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**REGIONAL ECONOMIC PLANNING
OF SHRIMP AQUACULTURE IN MEXICO**

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Para María Fernanda, porque aún en la distancia, siempre me permitiste vivir en tí hija,
siempre tan llena de amor.

Para mi madre, porque todo tu esfuerzo y carácter, que es a la vez de mi abuelo, se
plasma en cada uno de mis logros. Gracias por la lección de amor y vida.

A la memoria de mi abuelo, su ejemplo y guía

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ABSTRACT

Aquaculture plays a critical role in alleviating demand pressures caused by increasing fish consumption and over-exploitation of fishery stocks. While aquatic foods are generally considered low-revenue generators in comparison to other protein-sources, aquaculture products help to support food security, income, and higher standards of living, particularly in developing countries.

Decision makers, i.e. policy-makers and farmers, are challenged with the responsibility of planning and conducting aquaculture development in a sustainable way whereby social, environmental and economic goals are simultaneously satisfied. Existing studies that economically evaluate the industry for its current and historical performance, and future development scenarios are invaluable to sustainable planning, but have not been developed in Mexico. This dissertation is comprised of two essays applying Economics and Operations Research theory to regional economic planning for the sustainable development of shrimp farming in northwest Mexico. The analyses are carried out both at the micro (farm) and macro (industry planning and development) levels based on an unbalanced panel of shrimp semi-intensive farms containing primary-source information at pond level for the period 1994, 1996-1998.

Using an input distance function approach, the first essay examines total factor productivity (TFP) and technical efficiency (TE) using both traditional (T) and environmentally-adjusted (EA) indicators. The reduction in TFP was determined to be due to a technological regression as reflected by increased input-intensive production technology resulting in an increase in undesirable outputs. The learning curve resulting from a shift from white shrimp to blue shrimp production species resulted in higher FCRs, water exchange and pollution emissions, despite increasing shrimp yields. In all years except 1994, EA TE and EA TFP were lower than the traditional TE and TFP scores. TE and TFP had an opposite behavior than yields in this period of time. In order to improve the technological change (TC) component of TFP in light of stable TE scores, increased government assistance in disseminating technological know-how is necessary to improve TFP at a faster rate during the transition period. A sensitivity analysis also revealed the economic feasibility of the implementation of pollution abatement technology based on the calculated shadow price of N and P pollutants at USD \$6.35/kg and \$8.3/kg respectively.

In the second essay, a multi-criteria decision making (MCDM) model was developed to evaluate the sustainable development of shrimp farming in the northwest region of Mexico (States of Sonora, Sinaloa and Nayarit) based on government objectives for aquaculture development in Mexico. Three possible production systems among two species were investigated. The optimal combination of new shrimp farms within 22,500 ha over a five-year period is determined. The planning objectives assumed in the MCDM model are maximization of employment (E), foreign exchange earnings (XG), and economic rent (ER), and total pollution (TOTALPOLL) minimization, subject to land availability and local market demand constraints. Under a preliminary evaluation of single-objective optimization, XG and ER maximization produce similar results: USD\$ 888.6 and \$322.5 million in foreign exchange earnings and economic rent respectively, and the creation of 6,150 jobs. The MCDM model was implemented using Feasible Goals, which

allows for the simultaneous graphical evaluation of decision maps arising from trade-offs among efficient solutions. When fully allocating the available land (22,500 ha), the multi-objective development of the shrimp farming industry produces 7,490 new jobs, ER and XG of USD\$ 204.5 and \$ 497.6 million respectively, with a total pollutant discharge of 2,000 tons. The multiple-criteria optimization strongly favors semi-intensive systems (93% of the total 466 new farms), producing 57,119 tons of shrimp by 2005. The sustainable development of the industry based on the assumptions of this analysis does not suggest intensification of systems. Rather, the results of the MCDM analysis support the claim that semi-intensive farms, which are more common in Mexico, promote sustainability.

Based on the findings of each of the essays, it is suggested that production performance indicators are needed on a periodic basis for the evaluation of the shrimp industry of Mexico. Production performance measurements may better assist farmers in the decision-making for industry sustainability and growth. Moreover, direct determination of N and P discharges by farms are recommended in future studies as well as incorporating risk and employing longer time series.

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CHAPTER 1

BACKGROUND, AIM AND SCOPE OF THE STUDY

1.1 Background

1.1. 1. Current status of the shrimp farming industry in the world

Consumers in most western countries, particularly the United States, Canada and Britain increasingly prefer poultry and seafood to red meat. Within the broad category of seafood, shrimp and fish are the two products with the largest market demand.

Shrimp for human consumption comes from two sources: fisheries and aquaculture. Figure 1.1 shows the total world production of this crustacean in each of these two categories for the period 1992-2000. As illustrated, the fisheries share is increasing at a smaller rate than that of aquaculture. Most fisheries have reached their maximum sustainable output, while the development of shrimp aquaculture is increasing. Over the past three decades, the aquaculture industry has become the fastest growing food producing sector in the world, while several of the most important fisheries in the world are showing signs of overexploitation.

In the United States, the demand for shrimp has been continuously growing during the last decade. The total value of shrimp imports reached US\$ 3.6 billion in 2001, from a volume of 883 million pounds. This volume was 16% and 21% higher than in 2000 and 1999 respectively (Aquaculture Outlook, 2002).

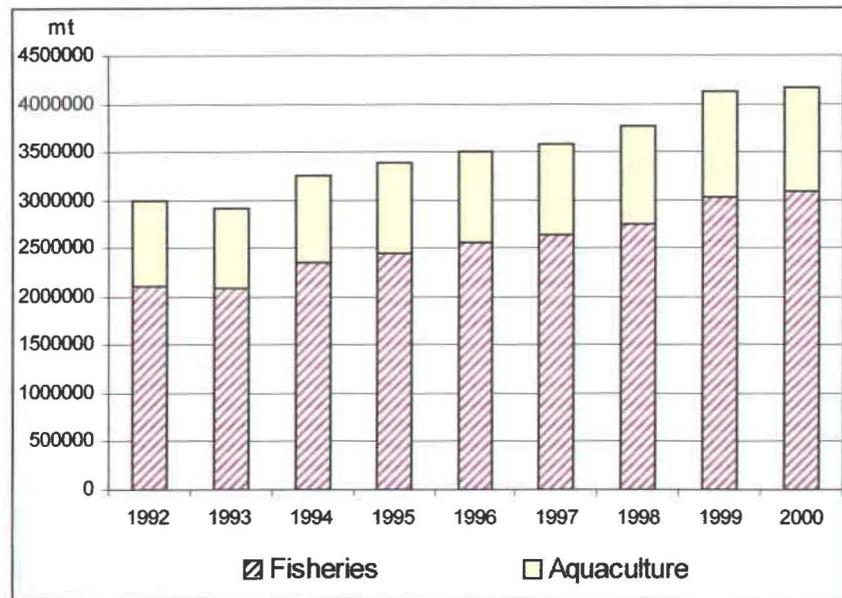


Figure 1.1 World shrimp production of shrimps and prawns by source 1992-2000 (Source: FAO, 2002)

Competition to supply this luxury product to the major markets in the United States and Japan is fierce. The management of aquaculture facilities and the strategy to produce and sell are key factors in remaining competitive, as shrimp prices have decreased continuously in the last 10 years. Asian countries, led by Thailand, are the main producers with historically the biggest shares of US imports (Fig. 1.2). Ecuador and Mexico are the two Latin American countries with the biggest shrimp exports to the United States, although Mexican exports have remained almost constant for the last 3 years. Smaller producers including Vietnam, Guyana, Honduras, Brazil and other Central and South American countries (represented as others in Figure 1.2) have shown a significant increase in aggregated supply for the last three years.

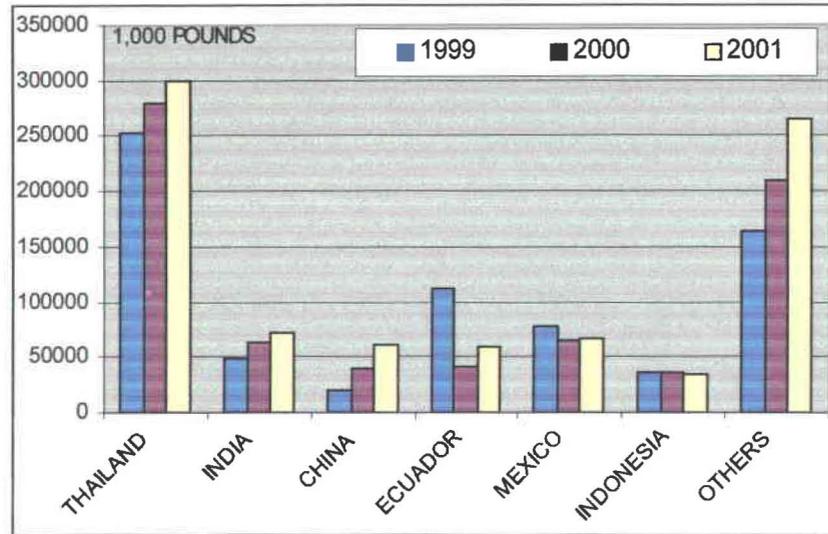


Fig 1.2. U.S. shrimp imports by country of origin. (Source: Aquaculture Outlook, 2002).

1.1.2. Current status of the shrimp farming industry in Mexico

Official data indicates that the Mexican aquaculture industry has grown from 151,124 tons produced in 1986 to 188,156 tons in 2000 (SAGARPA, 2002). The shrimp farming sector has developed at a fast pace, supported by continuous flows of capital attracted by a strong, growing export market to the United States. Hence, since the first official records (35 tons of shrimp produced in 1985), production area and total harvests have been increasing every year, and a record 47,450 tons were obtained from the shrimp farming industry in the year 2001 (SAGARPA, 2002). The northwestern States of Sonora, Sinaloa and Nayarit produced 94% of this amount and historically have had the biggest shares of total national production (Appendix A). If Yucatan were added, these four States accounted for 98% of the total Mexican production in the year 2000.

Shrimp farms operate at three levels: extensive, semi-intensive or intensive¹. Historically the semi-intensive level has been the production scheme preferred by Mexican farmers. In the year 2000, 71% of the farms (269 out of 379) were operating at this level, using 86% of the developed farming land, contributing TO 77% of total national production. Table 1 details the distribution of farms for this year by intensity level and State.

Table 1.1 Distribution of shrimp farms by production level and State in 2000. (Source: SAGARPA,2002)

	Total		Extensive		Semi-Intensive		Intensive	
	#	Has.	#	Has.	#	Has.	#	Has.
Sonora	53	6,975	----	----	51	6,738	2	237
Sinaloa	215	17,549	48	2,298	164	15,012	3	239
Nayarit	79	1,937	42	554	33	1,299	4	85
Yucatan	1	46	----	----	----	----	1	46
Others	31	1,079	----	----	21	646	10	433
TOTAL	379		90		269		20	

The history of shrimp aquaculture has been one of successes and sudden collapses due to diseases outbreaks, and this fact is reflected in the annual yields. The Pacific white shrimp (*Litopenaeus vannamei*) was for many years the preferred species for commercial ongrowing operations in Mexico. However, with the surge and spread of viral diseases in late 1995 and 1996 (Taura virus), which specifically affected this species, both hatcheries

¹ This classification follows primarily the use of inputs in the production process (and consequently operating costs), which determine yields and revenues. Extensive systems stock shrimp postlarvae (PL) at a very low density (1-5 PL/m²), in ponds usually of big dimensions (> 10 ha.), no artificial feeding but rather the system relies on natural productivity. Neither water exchange, nor aeration is carried out. Yields from these systems are low. In the other extreme, intensive growout is carried out in small, lined ponds (0.5-1 ha), with high aeration and artificial feeding, stocking densities (depending on species) between 50-70 PL/m² and yields in the range 2000-7000kg/ha. Semi-intensive systems are an intermediate scenario.

and on-growing farms were forced to seek alternatives and introduced the blue shrimp (*Litopenaeus stylirostris*) to their operations. In 1998, almost 85% of the shrimp farms stocked *L. stylirostris*, but at the beginning of 2000, captive blue shrimp populations were decimated by the white spot virus, forcing farms to switch again to white shrimp. These adjustments cannot be implemented without suffering reductions in survival rates and yields for one or two culture periods. Currently both shrimp species are reared in commercial operations.

