max**
1. Gender	1.089	0.285	1	2	1.105	0.308	1	2
2. Age	51.735	9.370	25	70	50.328	8.684	32	67
3. Education	7.257	3.303	0	12	6.269	2.453	0	11
4. Area	1.064	0.678	0.38	3.5	0.803	0.599	0.36	3.5
5. Salinity	2.044	0.849	1	3	2.448	0.558	1	3
6. Experience	16.080	4.627	8	37	13.702	2.474	5	19
7. Training course participation	2.372	0.734	1	3	2.060	0.649	1	3
No. of observations	***113***				***67***			

Source: Authors' calculation based on survey data, 2018

The statistical description of economic performance is summarized in Table 3. Despite having significantly lower gross revenue, polyculture has dramatically lower variable costs than the monoculture model. One noticeable point is that polyculture has an enormously lower feed cost than monoculture. Apart from the higher breed cost due to many different species in the polyculture model, the remaining variable costs were slightly lower than monoculture.

Table 3. Statistical description of the economic performance of polyculture and monoculture groups

(Unit: million VND/ha)

Variables	**Polyculture**				**Monoculture**			
	Mean	**Standard Deviation**	**Min**	**Max**	**Mean**	**Standard Deviation**	**Min**	**Max**
1. Gross revenue	119.741	43.003	31.52	275	154.373	79.341	5.04	369.444
2. Fixed cost	10.076	7.323	1.743	47.312	9.26	5.014	2.067	27.64
3. Variable costs	81.285	31.496	28	195.833	124.66	34.539	50.474	211.111
Breed	13.804	5.628	5.5	30	6.504	0.943	2.743	8.889
Aquafeed	47.646	21.361	10	133.33	91.279	27.868	36.842	161.111
Fuel	3.985	2.036	0.769	12.5	4.942	2.179	1.5	9.722
Chemical	4.793	2.963	1.143	20	8.237	4.8	1.429	30
Rented labor	0.212	1.03	0	6.571	0.375	1.783	0	12.857
Improvement & Repair	10.789	6.075	2.273	28	13.323	5.125	2.963	27.778
Others	0.056	0.385	0	3.5	0	0	0	0
4. Income	28.380	21.545	-68.435	83.179	20.453	64.248	-99.049	189.315
No. of observations	***113***				***67***			

Source: Authors' calculation based on survey data, 2018

The probit estimation of the propensity scores is presented in Table 4 with outputs from the STATA 14.2 software. R-squared indicated that the exogenous variables explained 17.9% of the endogenous variable (polyculture model participation). The positive coefficient of variables means that an increase in these variables leads to a rise in the projected probability of polyculture model participation and vice versa. Except for gender, age, and area, the four variables of education, salinity, experience, and training course participation are statistically significant. Education and experience are tremendously significant at the 1% level. An increased educational level of farmers resulted in a 13.1% increase in involvement in the polyculture model. Results also showed that the farmers with more experience have a 14.8% higher probability of engaging in polyculture than farmers with less experience. The salinity of water and training course participation rate also play an essential role in participation decisions. Low salinity has a 40.5% higher probability of joining the polyculture than high salinity. The farmer who attends more training courses has a 37.5% higher likelihood of participating in the polyculture. The statistical insignificance of gender, age, and area may be explained by the fact that there is no noticeable difference in these variables between the two groups. In short, participation in the polyculture model is more relevant to farmers with a higher education background, longer experience, higher training course attendance, and lower water salinity in TG-CH lagoon.

Table 4. Factors associated with the probability of polyculture participation

Factors	Probability of polyculture participation	
	Coefficient	**Standard Error**
1. Gender	-0.035	0.356
2. Age	0.010	0.014
3. Education	0.131***	0.041
4. Area	-0.111	0.206
5. Salinity	-0.405**	0.157
6. Experience	0.148***	0.048
7. Training course participation	0.375**	0.151
Pseudo R^2	0.179	
No. of observations	***180***	

Source: Authors' calculation based on survey data, 2018

This research aimed to explore whether there was any significant difference in the economic performance between the treatment group (polyculture) and the control group (monoculture). The balancing test of the individual variables before and after matching is represented in Table 5. The result by using a t-test shows that before matching, there were statistically significant differences in the education, area, salinity, experience, and training course participation at the 5% and 1% levels, respectively, between polyculture farmers and monoculture farmers.