1.1.3. Planning the industry's sustainable development

Little doubt currently exists among international organizations like the Food and Agriculture Organization (FAO) of the United Nations, and the Network of Aquaculture Centers in Asia-Pacific (NACA), that aquaculture will increasingly contribute to food security, poverty alleviation and social equity in the world. In most instances aquatic food supplies cost less than other animal protein supplies while at the same time aquaculture helps alleviate poverty and increase food security, and improve the standard of living in rural areas by providing a means to generate income (Subasinghe et al., 2001).

De Silva (2000) affirms that although 90% of the aquaculture product in the world market today comes from Asia, the most significant global change in aquaculture production comes from the increase in production in Latin America (South America specifically). With this trend expected to continue, planning plays a key role to ensure that sustainable development of the industry in the region is achieved.

Shrimp farming in Mexico is an industry that generates important economic and social benefits, while it also raises environmental concerns from resources utilisation and

the environmental impact of the associated effluents. With scarce resources and a growing world population, decision-makers (policy-makers and producers) face the challenge of developing a sustainable aquaculture industry by incorporating social, environmental and economic objectives, and taking into account the heterogeneous interests of the sectors involved.

The industry in Mexico has witnessed the development of large-scale operations over the last 10 years, which are not linked to the population's cultural background and preference for aquatic food products. However, the industry has also brought important social and economic benefits in the form of income and employment generation in coastal communities and through secondary channels to urban areas, as well as foreign exchange inflows. The annual performance of aquaculture in general and shrimp aquaculture in particular, needs to be evaluated in the same way as other important industrial sectors of the country's economy such as the textile, steel and automotive.

According to the National Plan for Development 2001-2006, the Aquaculture Plan 1995-2000 (SEPESCA, 1995) and the Program of Aquaculture and Fisheries 2001-2006 (SAGARPA, 2001), the Mexican government has a variety of objectives for the development of aquaculture including: food security, the generation of income, employment and foreign exchange, and development of sustainable, environmentally-friendly aquaculture systems. In practice, promotion of environmental-friendly aquaculture involves the explicit incorporation of the environmental component of the activity in every planning exercise of the industry, in addition to the evaluation of the performance of the industry, using indicators that take into account environmental effects. This can be carried out at a microeconomic (farm) or macroeconomic level.

1.2 The core of the problem

Presently, no studies have been conducted which provide economic evaluations of Mexican aquaculture development policies from a sustainable perspective, integrating social, economic and environmental objectives and constraints. Furthermore, no indicators of current and past economic and environmental performance of aquacultural farms exist. It is my belief that both are necessary elements for planning purposes if sustainability is an industry's goal². As Neiland et al. (2001) conclude, few studies on mechanisms for including environmental values in planning and production decisions for shrimp aquaculture development exist. The most recent study analyzing shrimp farming under a joint economic-environmental perspective in Latin America is the work by MacDougall (1999) for the industry in Ecuador.

1.3 Problem Statement

The competition among producing countries, the rapid advances in technology and the increase in market demand suggest that the shrimp industry at a global level and in Mexico in particular, needs to take appropriate measures to maintain its viability and to be able to compete successfully. This can be achieved by making better use of the available technology and scarce resources without further deteriorating the environment.

² There are many definitions of sustainability and sustainable development in the literature, and vast discussion regarding the convenience of one over the other. The objective of this dissertation is not to support any of them, or to develop the analysis according to a specific definition of sustainability. The sustainability framework in which shrimp farming is analyzed in this dissertation, basically points to the simultaneous inclusion of social, economic and environmental elements of the problem in the evaluations, rather than limiting the study to only the economic ones. This, the recognition of economic, environmental and social components as part of sustainable development, is a perspective shared by most definitions found in the literature (see for example Turner, 1999). Caffey and Karzmierek Jr (1998) state that "the recent focus on sustainable aquaculture has produced little consensus beyond the general recognition that sustainability embodies multiple environmental, economic and social objectives".

Proper planning is the key to finding a compromised solution among often conflicting social, economic and environmental objectives.

The generation and analysis of information is critical to provide decision makers and planners with elements needed for evaluations. Economic studies at farm and industry levels in Mexico can provide decision makers with the information necessary to assess the industry and plan its sustainable development.

Current operations must be evaluated to determine their economic and environmental performance, to ensure those that are supported are the most efficient, or at least to determine a certain minimum standard or benchmark. From the environmental perspective, efficiency with respect to environmental resources is necessary for environmentally sound production. Reduction in pollution levels in general can be attained by a more efficient use of resources or improvement of current practices and through the use of new, more environmentally sound production techniques. The focus of this dissertation is on economic analysis, not on the technical aspects of the production systems.

It is important to mention that agriculture and urban areas exert externalities on aquaculture as well. However, the environmental, social and economic effects of these externalities, which are elements of consideration when analyzing the sustainable development of the shrimp farming industry, are not taken into account in this dissertation due to lack of data for their quantification.

1.4 Objectives

1.4.1 General objective of the study

Applying production economics and operations research theory, this dissertation elaborates on two selected issues associated with the regional economic planning of shrimp farming's sustainable development in northwest Mexico, based on primary source information from a sample of farms in the State of Sonora. They are: 1) to assess different policies for the development of sustainable shrimp farming in Mexico, under a multiple criteria decision making (MCDM) approach and 2) to estimate and analyze the historic performance of shrimp aquaculture at farm level. These two interrelated components are essential for planning purposes.

1.4.2 Specific Objectives

The specific objectives are as follows:

1. To conduct economic analysis of shrimp farming at the farm level, evaluating productivity and efficiency, while taking into account the generation of undesirable outputs (pollutants).
2. To determine, for the farms in the database, how efficiently inputs containing N and P (i.e. feed) are being applied in the production process. Considering that feed is the biggest operation cost in shrimp farming, assessing its efficient use from an environmental perspective complements economic analysis of resource use.
3. To obtain shadow prices for pollutants. This information will be useful for future policy studies.

4. To develop a multicriteria decision making (MCDM) model to analyze the trade-offs of sustainable regional shrimp farming development. The model includes constraints for food supply to local market and land availability. This basic model is static, deterministic, and abstracts from general equilibrium effects..

1.5 Previous work

In the last decade, there has been a growing interest in the use of efficiency and productivity change measures, taking undesirable or pollutant outputs into account. Some of this work has been applied to agriculture (Ball et al., 1994; Oskam, 1991; Reinhard and Thijssen, 2000; Reinhard et al., 2000; Weaver, 1998).

Although the definition and measurement of technological change and technical efficiency share a common methodological basis (such as the production function), empirical analysis of productivity growth have evolved along two differentiated lines: the nonfrontier and the frontier literature. The former assumes that firms are conducting operations on their frontier and therefore technical change and Total Factor Productivity (TFP) are used synonymously. On the other hand, the frontier approach relies on the idea that firms are not necessarily conducting the best practice and hence the TFP variations of individual observations are measured.

The analytical tools used to measure TFP and incorporate pollutants into efficiency and productivity analysis fall into three broad categories: index number, parametric and non-parametric (Zepeda, 2001). The Index number approach involves compiling detailed accounts of inputs and outputs, aggregating them to calculate indexes.

Index numbers ignore efficiency or error estimations, but are computationally simple. Examples of applications of the index numbers are Pittman (1983) and Repetto et al. (1996). The parametric approach involve output or input distance function representations of multi-output production technologies. Hailu and Veeman (2000) conducted an analysis for the pulp and paper industry in Canada using an input distance function, whereas Färe et al. (1993) analyzed the paper and pulp mills in two States of the United States, using an output distance function. Finally, the non-parametric methods use linear programming (LP) techniques to calculate TFP and don't impose assumptions about the technology that generates output. They have been applied by Tyteca (1997) and Hailu and Veeman (2001) for the paper industry in Canada, and Chavas (2001) for agriculture in developing countries.

In the efficiency literature, methods to estimate the technical or economic performance are grouped into two clusters (Fried et al., 1993): 1) the mathematical programming methods (e.g. Data Envelopment Analysis or DEA) and 2) the econometric methods (Stochastic Frontier Approach or SFA, cost functions and distance functions). Examples of the first approach include Ball et al. (1994) and Reinhard et al. (2000) for DEA; while the second methodology is reported among others by Färe et al. (1989), Reinhard and Thijssen (2000), Hetemaki (1996) and Reinhard et al. (2000).

Hatch and Tai (1997) conclude that these areas of research have grown as aquaculture has matured as a commercial industry, focusing on species with relevance in US production and world trade (shrimp, trout, salmon, catfish). In the five years since the review by Hatch and Tai, economic studies applied to aquaculture primarily evaluate the efficiency of Asian-based aquaculture operations. These include assessments of shrimp

farming (Gunaratne and Leung, 1996 and 1997; Leung and Gunaratne, 1996), carp farming (Sharma and Leung, 1998; Iinuma et al., 1999; Sharma et al., 1999, Sharma and Leung 2000a and 2000b), tilapia growout in ponds (Dey et al., 2000), tilapia hatchery operations (Bimbao et al., 2000), mariculture of sea bass and sea bream (Karagiannis et al., 2000) and salmon aquaculture (Tveteras and Battese, 2000, Vassdal and Roland, 1998). Martinez-Cordero et al. (1999) measured Total Factor Productivity (TFP) in polyculture systems in Indonesia. However, all of this research applied to aquaculture shows a common feature: it doesn't include the generation of undesirable outputs in the productivity and efficiency assessments.

No single economic study exists for the productivity and efficiency of the Mexican aquaculture industry. Economic studies of shrimp farming at firm level include the work by Martinez and Seijo (2001), who evaluated the economics of alternative water exchange and aeration rates in semi-intensive shrimp farms, taking into account risk and uncertainty. Gomez-Galindo (2000) developed a nitrogen-based model which identifies Best Management Practices (BMP), to assess shrimp farming in northwest Mexico. Before that, Martinez Cordero et al. (1995, 1996a, 1996b) developed a bioeconomic model for a shrimp hatchery and by including uncertainty, assessed the feasibility of the project in the State of Yucatan under a precautionary approach.

1.6 Contribution

This dissertation's objective of quantification and assessment of environmental issues of shrimp aquaculture at farm and planning levels, applying production economics

theory and operations research methods produces original, innovative results. Specific? contributions are as follows:

- The Distance Function approach has seen a resurgence in the past five years and is being applied to the economic analysis of production, incorporating pollutants. Aquaculture performance, both traditional and environmentally-adjusted, are evaluated using this methodology. Distance functions are used for the first time to evaluate efficiency and productivity in aquaculture.
- This approach allows for the first time, reporting of shadow prices for the undesirable outputs in aquaculture . Although these prices are specific to the database available and the methodology applied, they are useful indicators for policy evaluation, future economic analysis and continuing work.
- Shrimp farming is modeled as a multi-output process with the pollutants of nitrogen and phosphorous considered as undesirable outputs. Technical efficiency and farm productivity is evaluated, based on both the shrimp harvest and the waste emissions.
- A MCDM model is developed for Mexico to evaluate options and weighs trade-offs of the shrimp farming development at regional level, for a variety of planning policies. The model can be improved in the future, as more information becomes available not only from shrimp farming but other commercial aquaculture sectors like tilapia farming, which is also an export-focused commercial activity.

1.7 Outline of the dissertation

The dissertation is organized as follows: Chapters 2 and 3 are two independent essays. The first one corresponds to the evaluation of traditional and environmentally-

adjusted technical efficiency and total factor productivity of shrimp farming in Mexico, and the estimation of shadow prices of pollutants. Chapter 3 develops the MCDM model for sustainable planning of shrimp farming in Mexico. Each of these two chapters is developed in an essay format, including introduction, material and methods, results and discussion.

Chapter 4 is an extended discussion of the results of both chapters, linking them to policy applications for industry planning. This chapter also discusses benefits of the periodic calculation and report of the production performance measurements. Finally, Chapter 5 presents the general conclusions of both essays, their joint implications for shrimp farming planning in Mexico, and recommendations for future work.