Table 5. Balancing test

Variables	Parameters	Before Matching	After Nearest Neighbor Matching
Gender	Mean (treated)	1.089	1.089
	Mean (controls)	1.105	1.044
	t-test (P-value)	0.725	0.183
Age	Mean (treated)	51.735	51.735
	Mean (controls)	50.328	53.805
	t-test (P-value)	0.319	0.125
Education	Mean (treated)	7.257	7.257
	Mean (controls)	6.269	6.947
	t-test (P-value)	0.035**	0.389
Area	Mean (treated)	1.064	1.064
	Mean (controls)	0.803	1.186
	t-test (P-value)	0.009***	0.234
Salinity	Mean (treated)	2.044	2.044
	Mean (controls)	2.448	2.212
	t-test (P-value)	0.000***	0.062
Experience	Mean (treated)	16.080	16.080
	Mean (controls)	13.702	15.903
	t-test (P-value)	0.000***	0.729
Training course participation	Mean (treated)	2.372	2.372
	Mean (controls)	2.060	2.212
	t-test (P-value)	0.005***	0.062

*(Note. ***, ** Significant at the 1% and 5% levels from the t-test, respectively)*

Source: Authors' calculation based on survey data, 2018

After matching, however, the balance of the variables is dramatically improved, and no significant differences in individual variables mean for the two groups are found in the Nearest Neighbour Matching method. Therefore, the bias selection could be ultimately eliminated from this process. Accordingly, the measurement of the causal effect of the transformation model on economic performance could be obtained more precisely.

The question of what has been happening to income when farmers change from shrimp monoculture to polyculture is of great interest to policymakers. To deal properly with this, it is crucial to evaluate the treatment effects of the transformation policy. This means that the objective is to determine the average treatment effect of the polyculture model participation on the economic indicators of farmers. Table 6 simultaneously shows the significant impact of polyculture on economic efficiency with statistical significance at the 1% level. Average Treatment Effect on the Treated (ATT) is calculated by Nearest Neighbor Matching algorithm, which showed that the gross revenue of polyculture was slightly higher than that of monoculture.

The income increased by 26.995 million VND/ha when farmers transferred from monoculture to polyculture, mainly because of the 24.486 million VND/ha decrease in variable costs. Phuc. N. T. also pointed out that compared with the shrimp monoculture model, the value-added from the polyculture model is about 36% higher in Quang Dien district (Phuc & Hung, 2009). It should be noted that the feed cost decrease contributed significantly to cost-reducing. In the case of polyculture, with shrimp as the main species, fish and crabs are subordinate species. Fish can eat excess feed from shrimp, and most of the waste is generated from shrimp. Some fish can also use natural feed sources such as organic mulch, seaweed, and moss. Crabs can eat small crustaceans in ponds and dead shrimp. Besides using natural and synthetic feed, polyculture farmers also used trash fish at a low price to reduce the feed cost.

Table 6. Average effect of farmer's participation in polyculture model on the economic efficiency

(Unit: million VND/ha)

ATT	*Nearest Neighbor Matching*		
	Mean (treated)	**Mean (controls)**	**Difference**
1. Gross revenue	119.741	115.212	4.529
2. Fixed cost	10.076	8.055	2.021***
3. Variable costs	81.285	105.771	-24.486***
Breed	13.804	6.181	7.623***
Aquafeed	47.646	74.655	-27.009***
Fuel	3.986	3.535	0.451
Chemical	4.793	7.182	-2.389***
Rented labor	0.212	1.167	-0.955***
Improvement & Repair	10.789	13.051	-2.262***
Others	0.056	0	0.056
4. Income	28.380	1.385	26.995***

*(Note. *** Significant at the 1% levels from the t-test)*

Source: Authors' calculation based on survey data, 2018

4.2. The sustainability of aquaculture models

ASI results represented that the polyculture and monoculture model scores were 2.609 and 2.3, respectively, considerably lower than the highest value by convention (3.442). It can be generally seen that difficulties facing aquaculture in the TG-CH lagoon have become apparent in recent times, where the destruction of the environment is one of the prime concerns regarding aquaculture. The data in Table 7 describes that the environmental indicator witnesses the lowest score with 2.299 and 1.949 for polyculture and monoculture, compared with the highest value by convention (3.667). Compared with monoculture, polyculture is considered a more sustainable model for the TG-CH lagoon system when the social, economic, and environmental indicators of the polyculture group are higher than those of the monoculture group.