CHAPTER 2

MEASUREMENT OF ENVIRONMENTALLY-ADJUSTED PRODUCTIVITY AND EFFICIENCY OF SHRIMP FARMS, AND MARGINAL COSTS OF POLLUTION ABATEMENT TECHNOLOGIES

2.1 Introduction

Shrimp was the aquatic species with the largest production by volume in Mexico in 2000 at 95,077 tons, including fisheries and aquaculture. Shrimp produced by aquaculture reached a value of US \$207.9 millions in that same year, the highest among all reared species in the country. Since the first official registers of 35 tons. in 1985, production area and total shrimp harvest have been increasing every year, with a record 47,450 tons. obtained in the year 2001 (SAGARPA, 2002). Total production and number of farms are expected to continue growing, responding to demands from local and export markets, primarily in the United States. With scarce resources and a growing population, decision-makers (policy-makers and farmers) face the challenge of developing a sustainable aquaculture industry whereby the social, environmental and economic objectives can be simultaneously satisfied.

The shrimp farming industry is generally perceived, however, as an activity that negatively impacts the environment. By-products and wastes in water outflows (phosphates and nitrates) are discharged into farm's surrounding water bodies or land¹. Hence, the challenge for the sustainable industry growth is to improve production

¹ Modifications to feed, feeding regimes and water exchange procedures are management strategies that significantly reduce the generation of these pollutants and their final impact on the environment. Zero-water exchange systems are already in operation at commercial level in Belize, and new, low-protein feeds are continuously tested for bioeconomic feasibility at commercial level.

performance while, at the same time, to minimize the environmental impacts. Therefore, measurement and analysis of producer performance becomes critical. At firm level, farmers must produce at maximum efficiency and productivity, while high levels of efficiency, productivity and productivity growth are also the policy maker's goals. These are, indeed, objectives for the development of the aquaculture industry in Mexico, according to the Program for Aquaculture and Fisheries 2001-2006 (CONAPESCA).

Productivity in its most elemental definition is a ratio of outputs to inputs (Fried et. al, 1993), with a more productive unit achieving higher outputs for a given set of inputs. The efficiency of a production unit, on the other hand, is a comparison between observed and optimal values of its output/input combinations (Fried et. al, 1993). A production unit is more efficient the closer it is to the frontier for its technology. Hence, efficiency and productivity are indicators of how producers are making use of different inputs to obtain outputs.

The traditional measures of productivity and efficiency, however, do not explicitly take into account the impact on the environment. Recent research concluded that these two indicators can be adjusted to measure not only the farm capability for obtaining the target product but also for how successfully farms are in generating the minimum amount of undesirable outputs (wastes or pollutants).

This first essay measures and analyzes production performance based on a sustainable perspective, for a group of shrimp farms in Mexico, applying recent developments in productivity and efficiency analysis. The input distance function approach was used to determine the technical efficiency of the farms, taking into account the generation of undesirable outputs (nitrogen and phosphorus loads in outflow water),

based on work by Hailu (1998) and Hailu and Veeman (2000), and previous work by Coggins and Swinton (1996) and Färe et al. (1993). A modified Malmquist index was then used to evaluate productivity considering again the emission of pollutants, using techniques developed by Hailu and Veeman (2001) and previous research by Caves et al. (1982) and Nishimizu and Page (1982). The Input Distance Function approach also allows for the estimation of shadow prices of pollution or pollution abatement technologies, taking advantage of the dual relationship with cost functions. In this essay, shadow costs of pollution abatement is determined as well. The parametric linear programming study by Färe et al (1993) was the first study to explicitly use the distance function approach to derive shadow prices of undesirable outputs, and Hetemaki (1996) was the first to use an econometric distance function to this end.

Finally, the objectives and relevance of this study are also in accordance with current global policies for aquaculture sustainable development. In February 2000 and as a result of the Conference on Aquaculture in the Third Millennium, the *Bangkok Declaration and Strategy* was issued (NACA/FAO, 2000). It recognises among other issues, that aquaculture policies and regulations should promote practical and economically viable farming and management practices that are environmentally responsible and socially acceptable. One of the key elements in the strategy for aquaculture development beyond 2000 is to improve environmental sustainability. This can be achieved by different means, one of which is (p.10):

“Development, adoption and application of environmental, economic and social sustainability assessment criteria and indicators of aquaculture development”

2.2 Materials and Methods

2.2.1 Primary-source information

Primary-source data of semi-intensive shrimp farms in the State of Sonora, Mexico is used, specifically an unbalanced panel of up to 11 farms for the years 1994, 1996-1998². This time period coincides with a “normal” year (1994) of operations with white shrimp (*L. vannamei*), and a transition to a different technology (1996-1998) using a different species (blue shrimp *L. stylirostris*) after the impacts of the viral outbreaks, that forced farmers to introduce the new species commercially after severe losses.

The primary information is given on a per-pond basis, and details input quantities (feed, seed, labor, water) and output (shrimp harvested). Although during shrimp farming operations monitoring and management analysis are conducted at pond level, which allows discussion of results on pond-basis, the farm is selected as the Decision Making Unit (DMU) to facilitate discussion and comparison of results with other work reported in the literature. The number of farms per year is 7 (45 ponds), 8 (75 ponds), 9 (87 ponds) and 11 (92 ponds) for the years 1994, 1996, 1997 and 1998 respectively (302 ponds total).

Since the Malmquist Index approach demands comparison in time of the same production units, this part of the analysis is carried out for 7 farms only (number of farms in the first year: 1994). Reported changes in productivity are only due to improvements in the units studied, and these changes may not be extended to other farms. Farms included in this study carry out one cycle per year per pond, due to climatic conditions.

2.2.2 Mass balances and calculation of undesirable outputs of shrimp farms

In the model developed to analyze environmentally-adjusted efficiency and productivity of shrimp farms, nitrogen (N) and phosphorous (P) surplus are the environmentally detrimental variables discharged from farms to adjacent water bodies. N and P contents in water discharges are estimated by means of nutrients flow balances reported in the literature for semi-intensive shrimp farms in northwest Mexico, depicted in Figure 2.1 (Paez-Osuna et al., 1997).

Information on several of the variables in the mass balances of Figure 2.1 are contained in the database available for this study including total feed, total postlarvae stocked and total shrimp harvested. These quantities are directly inserted in the balances and the total amounts are recalculated. For example, for pond 1 of farm ACR in year 1994, the nitrogen balance is (values given in the dataset are underlined, others are calculated using the mass balance):

$$\begin{aligned} & \underline{\text{Inlet Water}} + \text{Fertilization} + \underline{\text{Shrimp stocked}} + \underline{\text{Food}} = \\ & \text{Ammonia volatilization} + \underline{\text{shrimp harvest}} + \text{macrofauna associated} + \text{N discharged} \\ & \quad \quad \quad \Downarrow \\ & (0.11\text{kg/ha/day} \cdot \text{cycle length} \cdot \text{pond size}) + (8.8 \text{ kg/ha} \cdot \text{pond size}) + (1,293,149 \\ & \text{PLs} \cdot \text{N in PL body}) + (19,398 \text{ kg feed} \cdot \text{N in feed}) = (27.4\% \text{ total N input}) + (14,500 \\ & \text{kg} \cdot 3.41\%) + (0.4\% \text{ total N input}) + \text{N discharged} \rightarrow \mathbf{83.91 \text{ kg/ha}} \end{aligned}$$

² Year 1995 is excluded for empirical reasons: that was the year (and the beginning of 1996) when shrimp farms in Mexico were hit by viral diseases. Most of the farms suffered severe losses and there is no point in estimating productivity and efficiency of firms when at that time they were struggling to survive.

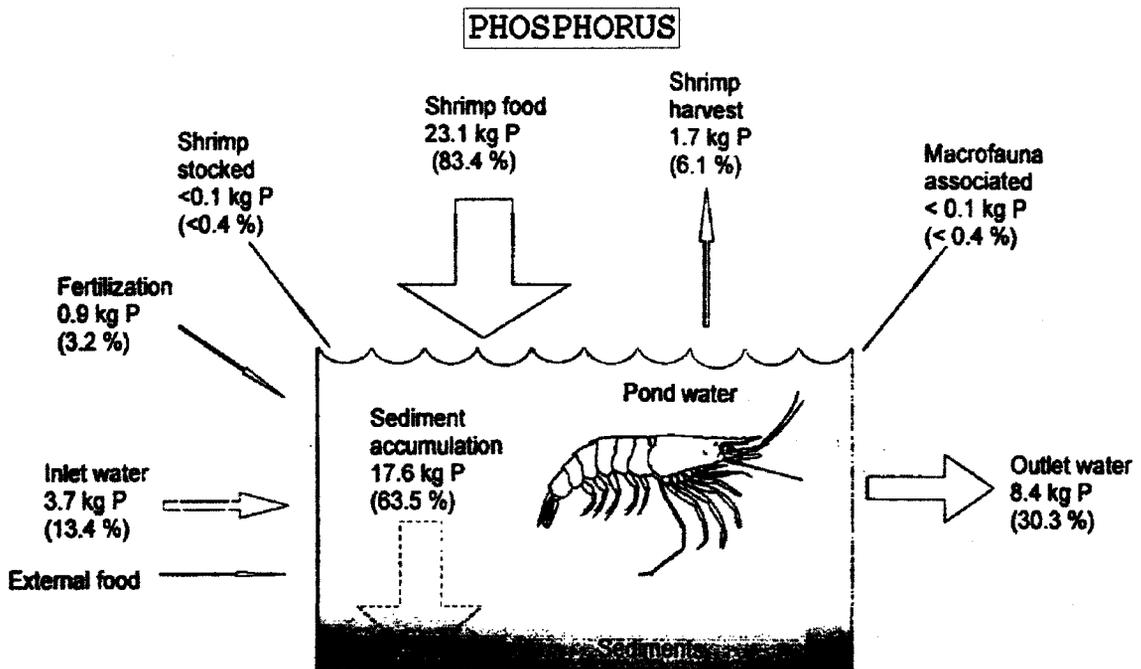
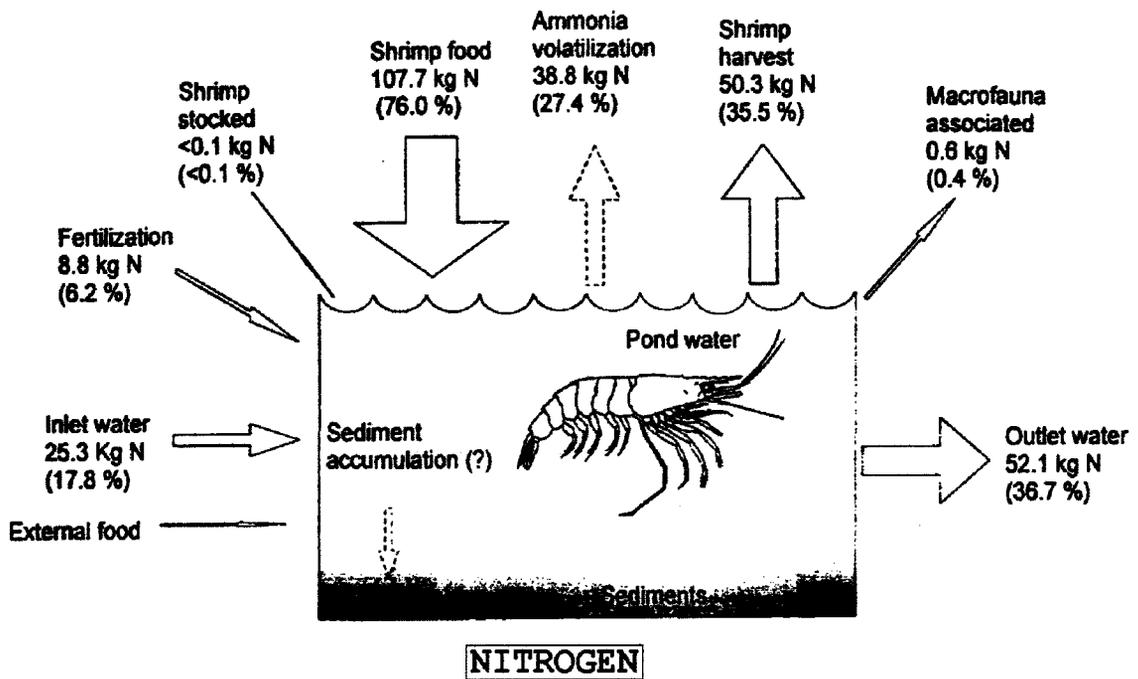


Fig. 2.1 Nitrogen and Phosphorus mass balances for one growout cycle of a 1 ha. semi-intensive pond, from a representative shrimp farm in NW Mexico (From Paez-Osuna et al., 1997)

and similarly for the phosphorus mass balance:

$$\begin{aligned} & \text{Inlet Water} + \text{Fertilization} + \text{Shrimp stocked} + \text{Food} = \\ & \text{Sediment accumulation} + \text{shrimp harvest} + \text{macrofauna associated} + \text{P discharged} \\ & \quad \quad \quad \downarrow \\ & (0.04\text{kg/ha/day} \cdot \text{cycle length} \cdot \text{pond size}) + (0.9 \text{ kg/ha} \cdot \text{pond size}) + (1,293,149 \text{ PLs} \cdot \text{P in} \\ & \text{PL body}) + (19,398 \text{ kg feed} \cdot \text{P in feed}) = (63.5\% \text{ total P input}) + (14,500 \text{ kg} \cdot 0.37\%) + \\ & (0.4\% \text{ total P input}) + \text{P discharged} \rightarrow \mathbf{25.84 \text{ kg/ha}} \end{aligned}$$

The total amounts of nutrients discharges reported in any mass balance are site and species-specific, since water quality, weather and the characteristics of organisms influence the total amount released to the environment. Likewise, farm operation and management are reflected in variables like stocking density, survival, growth rate, feeding regime, water exchange regime.

The mass balances of Paez-Osuna et al. (1997) were selected in this study for the calculation of nutrients outflows because they were obtained from shrimp farms in the same region of Mexico, operating under the same semi-intensive production system. Similar mass balances for extensive and intensive systems (Paez-Osuna, 2001), which are useful for the second essay of this dissertation, also exist. While calculating effluents indirectly using mass balances is not perfect, the associated errors are minimized if the base is kept consistent by working with these balances rather than using others developed in other countries and under other production systems. For example, Paez-Osuna et al. (1997) discuss that the big differences between their calculated net fluxes and those of

Hopkins et al. (1993) for intensive shrimp ponds in South Carolina, USA, are a result of different production parameters like water exchange and feeding rates.

There are several mass balances reported in the literature for shrimp and fish farming around the world. They are summarized in Table 2.1 for comparison with the mass balance used in this study. N and P discharges in this study are higher than others reported for semi-intensive systems, because at that time rearing practices for the farms analyzed were closer to intensive systems.

Table 2.1 Nitrogen and phosphorous discharges reported for fish and shrimp farms, as kg. per ton. of fish/shrimp produced.

Production system	P discharge	N discharge	Reference
Cage freshwater fish	23	100	Penczac et al. (1982)
Fish farming	16	68	Solbe (1982)
Cage marine fish	20	90	Enell (1987)
Cage marine fish	9.5	78	Ackefors and Enell (1990)
Cage salmon	11	50	Bergheim and Asgard (1995)
Shrimp, intensive	42	104	Briggs and Funge-Smith (1994)
Shrimp, intensive	16	53	Phillips (1994)
Shrimp, intensive	31	114	Robertson and Phillips (1995)
Shrimp, semi-intensive	9	10	Phillips (1994)
Shrimp, semi-intensive	14	50	Paez-Osuna et al. (1997)
Shrimp, semi-intensive	16	58	Paez-Osuna et al. (1999)
Shrimp, semi-intensive	-----	27-62	Rivera-Monroy et al. (1999)
Shrimp, semi-intensive	25	85	This study

2.2.3 The Input Distance Function approach to evaluate economic and environmental efficiency, productivity, and shadow price of pollutants

The parametric linear programming approach is applied here for the estimation of the production frontier and measurement of efficiency and productivity in shrimp farms, by means of the Input Distance Function approach.

Production processes transform inputs into outputs and simultaneously create by-products. Depending on the process, some of these by-products may be recycled or secondarily used, but a portion is discarded to the environment as pollutants (also called undesirable outputs). The efficiency of a process is negatively related to the volume of waste generated, since lower percentages of the inputs are directed towards the production of the desired output with larger amount of waste generation. This joint production of good and bad outputs is usually ignored in traditional measures of economic productivity and efficiency, because prices are unavailable for pollutants. In addition, conventional studies have implicitly assumed that the firms are operating on the production frontier and that pollution control or regulation does not have an impact on production efficiency (Hetemaki, 1996).

Recent research developments using a standard efficiency methodology are a convenient framework to analyze the environmental performance of farms. Methods to estimate the technical or economic performance are readily available since Farrell (1957), but few studies other than Pittman (1983) and Fare et al., (1989) occurred before the 1990's that directly incorporate the pollution variable into the production technology model.

Efficiency scores are performance measures based on the production units evaluated. Farrell proposed in his seminal work (1957) that the efficiency of a firm is composed of two components: technical efficiency, which reflects the ability of a firm to obtain maximum output from a given set of inputs, and allocative efficiency, which reflects the ability of a firm to use the inputs in optimal proportions, given prices. The combination of these two measures provides the overall or total economic efficiency.

In the calculation of the efficient frontier function, the mathematical programming method is non-parametric, non-stochastic, and groups noise and inefficiency together. On the other hand, econometric methods require the specification of a functional form of the production process and incorporate stochasticity, thereby distinguishing the effects of noise from the effects of inefficiency. Battese (1992) and Kumbhakar and Lovell (1999) present overviews of the extensive literature of applications of this methodology. Sharma and Leung (1998, 2000a, 2000b), Sharma et al. (1999) are recent applications to aquaculture.

The stochastic frontier approach (SFA) to measuring production efficiency was simultaneously developed in three continents by Aigner, Lovell and Schmidt (1977), Battese and Corra (1977) and Meeusen and van den Broeck (1977). This methodology is motivated by the recognition that deviations from the production frontier are not completely controlled by the producer. The determinants of inefficiency are exogenous variables, which are neither inputs to production process nor outputs, but which nonetheless influence the process.

The principal advantage of the Distance Function (DF) Approach, also known as gauge function, transformation function or deflation function, over SFA is that it permits

the specification of a multi-input, multi-output technology, which is a necessary characteristic of the methodology when incorporating the undesirable output in the model. Equally necessary is the weak disposability assumption embedded in the DF approach. So that if x can produce u , then x can also produce a scaled down version of u :

$$\text{if } u \in P(x) \rightarrow \theta u \in P(x); \quad \forall \theta \in [0,1] \quad (1)$$

where $P(x)$ represents the output possibility set for x . In the absence of undesirable outputs, weak disposability is a trivial assumption since desirable outputs are freely disposable. However, for the undesirable outputs (pollutants) the weak disposability condition is necessary to reflect the fact that disposal of an undesirable output would impose a cost in the form of a proportional reduction in desirable outputs (Hailu and Veeman, 2000).

DF also provides a measure of the distance of each producer from the frontier. Shepard (1953) formulated the distance function in the production theory context and Malmquist (1953) did so simultaneously for consumer theory. However, this methodology and its benefits were not used in duality theory until the 70's. The indirect duality versions of both the input distance-cost function and output distance-revenue function were developed by Shepard (1974) and are presented in Table 2.2.

Table 2.2 Duality between technology and Value Functions

Technology	Duality	Value Function
Input distance function	↔	Cost function
Output distance function	↔	Revenue function
Indirect input distance fn.	↔	Revenue indirect cost fn.
Indirect output distance fn.	↔	Cost indirect Revenue fn.

The parametric linear programming study by Fare et al (1993) was the first study to explicitly use the distance function approach to derive shadow prices of undesirable outputs, and Hetemaki (1996) was the first to use an econometric distance function to this end.

The Input Distance Function Approach

Just as the production function defines the maximal output that can be produced from an exogenously given input vector, the direct input distance function describes how far an input vector is from the boundary of the representative input set, given a fixed output vector.

Following Fare and Primont (1997), a vector of N inputs, denoted by $x=(x_1, \dots, x_N)$, a vector of M outputs denoted by $y=(y_1, \dots, y_M)$, and a technology set $T = \{(x, y) : x \in R_+^N, y \in R_+^M, x \text{ can produce } y\}$ define a production function (with $M=1$):

$$F : R_+^N \rightarrow R_+^M$$

$$F(x) = \max_y \{y : (x, y) \in T\} \quad (2)$$

Define the input requirement set as:

$$L(y) = \{x : (x, y) \in T\} \quad (3)$$

where T is the set of all feasible input-output vectors, so that

$$T = \{(x, y) : x \in L(y), y \in R_+^M\} \quad (4)$$

the input distance function for the single-output case is given by:

$$D_i(y, x) = \sup_{\lambda} \left\{ \lambda > 0 : \left(\frac{x}{\lambda} \right) \in L(y) \right\} \quad \forall y \in \mathbf{R}_+^M \quad (5)$$

Equation 5 measures the maximal equi-proportional contraction of all inputs consistent with keeping the output vector in the technology set. In other words, the input distance function is the largest radial contraction of the input vector for a given output vector, which is consistent with the production possibility set, which still belongs to the same production possibility set.

The input distance function is non-increasing in the outputs y , non-decreasing in x , linearly homogeneous (degree one) and concave in x . If inputs are weakly disposable, then a complete characterization of the production technology exists. The disposal of an undesirable output would impose a cost in the form of a reduction in desirable outputs, and the treatment of the derivative properties for desirable and undesirable outputs has to distinguish between the two. Therefore, the input distance function is non-decreasing in undesirable outputs, because pollution abatement can also be achieved through the use of additional inputs, with desirable outputs constant. This condition embeds the assumption that a reduction in pollutant outputs requires the use of additional inputs for abatement, other inputs being held constant.

One way to measure the extent of the input efficiency is to calculate the input distance function. The greater the value of the Input Distance Function, the less efficient x is in producing y . If, instead, the reciprocal of the Input Distance Function is computed, then an efficiency measure is obtained that lies between zero and one and that takes higher values the more efficient x is in producing y . The Debreu-Farrell input oriented measure of technical efficiency is:

$$TE_x(y, x) = \frac{1}{D(y, x)} \quad (6)$$

Figure 2.2 explains this relationship: the input vectors x^A and x^B can be contracted radially and still remain capable of producing output vector y , while input vectors x^C and x^D cannot be contracted in the same way. Consequently $DF(y, x^C) = DF(y, x^D) = 1 > \max\{DF(y, x^A), DF(y, x^B)\}$. The input vector $(\lambda^B x^B)$ cannot be contracted radially and still be capable of producing output vector y (Lovell, 1993).

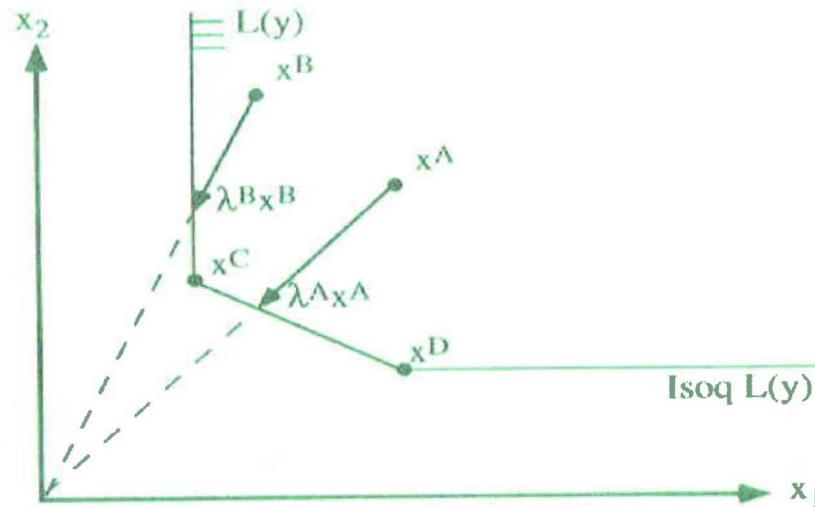


Fig. 2.2 Debreu-Farrell input oriented technical efficiency measurement

The input-oriented measure of technical change is defined as the rate at which inputs can be proportionally decreased over time without changing output levels. This rate is equal to:

$$TCx(y, x) = \frac{\partial D(y, x)}{\partial t} \quad (7)$$

The “standard” properties of the input distance function when only desirable outputs are obtained, must be distinguished from those used in this study where one desirable output (shrimp) and 2 undesirable ones (P and N discharges) are obtained. Based on Hailu and Veeman (2000), the model setup considers that desirable outputs are freely disposable, but the reduction of undesirable outputs (or pollution abatement) is not free. Ignoring technological change, undesirable outputs can be reduced through the use of additional inputs for pollution abatement if the level of desirable outputs is to be maintained. These extra inputs and additional production costs might take the form, for example, of labor, energy or capital inputs, necessary to establish an outflows treatment system.