Table 7. ASI for polyculture and monoculture model

Indicators	**Calculated value**		**The smallest value by convention**	**The largest value by convention**
	Poly	Mono		
Environmental	2.299	1.949	1	3.667
Social	2.684	2.554	1	3.458
Economic	2.844	2.397	1	3.200
ASI	**2.609**	**2.300**	**1**	**3.442**

Table 8. Environmental, Social and Economic Sustainability Index

Indicators		Calculated value		Minimum value by convention	Maximum value by convention	t-test (P value)
		Polyculture	Monoculture			
1. The origin of aquatic animal seeding		2.168	2.955	1	3	0.000
2. Number of aquatic species		2.956	1	1	3	0.000
3. Types of aquafeed		3.363	2.925	1	5	0.000
4. Aquacultural system		2.876	1.119	1	4	0.000
5. The water supply and sewerage systems		1.159	1.896	1	3	0.000
6. Quality water control		1.274	1.799	1	4	0.000
1. Academic level	Educational background	2.858	2.612	1	5	0.043
	Cultivation experience	3.372	3.045	1	4	0.031
2. Use of chemical products		2.487	2.299	1	3	0.013
3. The right to use water surface		3.000	3.000	1	3	0.199
4. Human resource development	Attendance rate of training course	2.372	2.060	1	3	0.005
	Training effectiveness	2.106	2.090	1	3	0.845
	Practical application of trained techniques	1.920	2.119	1	4	0.015
1. Stability of output markets		3.805	3.925	1	4	0.029
2. The contribution of aquaculture to local livelihoods		2.823	2.761	1	3	0.051
3. Diversity of aquatic species		2.956	1	1	3	0.000
4. Record aquaculture diary		1.221	1.313	1	2	0.172
5. Mortality rates in aquaculture		3.416	2.985	1	4	0.017

Detailed scoring of each criterion in ASI is described in Table 8. Regarding social indicators, most criteria showed that the polyculture model has higher scores than the monoculture model, except for the application level of training techniques. Many polyculture farmers suppose applying techniques that follow the guiding process will be costly and unnecessary. Furthermore, many considered that the instructor in many training sessions needed to be more knowledgeable about the actual conditions of aquaculture in the TG-CH lagoon. The difference in training effectiveness and the right-to-use water surface between the two models was not statistically significant.

As for economic indicators, 3 out of 5 indicators show that the polyculture model has a higher sustainability score than the monoculture model. In particular, the diversity of aquatic species in the polyculture model has a score close to the maximum sustainable value according to the convention. In addition, the low mortality rates of the polyculture model resulted in a more economically sustainable score than the shrimp monoculture model. However, the stability of the output market and the record aquaculture diary are two criteria that the polyculture model has a lower sustainability score than the monoculture model. A smaller score in the stability of output markets comes from the characteristic of the polyculture model. Firstly, low densities of species mean low yields per unit area. Therefore, many polyculture farmers bring their products to small businesses in the local market instead of local traders coming to their ponds. Furthermore, different species have different harvest times, and the size of aquatic species usually deviates. The cull harvesting method of the polyculture model leads to difficulty in recording and cost accounting, but the difference in this indicator between the two models is not statistically significant.

According to the local authorities, reducing the burden on the TG-CH lagoon environment is an outstanding feature of the polyculture model. The ASI result indicated that 3 out of 6 environmental indicators of polyculture model are markedly higher than those of monoculture group. Regarding the sustainability of aquafeed, in addition to using industrial feeds, polyculture farmers take advantage of mainly natural food sources, which has brought high sustainability to the model. However, a few polyculture farmers use trash fish with good quality, and there is still a risk of environmental pollution in the long run (according to the research results of Phuc & Hung, 2009). Regarding the aquacultural system, most polyculture farmers apply improved extensive farming methods with low stocking density and little use of industrial feed to be more sustainable than monoculture.