The pollutants shadow price derivation makes use of the duality between the input distance function and the cost function, via Shephard’s Lemma and indicate the marginal costs of pollution abatement to the producer. A cost function is the solution to the problem:

$$C(y, p) = \min_x \left\{ p * x \mid D(y, x) \geq 1, x \in R_+^N \right\} \quad (8)$$

where $p \in R_+^N$ is the input price vector. This is the duality relationship between the cost and input distance function developed by Shephard (Fare and Primont, 1997). Applying the envelope theorem to the first order conditions, the shadow price is:

$$\nabla_y C(y, p) = -\Lambda(y, p) \cdot \nabla_y D(y, x) = -C(y, p) \cdot \nabla_y D(y, x) \quad (9)$$

Equation 9 is derived from the first order conditions of (8). The right hand part of the equality is obtained from the Lagrangian multiplier Λ , and is equal to the value of the optimized cost function. In words, the shadow price of a given output is the increase in costs that the production of an additional unit of the output entails. The minus sign means that the shadow price of the N and P outflows will be negative, as the input distance function is non-decreasing in pollutant outputs.

If the accuracy of the cost of production estimates cannot be assured (not having input prices for example), the following formula can be used to calculate the ratio of the shadow price of output i to output j:

$$\frac{r_i^*}{r_j^*} = \frac{\frac{\partial D(y, x)}{\partial y_i}}{\frac{\partial D(y, x)}{\partial y_j}} \quad (10)$$

This relationship has an interesting economic interpretation. The ratio of shadow prices is equal to the trade off between the 2 outputs and indicate how much of output j the producer would be willing to forego so he can emit one more unit of pollutant output i. This ratio is the marginal rate of transformation between pollution abatement and the desirable output. Furthermore, assuming that the market price of the desirable output y_j equals its shadow price, the shadow price of the pollutant output r_i^* is:

$$r_i^* = r_j^* \frac{\frac{\partial D(y, x)}{\partial y_i}}{\frac{\partial D(y, x)}{\partial y_j}} \quad (11)$$

Productivity measurement with Undesirable Outputs

While the Malmquist quantity index was formulated as a standard-of-living index in the theory of the consumer, application to production theory is equally possible. The distance function approach used in the efficiency determination can be used in the productivity analysis, since the distance functions can be employed as indexes of technological change, or differences in technologies across production units, assuming that production units operate efficiently. Thus, efficiency measurement takes the technology as given and attempts to obtain a scalar index of the distance from the frontier, while productivity measurement takes efficiency as given and attempts to obtain a scalar index of the change in (or difference in) technologies (Russell, 1998).

In this research, the environmentally sensitive input-based measure of technical efficiency are defined in equation 6 as the reciprocal of the input distance function and rewards the producer who increases desirable outputs (since the Distance Function is non-increasing in desirable outputs) and decreases undesirable outputs (since DF is non-decreasing in undesirable outputs). Hence, the Malmquist index, obtained using the DF estimations, is defined as a composite of the technical efficiency and technical change, also credits producers in these two ways.

Caves, Christensen and Diewert (1982) generalized the Solow's notion of technological change (or comparison) to the case of multiple outputs using distance functions. They treated this new Malmquist productivity index as a theoretical one and proved that the Tornqvist index can be derived from it. For 2 firms, k and l (can be the same firm at 2 different points in time) with output-input vectors (y^k, x^k) and (y^l, x^l) and production technologies given by the input distance functions $D^k(\cdot)$ and $D^l(\cdot)$, the input-

based Malmquist productivity index that compares the productivity of l to k is:

$$M(x^l, x^k, y^l, y^k) = \left\{ \frac{D^k(y^k, x^k)}{D^k(y^l, x^l)} \frac{D^l(y^k, x^k)}{D^l(y^l, x^l)} \right\}^{1/2} \quad (12)$$

M is a geometric mean of the two Malmquist input-based productivity indexes, each defined with a different reference technology. On the right-hand side of the equality, the first term indicates the minimal input inflation factor such that the inflated input for firm l and output vector of firm l lie on the production surface of firm k. This term is greater than one only when l has a higher productivity level than firm k. The second part of the right-hand part of the equality measures the maximal input deflation factor such that the deflated input from k and the output vector of k lie on the production surface of l. This is also greater than one for l more productive than k.

The Malmquist index in equation 12 can be decomposed into the efficiency and technical change components following Färe et al. (1994) as follows:

$$M(x^l, x^k, y^l, y^k) = \frac{D^k(y^k, x^k)}{D^l(y^l, x^l)} \cdot \left\{ \frac{D^l(y^l, x^l)}{D^k(y^l, x^l)} \frac{D^l(y^k, x^k)}{D^k(y^k, x^k)} \right\}^{1/2} \quad (13)$$

The technical change part of (13) is obtained by taking the geometric mean of the shift in the technology as measured on 2 observations instead of one. To explain this graphically, Figure 2.3 shows the 3 components of productivity gain: efficiency, scale effects and technology for two production technologies. Assuming that firm k operates at B with technology $F^1(X)$ and firm l produces at point H with production technology $F^2(X)$. The efficiency and technical change components of equation 13 are represented in

the figure respectively by: $\frac{OA}{OS} / \frac{OD}{OR}$ and $\left[\left(\frac{OT}{OR} \right) \cdot \left(\frac{OS}{OV} \right) \right]^{1/2}$

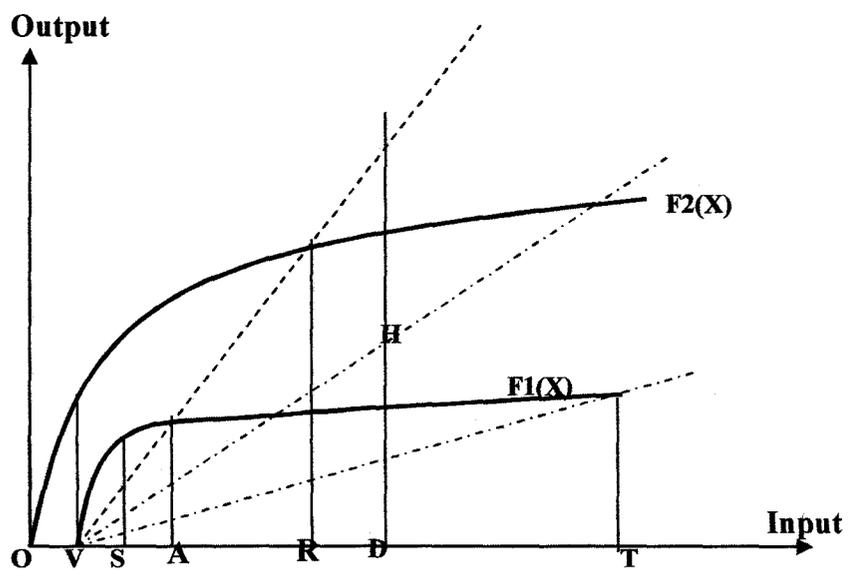


Fig. 2.3 The Malmquist total factor productivity index

2.2.4 Input distance function functional form and linear programming (LP) model

Based on Christensen et al. (1973), a flexible functional form, specifically the flexible translog functional form, was selected to represent the production technology (input distance function) as follows:

$$\begin{aligned} \ln D(y, x, t) = & \alpha_0 + \sum_{n=1}^N \alpha_n \cdot \ln x_n + \sum_{m=1}^M \beta_m \cdot \ln y_m + (0.5) \sum_{n=1}^N \sum_{n'=1}^N \alpha_{nn'} \cdot \ln x_n \cdot \ln x_{n'} + \\ & (0.5) \sum_{m=1}^M \sum_{m'=1}^M \beta_{mm'} \cdot \ln y_m \ln y_{m'} + (0.5) \sum_{n=1}^N \sum_{m=1}^M \gamma_{nm} \cdot \ln x_n \ln y_m + \alpha_t \cdot t + (0.5) \alpha_{tt} t^2 + \\ & \sum_{n=1}^N \alpha_{nt} \cdot t \cdot \ln x_n + \sum_{m=1}^M \beta_{mt} \cdot t \cdot \ln y_m \end{aligned} \quad (14)$$

where:

N=production inputs: feed (n_1), seed (n_2), water (n_3), labor (n_4)

M=outputs:shrimp (m_1), pollutant output N-outflow (m_2), pollutant output P-outflow (m_3)

t= time trend

Mathematical programming was used to estimate the parameters of the non-stochastic Input Distance Function in equation (16). The technique was first used by Aigner and Chu (1968) and relies on the minimization of the sum of deviations of the values of the function from the unknown frontier that is being estimated (deviations from unity). Inequality restrictions are included to represent the asymmetric treatment of desirable and undesirable outputs, so that weak inequality restrictions on the first derivative of the input distance function are necessary. The objective of the problem is to choose the set of parameter estimates that minimize the sum of deviations of the logarithmic value of the distance function from zero. Monotonicity, homogeneity and symmetry are imposed (Hailu and Veeman, 2000):

$$\text{Minimize}_{(\alpha, \beta, \gamma)} \sum_{k=1}^{302} \ln D(y, x, t)$$

subject to the following constraints:

$$1) \ln D(y, x, t) \geq 0, \quad t = 1, \dots, 4$$

$$2) \frac{\partial \ln D(y, x, t)}{\partial x_n} \geq 0, \quad t = 1, \dots, 4 \quad n = 1, \dots, 4$$

$$3) \frac{\partial \ln D(y, x, t)}{\partial y_m} \leq 0, \quad t = 1, \dots, 4 \quad m = 1$$

$$4) \frac{\partial \ln D(y, x, t)}{\partial y_m} \geq 0, \quad t = 1, \dots, 4 \quad m = 1, 2$$

$$5) \sum_{n=1}^4 \alpha_n = 1$$

$$6) \sum_{n=1}^4 \alpha_{n'n} = 0, \quad n' = 1, \dots, 4$$

$$7) \sum_{n=1}^4 \gamma_{nm} = 0, \quad m = 1, \dots, 3$$

$$8) \sum_{n=1}^4 \alpha_{nt} = 0,$$

$$\alpha_{nn'} = \alpha_{n'n} \quad n, n' = 1, \dots, 4$$

$$\beta_{mm'} = \beta_{m'm} \quad m, m' = 1, \dots, 3$$

where n and m were defined as in equation 14, t represents each of the four years analyzed. The constraints indicate the following: 1) the observation is within the technology frontier: feasible and with distance function value ≥ 1 ; 2) monotonicity condition: the distance function is non-decreasing in inputs; 3) the function is non-

increasing in the marketable output (shrimp); 4) the input distance function is non-decreasing in the two pollutants or undesirable outputs; 5) linear homogeneity of the input distance function with respect to inputs; 6,7,8) symmetry conditions of the translog functional form. t is time (4 years of data) and k is each of the observations (= shrimp pond). A code for this problem was developed and solved using Mathematica[®] and MathOptimizer[®].

The database used in this analysis was described in section 2.2.1. This four-year time series coincides with a switch in the species reared in commercial shrimp farms from white shrimp (first two years) to blue shrimp, as a consequence of viral diseases outbreaks in the former species which impacted operations in Mexico in 1995 and 1996. Therefore, efficiency and productivity can be measured and the results can be analyzed in correspondence with three events:

- 1) use of white or blue shrimp in operations;
- 2) the effect of experience of working with one species after many years (white shrimp), to initiate a learning curve with a new species (blue shrimp) after 1996; and
- 3) the effect of the viral outbreak on production performance.