Looking at the water supply and sewerage system, 32 out of 67 monoculture farmers (located in Quang Cong commune) have both settling pond and sedimentation ponds for input and output water, whereas only 8 out of 113 polyculture farmers have settling or sedimentation ponds. This is the reason why the score of monoculture group was moderately higher than the score of polyculture group. The infrastructure system of Quang Cong commune is relatively assurance for the development of shrimp production. The infrastructure includes settling ponds for input water, sedimentation ponds for output water, sewerage, substation, pumping station, power lines, etc. In the period of 5 years (2003-2008), this region was managed by Aquaculture Development Joint Stock Company in TTH province. Due to ineffective business, this area has been handed over to the farmers since 2009. Even though many farmers argue that with low density and small feeding amount compared with monoculture, polyculture model does not need the settling pond and sedimentation pond. Nonetheless, it is difficult to find any regulations related to national or local technical conditions of infrastructure systems in the polyculture model. As previously mentioned, the widespread species in polyculture model include Black Tiger shrimp, crab, and fish. Whereas shrimp and crabs have artificially produced seed, most fish (Siganus Guttatus, Siganus Canaliculatus, Scatophagus Argus, etc.) depend on nature. The lack of hatchery-produced breed supply of various farmed fish species explains why the score of stability of commercial seed market is lower in polyculture group. Lower scores on water quality control indicators show that polyculture farmers pay less attention to water quality parameters in ponds than monoculture farmers. The leading cause may stem from low density and low-risk characteristics. Meanwhile, the monoculture model is high in density and prone to significant risks, so monoculture farmers tend to control water quality regularly to handle when abnormal signs occur.

5. CONCLUSION

This study used PSM method to evaluate the impact of aquaculture model transformation from shrimp monoculture to polyculture on economic performance. Overall, the results indicate that polyculture significantly differs in variable costs compared to monoculture. Polyculture farms tend to have higher breed costs due to many different species in the model, but the remaining costs were lower than monoculture, with a noticeable point in feed cost. Therefore, the income increases by 26.995 million VND/ha when farmers transfer the model from shrimp monoculture to polyculture; the main reason is that the variable cost decreases by 24.486 million VND/ha. This result could support the explanation for why the polyculture area has dramatically increased in recent years.

The aquaculture Sustainability Index (ASI) focuses on three vital dimensions: economic, social, and environmental- and is used to determine the sustainability of these two models in the TG-CH lagoon. The ASI result represents that the scores of the polyculture and monoculture models are 2.609 and 2.3, respectively, considerably lower than the highest sustainable value by convention (3.442). Three indicators of polyculture group's economic, social, and environmental are higher than the monoculture group. It means that in comparison with monoculture, polyculture is considered a more sustainable and suitable model for the TG-CH lagoon system. The data describes that the environmental indicator has the lowest scores, with 2.299 and 1.949 for polyculture and monoculture, compared with the highest value by convention (3.667). Low density and utilization of natural feed and waste from species help significantly reduce the variable costs and environmental pollution, which are the main advantages of the polyculture model. This result is similar to the study of Huong et al., from the system of indicators to measure sustainable livelihoods based on four groups of economic, social, environmental, and institutional and policy criteria; this study has shown that polyculture is the model with the best ability to develop sustainable livelihoods compared to the intensive farming and cage fish model.

According to the local authority, polyculture could be the way towards sustainability in aquaculture. These findings can be concluded that polyculture is considered an ideal model for sustainable development in the TG-CH lagoon system in the context of a lack of infrastructure investment, a declining salinity level, and an increased risk of environmental incidents. Utilizing natural feed and waste from species helps significantly reduce the variable costs, a significant advantage of the polyculture model. Therefore, this study is a basis for policymakers to make incentive policies for shrimp polyculture in the TG-CH lagoon.

6. SUPPLEMENT LIMITATION

The present findings must be interpreted in the context of some potential limitations. One of those is that data on economic performance was collected for 2018. However, there is a need to determine whether the income is eroded over time.

Furthermore, different matching algorithms can be used to estimate the Average Treatment Effect on the Treated (Nearest Neighbor Matching, Caliper and Radius matching, Kernel matching, etc.). Although each method has its strengths and limitations, using more matching methods has the advantage of testing the robustness of the effect estimates.

In addition, it will be better if there is a balance between the number of observations in the control and treatment groups.

Despite its limitations, the treatment evaluation using the PSM method is helpful for strategically planning the aquaculture development in TG-CH lagoon. Most importantly, the above limitations can be overcome in future intensive studies. To the best of my knowledge, this study is the first contribution to the literature regarding Aquaculture Sustainability Index (ASI) in Tam Giang - Cau Hai lagoon. To improve the ASI, it is necessary to add some environmental indicators such as stocking density, Feed Conversion Ratio, types of chemicals used in aquaculture, etc.

Appendix

Description environnemental indicator

Table A. Environnemental Indicator

Environmental indicator	Description of the criteria	Interpret the criteria and scoring system	Source
1. The origin of aquatic animal seeding	Aquatic seeds have clear origins and verification will bring sustainability.	= 3 if farmer buy seed from hatcheries = 2 if farmer buy from hatcheries and caught from nature = 1 if farmer get seed from caught	Pablo Trujillo (2007) Boi & Tem (2013) Thao & Tung (2020)
2. Number of aquatic species	Some species can feed on excess organic matter and assimilate most of the wastes generated from shrimp aquaculture. Therefore, adding subordinate species to co-culture with shrimps can improve water quality and minimize the environmental impact of effluent discharges.	= 3: 3 or more aquatic species = 2: 2 aquatic species = 1: 1 aquatic species	Pablo Trujillo (2007) Valenti, W.C. et al. (2018)
3. Types of aquafeed	Natural foods for herbivorous species (such as filter feeders) have the highest sustainability. In addition, industrial feeds on the list of feeds allowed to be circulated in Vietnam, with full labels, are also sustainable. However, using poor-quality fresh food (trash fish) can pollute the water source in the farming area or increase the risk of disease.	= 5: Natural feed = 4: Natural feed combine with synthetic feed. = 3: Synthetic feed. = 2: Natural feed combine with synthetic feed and trash fish. = 1: Trash fish.	Pablo Trujillo (2007) Boi & Tem (2013) Thao & Tung (2020)
4. Agricultural system	The reasonable density of aquatic species on a water surface area and the promotion of the natural feed chain will ensure the sustainability of aquaculture models. Extensive farming based entirely on natural feed in ponds with low stocking	= 4: Extensive farming = 3: Improved extensive farming = 2: Semi-intensive farming = 1: Intensive farming	Pablo Trujillo (2007) Valenti, W.C. et al. (2018)

Environmental indicator	Description of the criteria	Interpret the criteria and scoring system	Source
	densities is the most ecologically sustainable aquacultural system.		
5. The water supply and sewerage systems	Owning settling ponds to ensure input water quality and sedimentation ponds to improve discharged water quality have the highest sustainability. In contrast, discharging all of the wastewater to the lagoon without previous treatment can cause environmental contamination of the receiving ecosystems and then taking input water without treatment leads to disease risks.	= 3: Having both of settling pond and sedimentation pond for input and output water. = 2: Having settling pond for input water or sedimentation pond for output water. = 1: Not having settling pond and sedimentation pond.	Pablo Trujillo (2007) Circular No. 45/2010 and No. 22/2014 of the Ministry of Agriculture and Rural Development
6. Quality water control	Farmers' knowledge of technical standards related to water quality control and pond bottom management is essential for sustainable aquaculture development. Check daily for indicators: Dissolved oxygen (DO), pH, salinity, transparency, and temperature and every 3-5 days for indicators: Alkalinity, NH3, and H2S to ensure a favorable pond environment is essential.	(i) DO, water temperature, salinity, pH, transparency = 1: No check = 2: Checking only when needed = 3: 1 time/day = 4: 2 times/day (ii) Alkalinity, H_2S, NH_3 =1: No check = 2: Checking only when needed = 3: 1 time/week = 4: 2 times/week	Circular No. 45/2010 and No. 22/2014 of the Ministry of Agriculture and Rural Development