In order to contrast technical efficiency and productivity with and without pollutants, the analysis is also carried out for a second scenario which considers only the desirable output, i.e., production of shrimp.

2.3 Results

2.3.1 Descriptive statistics of the data used

Table 2.3 presents descriptive statistics of the variables included in the measurement of total factor productivity (TFP) and technical efficiency (TE). Standard deviations are high signifying wide variation in input use and output obtained as well as wide annual variation among and within farms.

Table 2.3 Four-year descriptive statistics of variables included in the analysis (302 ponds)

Variable (units)	Mean	Std.Dev.	Min.	Max.
Inputs				
Feed (kg/ha)	4,792	2,293	324	11,516
Seed (# postlarvae/ha)	198,096	63,702	70,777	493,431
Water (cubic meters/ha)	62,956	14,722	14,207	92,800
Labor (\$/ha)	9,514	4,475	1,999	23,026
Outputs				
Desirable output				
Shrimp (kg/ha)	2,334	1,071.5	363.1	9,200
Undesirable outputs				
Nitrogen effluents (kg/ha)	134.8	70	13.75	409.59
Phosphorus effluents (kg/ha)	14	6.9	2	44.36

Figures 2.4 and 2.5 show the annual frequency distribution of discharges of the detrimental outputs (Nitrogen (N) and Phosphorus (P)) from shrimp ponds, in kg/ha, for the years 1994, 1996, 1997 and 1998. They were calculated using mass balances for semi-intensive farms in northwest Mexico, developed by Paez-Osuna (1997), as explained previously. A general evaluation of these figures shows that, compared to 1994, nutrient discharges increased annually. Annual yield grew simultaneously, which demonstrates that farm managers improved their productive performance (at least from

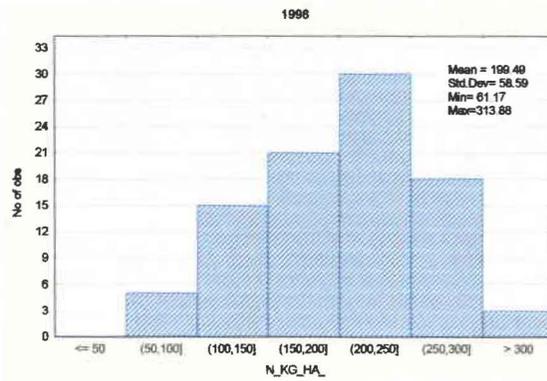
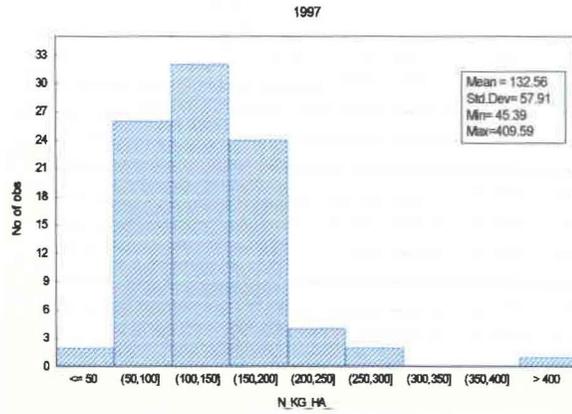
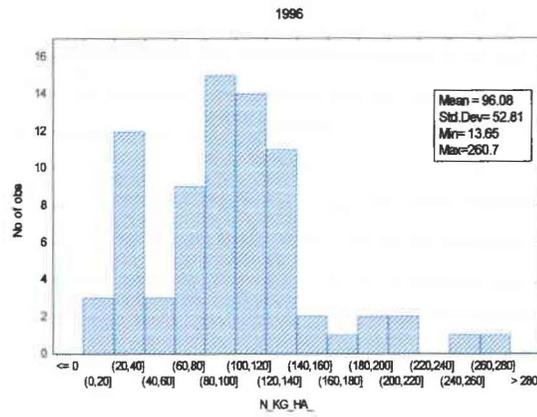
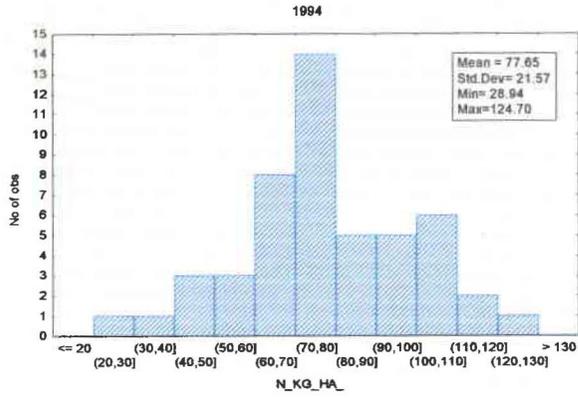


Fig.2.4 Frequency distribution of nitrogen discharges for 1994, 1996-1998.

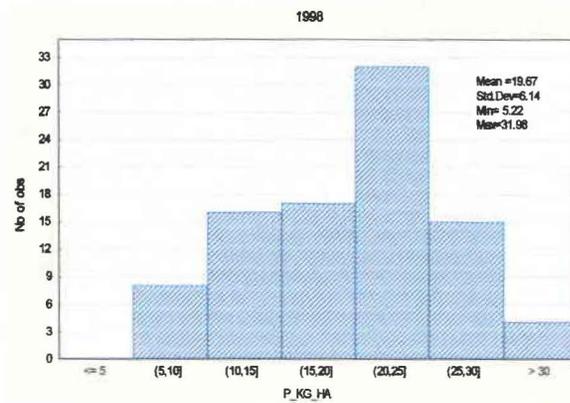
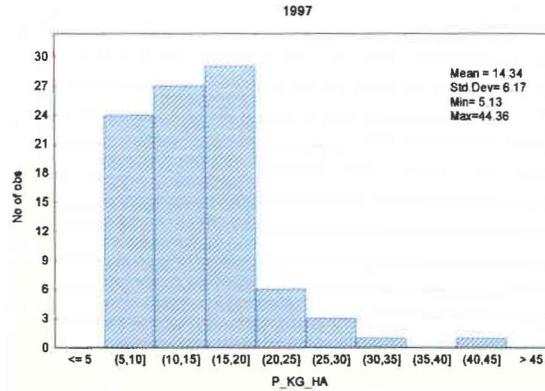
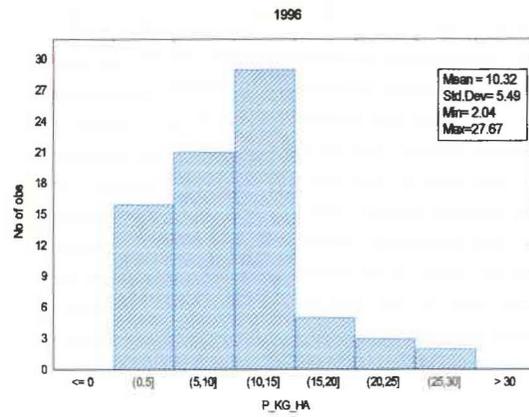
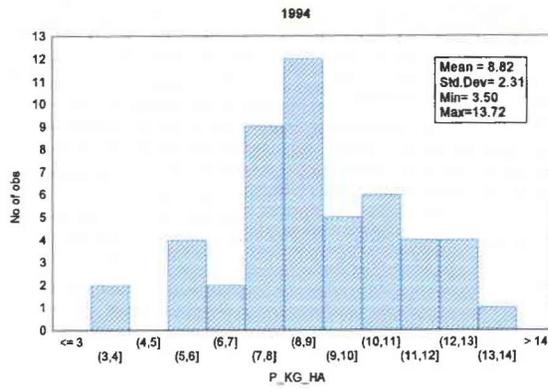


Fig.2.5 Frequency distribution of phosphorus discharges for 1994, 1996-1998.

the perspective of a traditional estimator: yield) with a simultaneous increase in discharge of nutrients. The effects of these two opposite results on traditional and environmentally-adjusted production performance will be properly tested later on in this essay, by means of TFP and TE.

With many years of experience with white shrimp and following a tradition established in Mexico for a long time, farmers in the initial year (1994) reared white shrimp (*L. vannamei*) as monoculture, and they were believed to be in the upper part of the learning curve with this species. However, beginning in 1996 both white and blue shrimp (*L. stylirostris*) are alternatively used in monoculture, until the transition is completed in 1998, first year of full blue shrimp operation. The nutrients discharge increases in 1997 and 1998. Working with the new species brings about higher feed conversion rates (FCR) and consequently increased nutrient's discharges, as reflected in the graphs.

2.3.2 Input Distance Function Parameters

Tables 1 and 2 in Appendix B show the estimated parameter values of the translog Input Distance Function (α, β, γ) for the two cases with and without undesirable outputs for 1994. The symmetry condition of the translog functional form, fulfilled during the optimization procedure, reduces the number of parameters shown (e.g., $\alpha_{34} = \alpha_{43}$).

2.3.3 Technical efficiency (TE) of farms

Using the whole data set of 302 ponds, four series of mean annual technical efficiency (TE) scores for farms operating in each year were obtained according to four individual frontiers (one frontier per year). They are shown in Table 2.4, aggregated for the cases of single-output (shrimp) and multiple-output (shrimp plus pollutants) production, including the standard deviations. These four series are asymmetric because ponds (and farms) were not all established at the same time and also because after the viral diseases, ponds returned to operations at different times. Figure 2.6 summarizes the results per year, contrasting annual average TE scores against a traditional performance measurement: yield.

The interpretation of the TE values from Fig. 2.6 is as follows: for the case of TE without undesirable outputs, on average, in 1994 the same amount of output (shrimp) could be produced with a reduction in inputs use in the order of 8.29%. This inefficiency level was increased in the following year, with possible reductions in inputs to achieve same desirable output of 10.54% in 1996, and 8.63% in 1997. These years coincide with the recovery of the heavy viral losses and the partial introduction of blue shrimp into operations. TE goes down again in 1998, first year of full blue shrimp operations, when a possible reduction of 12.66% in inputs would have resulted in the same shrimp production.

On the other hand, the environmentally-adjusted technical efficiencies are always lower than the traditional ones, since the score is reduced for the use of inputs in generating the undesirable outputs. Similar to traditional efficiency, the highest annual average score is in 1994, the year of full white shrimp operations. The difference

Table 2.4 Technical Efficiency of shrimp farms by farm and year, with (W) and without (WO) undesirable outputs, and within farm standard deviations.

Year	Farm	T.E. (WO)	Std. Dev.	T. E. (W)	Std. Dev.
1994	1	0.9750	0.0378	0.9450	0.0331
	2	0.8817	0.1045	0.8467	0.1162
	3	1.0000	0	0.9667	0.0152
	4	0.8983	0.1513	0.9050	0.1019
	5	0.9117	0.1059	0.9025	0.1124
	6	0.8457	0.1199	0.8314	0.1183
	7	0.9071	0.2197	0.8886	0.2249
	Average	0.9171		0.8980	
1996	1	0.8750	0.1264	0.8305	0.123
	2	0.8570	0.1294	0.8270	0.1289
	3	0.9343	0.087	0.9114	0.1037
	4	0.8317	0.1383	0.8125	0.1355
	5	0.9015	0.1155	0.8577	0.1051
	6	0.9471	0.0706	0.9300	0.0698
	7	0.8100	0.198	0.7800	0.1697
	8	1.0000	0	0.9433	0.0404
Average	0.8946		0.8616		
1997	1	0.8776	0.0948	0.8257	0.088
	2	0.9050	0.068	0.8463	0.0689
	3	0.8209	0.066	0.7664	0.0652
	4	0.9940	0.0134	0.9560	0.0456
	5	0.9814	0.0267	0.9671	0.0364
	6	0.9475	0.0618	0.9131	0.0575
	7	0.9300	0.099	0.9100	0.1273
	8	0.9318	0.0776	0.9027	0.0949
	9	0.8350	0.1584	0.7925	0.1608
Average	0.9137		0.8755		
1998	1	0.9457	0.0378	0.9271	0.0411
	2	0.9340	0.0631	0.9060	0.0658
	3	0.8380	0.1083	0.8000	0.1039
	4	0.8914	0.0825	0.8557	0.0873
	5	0.8214	0.0505	0.7900	0.0529
	6	0.9533	0.0789	0.8983	0.0763
	7	0.9200	0.0834	0.8867	0.0906
	8	0.8675	0.0082	0.8318	0.0843
	9	0.8444	0.0726	0.8069	0.0789
	10	0.7730	0.1573	0.7510	0.16
	11	0.8189	0.1189	0.7922	0.1412
Average	0.8734		0.8405		