Description social indicator

Table B. Social indicator

Social indicator	Description of the criteria	Interpret the criteria and scoring system	Source
1. Labor quality	For this criteria, experience and education are combined to assess. Household heads with higher education levels are more likely to be highly aware of ensuring technical standards in culturing and able to apply well-trained knowledge and skills than those with lower levels of education or no education at all. Long-term experience helps the household head have the ability to respond flexibly to incidents.	+ Educational background = 5 for university/college or higher = 4 for high school = 3 for secondary school = 2 for primary school = 1 if farmer has no schooling + Cultivation experience = 4 if cultivation experience is > 15 years = 3 for 10 – 15 years = 2 for 5 – 10 years = 1 for < 5 year	Boi & Tem (2013) Thao & Tung (2020)
2. Use of chemical products	The use of drugs and other chemicals in ways that ensure the safety of treated animals, end-users, consumers and the environment increase the sustainability of aquaculture activity.	= 3: The use of chemicals is followed national technical regulation and local authorities recommend. = 2: Combined your own experience with advice from extension officers. = 1: The improper use of chemical and the use of banned chemicals that cause harm to human health is the most unsustainability case.	Pablo Trujillo (2007) Boi & Tem (2013) Thao & Tung (2020)
3. The right to use water surface	Social fairness affects the sustainability of aquaculture systems. Aquaculture with permits is considered the most sustainable because it is located in a planned area by the local government, which means it has enough	= 3: Shrimp ponds located in the planned area (have a permit) = 2 if farmers have the ponds in the planned and unplanned areas. = 1: Do not have permission (development of	Boi & Tem (2013) Thao & Tung (2020)

	conditions for water sources and infrastructure.	shrimp farming is spontaneous).	
4. Human resource development	Labourers participating in aquaculture activities are trained on food safety and environmental protection; guiding how to preserve and use food, drugs, microorganisms, biological products, chemicals, and environmental remediation substances will improve the quality of labour resources. The high rate of participation in training, high appreciation of the effectiveness of the training courses, and applying the trained knowledge in practice will enhance the sustainability of aquaculture activities.	**+ Participation rates** = 3 if farmer has been participating > 80% the training course. = 2 for 40 – 80%. = 1 for < 40%.	Boi & Tem (2013) Thao & Tung (2020) Valenti, W.C. et al. (2018)
		+ Training effectiveness = 3 if the training effectiveness is evaluated high quality. = 2 for average level. = 1 for ineffective training.	Boi & Tem (2013)
		+ Practical applications of trained techniques = 4: Apply most techniques (> 80%) = 3: Apply some techniques (40 – 80%) = 2: Apply a few techniques (< 40%) = 1: No application (0%)	Proposal of the author team

Description economic indicator

Table C. Economic indicator

Economic indicator	Description of the criteria	Interpret the criteria and scoring system	Source
1. Stability of output markets	Stable output markets contribute to sustainable livelihoods and aquaculture development	= 4: Sell to the local traders in their pond (stable output markets) = 3: Sell to the small business in the local market. = 2: Sell to restaurants, hotel. = 1: Sell your aquaculture products in the local market by yourself (unstable output markets)	Pablo Trujillo (2007) Boi & Tem (2013) Thao & Tung (2020)

Economic indicator	Description of the criteria	Interpret the criteria and scoring system	Source
2. The contribution of aquaculture to local livelihoods	The higher the contribution rate of aquaculture activities to people's livelihood, the more sustainable farming activities are.	= 3 if contribution rate of aquaculture > 80 % of the total income = 2 for 40 – 80% = 1 for < 40%	Pablo Trujillo (2007) Boi & Tem (2013) Thao & Tung (2020)
3. Diversity of aquatic species	Different species cultured together in the same pond help optimize the water area and reduce feed and pond water treatment costs because some species can feed on excess organic matter and assimilate most of the wastes generated from shrimp aquaculture. In addition, diversification allows farmers to produce other species with commercial value and increase their farms' economic performance with little or no financial investment because most of the costs have already been met.	= 3: 3 or more aquatic species = 2: 2 aquatic species = 1: 1 aquatic species	Valenti, W.C. et al. (2018)
4. Record aquaculture diary	Farmers who record revenues and expenditures can estimate reasonable costs and increase input use efficiency. In addition, keeping a diary helps farmers to monitor and deal with epidemics actively.	= 1: No = 2: Yes	Proposal of the author team
5. Mortality rates in aquaculture	The higher the mortality rate of aquatic products, the lower the yield will be, affecting the revenue and profit of aquaculture households.	= 4: < 20% = 3: 20 – 40% = 2: 41 – 80% = 1: > 80%	Proposal of the author team

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