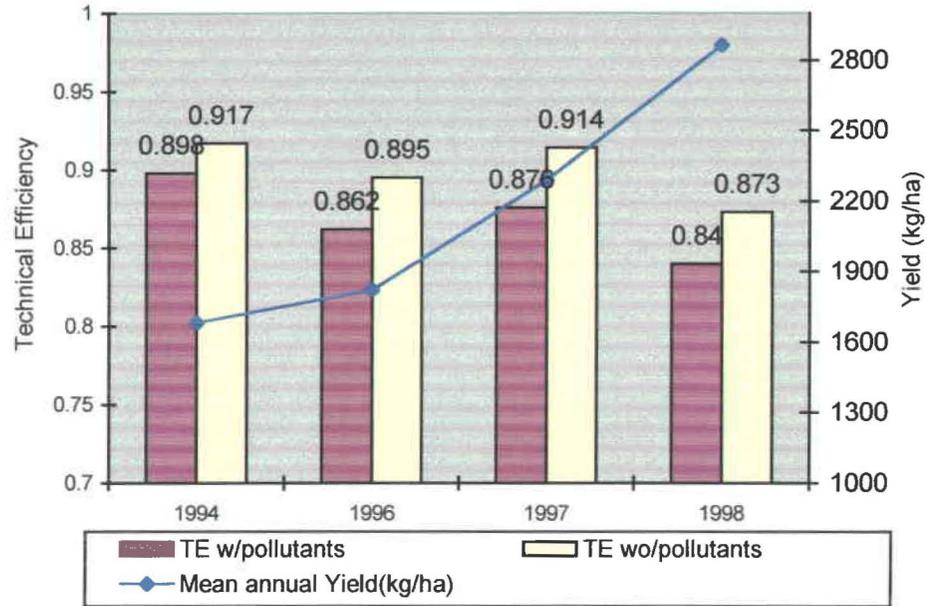


Fig.2.6 Comparison of average technical efficiency by year, with and without undesirable outputs, and yield (kg/ha).

between both TE scores is the smallest (1.91%). This shows that farmers were almost equally successful not only in producing the target output but when technical efficiency is penalized for the simultaneous generation of undesirable by-products (N and P outflows), they were able to maintain their relative distance to the frontier. On average, farmers during this year were closer to the frontier, including desirable and undesirable outputs. As was the case in traditional TE scores, once the viral diseases hit, environmentally-adjusted TE on average goes down, affected by the viral outbreak and the posterior transition stage to a new species, which reduced the capability of farmers to achieve the best environmentally-adjusted production scenario. Improvements in input use to achieve the same amount of outputs are in the order of 13.82%, 12.45% and 15.95% for 1996, 1997 and 1998 respectively.

2.3.4 Malmquist Total Factor Productivity (TFP) of farms

As discussed, the Malmquist Index approach provides a comparison across time of the same production units. Therefore, the same DMUs must be present in the sample each year. This reduces the number of observations to 49 and the results from the TFP evaluation are representative only of this data subsample.

An important decision when developing TFP evaluations using the Malmquist Index is the choice of the base of reference, t_0 , since the successive annual evaluations will be compared against this year. The first year in the time series can be t_0 or the last one. The possibility exists to let the base change, considering t_0 as the first year in a successive comparison of pairs of data. Letting the base change according to the succession of periods, is analogous to a Paasche Index, while keeping the same reference is analogous to a Laspayre Index (Førsund,, 1993). The TFP results from different base years or changing base can differ, which makes the selection, based on the characteristics of the problem to be analyzed, important.

In this study the analysis is more interesting if it centers on discerning productivity change from an initial state of efficient and high productivity production (year 1994). Therefore, focusing on the analysis of the viral outbreak and the transition through a new technology, the base year is kept as the initial year (1994). With only four years of information no possibility of carrying out a comparison against an old fashioned practice (base year) exists. Annual TFP Malmquist Productivity Indexes are shown in Tables 2.5 and 2.6, for the performance measurement with and without undesirable outputs. The tables include mean technical efficiency (TE) and technical change (TC) for analysis. Results are discussed in the next section.

Table 2.5 Mean annual Malmquist Productivity Index (1994=1.00), TE and TC with (W) undesirable outputs.

Comparison	Malmquist Index	TE	TC
1994/1996	0.853	0.971	0.878
1994/1997	0.840	0.947	0.887
1994/1998	0.870	0.942	0.923

Table 2.6 Mean annual Malmquist Productivity Index (1994=1.00), TE and TC without (WO) undesirable outputs.

Comparison	Malmquist Index	TE	TC
1994/1996	0.878	0.966	0.908
1994/1997	0.882	0.987	0.893
1994/1998	0.919	0.948	0.969

2.3.5 Shadow price of pollution abatement

One of the remarkable characteristics of using the Distance Function approach is the additional possibility for obtaining shadow prices of pollutants or shadow costs for pollution abatement, taking advantage of the duality between the Distance Function, and the Cost and/or Revenue Functions (for input-oriented and output-oriented approach, respectively). Using the full dataset (302 ponds), the calculation of the shadow prices uses equations 9-12. The ratio in equation 11 can actually be interpreted as the marginal rate of transformation between pollution abatement and the desirable output, indicating how many units of shrimp the producer would be willing to forego for the right to emit one more unit of pollutant output. In obtaining these pollution abatement costs, the shadow price of the good output (shrimp) is assumed to equal its market price, for each

year. Means of pollution abatement shadow costs are reported in Table 2.7 for N, P and at pond level.

Table 2.7 Annual mean shadow costs of pollution abatement for N and P outflows, and total (P+N) at DMU (pond).

Year	P-shadow price (USDS /kg)		N-shadow price (USD \$/kg)		Pond total abatement cost (USD)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
1994	-10	5.25	-7.09	1.08	10,740	5,484
1996	-9.32	1.31	-6.58	0.75	4,511	2,896
1997	-7.75	0.68	-5.23	0.45	5,772	2,291
1998	-6.32	0.37	-3.6	0.32	6,249	2,651

The sign of the shadow prices is as expected: imposing the specific constraints that incorporate the heterogeneous treatment to desirable and undesirable outputs (the input function should be non-decreasing with respect to undesirable outputs but non-increasing in desirable ones), make the ratio of equation 11 negative, and the market price of shrimp is obviously positive so the product is negative. These non-positive pollutant shadow prices indicate the marginal cost of pollution abatement to the producer, or the opportunity cost of pollution abatement.

The results show that the average marginal cost of pollution abatement for N and P emissions decreases from US \$ 10,740 per pond in 1994, to \$4,510 the next year, since marginal abatement costs are lower. Although pollutant shadow prices continue to decrease in subsequent years, the amount of pollutants almost doubled, affecting the total pollution abatement cost per pond, reaching in 1998 an average of US \$ 6,249.

Pollutants discharged from shrimp farming operations don't have a market price, as inputs and desirable outputs do³. Therefore these shadow prices are non-observed prices and give an estimation of an internal (to the firm) price, thereby providing a consistent measure of private costs. With the input orientation of this research, they serve as proxy for the cost of pollution abatement. At the same time, technological change or efficiency change may cause both good and bad output to simultaneously increase or decrease, and without knowledge of the economic value placed on the good and bad outputs, whether the change has been welfare improving cannot be ascertained. Thus, estimation of shadow prices for undesirable outputs will enhance our ability to evaluate changes in the production of good and bad outputs, and to assess changes in the use of inputs including costs incurred in the establishment of pollution abatement technologies, if the approach is input-oriented as in this work.

Whether the shrimp farms analyzed in this essay, were already implementing pollution abatement measurements, and to what extent, is not known⁴. Nevertheless, evaluation of the total pollution cost (which is an estimation of total pollution abatement cost) for the shrimp farms, according to the production information available for this study and assuming that the firms were not incurring any expense to reduce pollutants emissions is useful. Since this is an estimation of an internal (firm) price, it is again specific to the database and to the characteristics of the firms analyzed, and serves as a reference point for future industry studies.

³ This can be generalized to all pollutants originating from the aquaculture industry worldwide. However, market price information for pollutants from other more regulated industries, like SO₂ from the power generation industry exists. Emission permits for this pollutant were traded on the Chicago Mercantile Exchange in 1993. SO₂ allowances are a valuable and tradable commodity.

The following analysis evaluates what is the relative magnitude of this cost (opportunity cost of pollution abatement) to the firm, related to farm revenues and estimated profits. A sensitivity analysis is performed to assess this extra cost per year. The proportion of the abatement cost to annual revenues, and to annual profits, assuming total operation costs as different percentages of revenues (30%, 45%, 60% and 75%), are illustrated in Figure 2.7. The detailed results are included in Appendix C, Tables C.1-C.4, and are discussed in the next section of this essay.

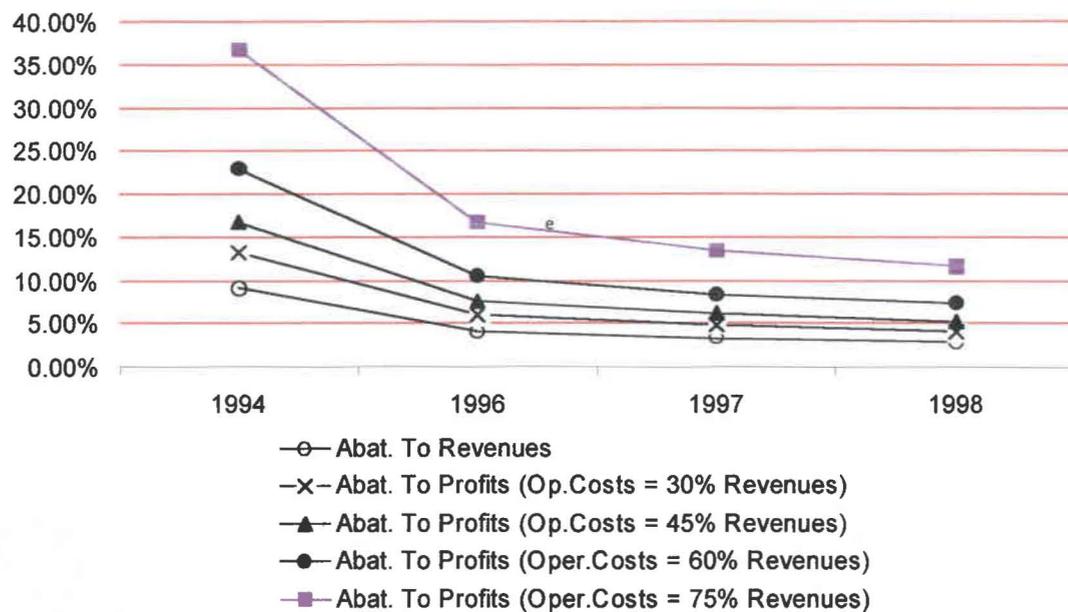


Figure 2.7 Sensitivity of revenues and profits to pollution abatement technology costs (Abat to Revenues= % of pollution abatement cost to annual revenues).

⁴ Little evidence exists for, at least the period of time analyzed in this study, which shows that pollution abatement was implemented, since the farms were recovering from an emergency due to the viral outbreak.

2.4 Discussion

2.4.1 Technical Efficiency and Total Factor Productivity

The separation of the TE effect from the technological change (TC) in the Malmquist TFP Index is an important distinction for the analysis of results. TFP scores decrease after the viral diseases, both traditional and environmentally-adjusted. The first TFP regression (in 1996, compared against the base year of 1994) is a direct indication of the viral diseases, and is the biggest reduction in TFP in the 4 years analyzed. Since TE is very uniform across the 3 periods (always close to 1, which reflects that on average most of the ponds maintained or even reduced their distance to the respective annual frontier), the productivity changes have their origin in the negative impact of the sudden change in technology (TC) as consequence of the viral outbreaks, which forced producers to introduce a new shrimp species in their operations⁵.

How does the new technology (regression) impact the production performance? Based on Figure 2.8, the new technology increases input use. Feed conversion rate (FCR), water use and labour increased annually, while seed use was reduced only in the last year. Though yields also increased, the output/input ratio was smaller after the introduction of the new technology, since all inputs were more intensively used every year (with the exception of seed use in 1998). When nutrient outflows are considered, environmentally-adjusted TFP scores are smaller.

⁵ The blue shrimp had already been used in the past in commercial operations in Mexico (Salgado 1994), but very sporadically and with a small presence, never taking the role of the industry's predominant species. However, when viral diseases impacted operations with white shrimp, the industry strongly demanded blue shrimp postlarvae to stock ponds in the period 1997-2000. This boom finished in 2000, again due to viral diseases, and most of the farmers returned to stock white shrimp. In addition, for warmer climates (Sinaloa), white shrimp is a better species to rear.

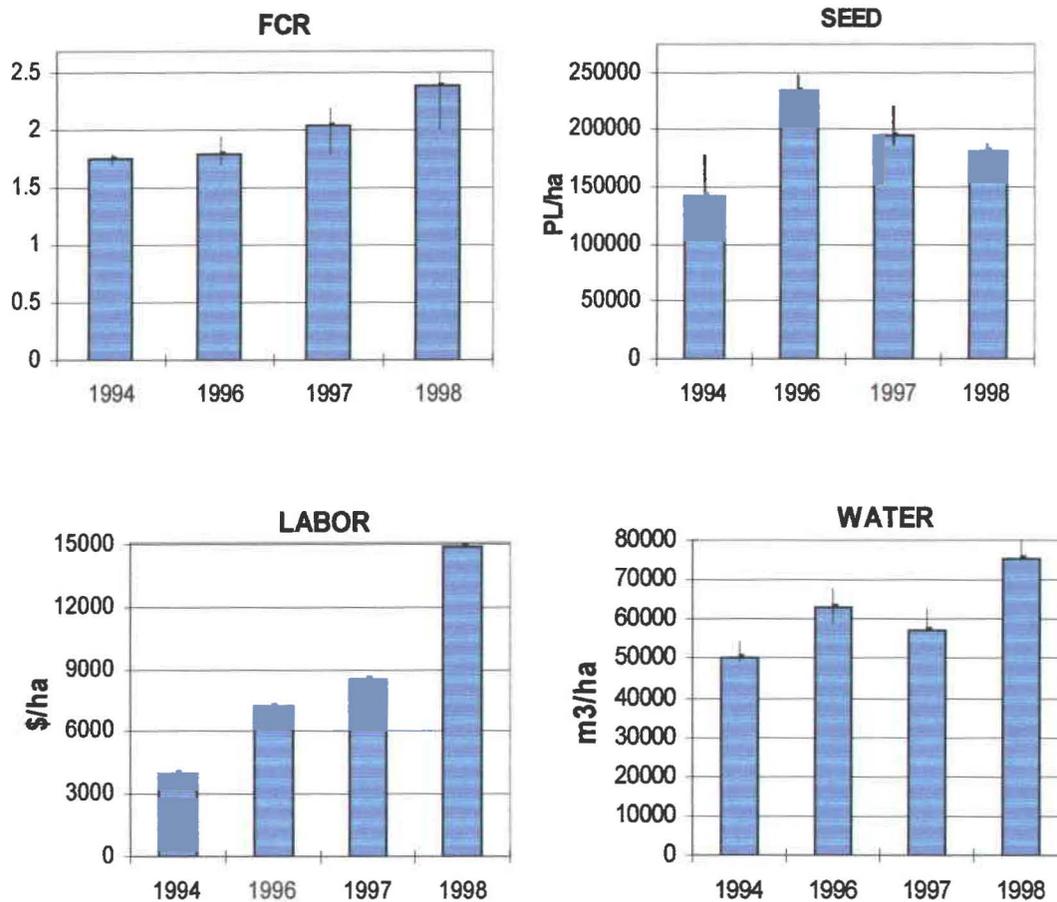


Figure 2.8 Annual mean input use during the four years analysed, with 95% confidence intervals.

This result and conclusion is similar with the findings of Tveteras and Heshmati (1998) in their productivity analysis of the Norwegian salmon farming industry. They also concluded that productivity growth is negatively correlated with economic losses due to diseases and weather changes. In this essay, the magnitude of the TC decay - resultant from a disease outbreak- brings down TFP in 1996 and 1997, despite positive

and uniform TE of ponds. Therefore, the main source for negative TFP growth rates is a technical regress, since with a new technology farmers were using more units of inputs to obtain the same amount of output (following the input orientation of this essay).

While a TC regression similarly reduces TFP as a consequence of the adjustments from diseases, an improvement in technology similarly inverts the negative trend in TFP in 1998. In this period, average traditional TE is reduced slightly and environmentally-adjusted TE maintains its level, supporting again the hypothesis that whatever modification was taking effect in the frontier, most ponds and farms were able to incorporate it. On average, room for improvement in ponds in the last year (1998) is reduced 5.2% for traditional TE and 5.8% for the environmentally-adjusted one, compared to 1994's TE score. The technological effect (in this case an improvement) is the main influence for the growth in TFP. It is a shift in the production frontier (inwards, according to the input orientation of the study) that makes it possible to use less inputs to generate a fixed amount of outputs. This technological improvement might be the result of the farmers by themselves learning the new technology and adapting to its requirements. Although nutrients discharged registered their peak, at an average of 199.49 kg/ha for N and 19.67 kg/ha of P, yields also grew to a high of 2864 kg/ha. With both elements influencing the measurements of environmental production performance, the increase in yields was strong enough to at least revert the negative growth rate in TFP, together with the capability of more ponds to operate closer to their 100% efficiency scenario in that period. Consequently, for the first time in 3 periods after diseases outbreaks, TFP grows. However, as expected, environmentally-adjusted TFP is smaller than the traditional score (0.919 vs 0.870).

Mean environmentally-adjusted TE for the three periods is 0.953 and 0.967 for traditional TE. This shows that most of the ponds and farms were able to react uniformly, which might be the result of uniform technical assistance to cope with the problem and farmers' ability to learn to adjust. Notwithstanding that, the frontier adjustment was, in the first two years, not a technological improvement but a regression, that made firms use more inputs and in the case of nutrients discharges, to increase the average amount of N and P discharged.

The analysis of TFP values with undesirable outputs is complemented with the use of the mean annual N and P discharges for the four years, depicted in Figs. 2.2 and 2.3. As can be seen, mean discharges of N and P dramatically increased in 1997 and 1998. Under the "fair" environmentally-adjusted TFP Index, which rewards producers not only for inputs used to generate the desirable product but also for those not directed towards the production of undesirable outputs, farmers have lower productivity in the period 1996-1998, compared to the TFP scores without pollutants for the same years. The conventional productivity measure, by neglecting the increments in pollutants emitted in these two years, fails to indicate that a higher percentage of inputs could have been saved if there had been fewer undesirable outputs generated.

Comparative results between traditional and environmentally-adjusted indicators differ in this essay to the ones reported by Hailu and Veeman (2000) in their analysis of the Canadian pulp and paper industry. They found that environmentally-adjusted productivity is higher than the traditional one, because the pulp and paper industry in Canada has been successful in reducing average annual rates of pollutant emissions, so the adjusted performance measure rewards the producer or industry for this achievement.

That might be the case of the shrimp farming industry in Mexico before the viral diseases, as shown by the only year analyzed where operations were “normal” (in 1994 conventional mean TE is 0.91 vs 0.9 of environmentally-adjusted TE). In this year the ponds and farms on average are almost equally efficient when considering all outputs produced and under conventional TE estimations.

Reinhard et al. (2000), in their analysis of Dutch dairy farms, found that conventional technical efficiency scores are higher than environmental ones, where environmental efficiency is defined as the ratio of minimum feasible to observed use of environmentally detrimental inputs, conditional on observed levels of the desirable output and conventional inputs. Reinhard et. al. model the pollutants as inputs in the production technology. Finally, in his study of the agricultural sector of the Netherlands, Oskam (1991) also found that the inclusion of the environmental effects reduces total and net factor productivity scores, with respect to traditional TFP. Oskam calls the performance measurement adjusted by environmental effects and the one which is not, “social” and “private” productivity and productivity change, respectively.

Economists commonly use partial productivity ratios such as output per worker and output per hectare to compare productivity of production enterprises. However, they have also recognized the inadequacy of these partial productivity ratios which can provide a misleading picture of productive performance and have subsequently developed a more comprehensive concept (Total Factor Productivity Indexes), which compare outputs with the combined use of all inputs (resources). The relevance of measuring and analyzing other production performance indicators in addition to yield (which is a partial productivity ratio) is clear from Figure 2.6 and Tables 2.5 and 2.6. While yields were

always increasing⁶, TE and TFP show that firms were less successful in transforming inputs to a fixed amount of output (including pollutants) in the two years that followed the disease problems. The year when the transition to blue shrimp started (1997) had lower efficiency and negative productivity growth that continued when blue shrimp became the main species (1998). Also, the results show that the recovery in TFP seems to begin in 1998. The highest TFP scores (both traditional and environmentally-adjusted) are found in 1994, when farmers were more efficient, demonstrating their expertise in rearing white shrimp. After bouncing back in 1997, 1998's production performance (TFP) improved slightly.

The joint analysis of yields and production performance measurements, including environmentally-adjusted ones, indicates that although farmers were always able to increase annual yields, the managerial tool behind this achievement changed as a consequence of the diseases and the ensuing adjustments, in addition to the learning-by-doing they were performing with the new technology and species. After the diseases, the increased yields were achieved with increased use of inputs, mainly feed and water. Since the additional feed also increased the amounts of nutrients discharged into water, the environmentally-adjusted performance indicators were lowered even further. Water exchange was likely to be increased once high FCR were realized, in an effort to maintain good water quality in the ponds for high growth and survival rates.

The value of the time series characteristic of the panel of data should also be highlighted. Although only four years of information are available, it allows the analysis

⁶ Yields actually were down in 1995, but data available from operations are minimal, since most of the ponds and farms suspended activities at some point, or mortalities were above 90%.

of production performance over time in response to the viral outbreak and the transition from one species to the other as an adjustment. Farmers in this region are experts after many years rearing shrimp commercially. They have been an important element for the development of the shrimp farming industry in Mexico as well. Despite not having this study data available before 1994, which would have shown the years when these farms learned to successfully rear white shrimp, TE scores in 1994 are the highest in the sample, with environmentally-adjusted measures of performance almost equal to standard ones. Thus, producers are capable of achieving a high yield efficiently in an environmentally-friendly way, by directing inputs more successfully to the generation of the desirable outputs and not of the by-products. When an event of the magnitude of a viral outbreak occurs, the time series analysis of TE and TFP allows analysis of its real impact, the dynamics of TE and TC effects and how the adjustment was carried out.

The lower TFP scores found in this study, corresponding to the years of transition and adjustments after viral diseases, were certainly expected. The consequences of the viral diseases were strong for the industry in general. The blue shrimp was rapidly and intensively introduced into operations in northwest Mexico, with the TFP and TE values in the last year (1998) showing an improvement in production performance.

The decomposition of productivity into its constituent parts (TE and TC) provides valuable information for strategic decisions, again, both at farm and planning levels. If a lack of growth occurs due to technological regress (for example technological obsolescence), the situation could be corrected with more research into new technologies. On the other hand, if a lack in productivity growth is due to low TE, then the managerial incompetence of producers should become the focus. Training and education plays an

important role so that those firms with lower TE values (“laggers”) “catch-up” with more efficient ones.

At the heart of this study are the policy implications of measuring production performance. The result, that the regression in productivity as a result of the viral outbreak, took primarily the form of a technological regress is interesting. Although farmers were not too far from the annual frontier, the technological change required more inputs to get the same level of output. The capability for transmission of knowledge about these new procedures is a key factor for a fast recovery in production performance. Therefore, training in the new technology know-how must be expedited to cope with the problem. The environmentally-adjusted estimators further prove the need for a rapid transition period. The uniform and high TE scores indicate that farms in this region share and exchange information, which can be a competitive advantage.

The environmentally-adjusted indicators in the year of normal operations (1994) indicate that the shrimp farmers can achieve high production and can be environmentally efficient at the same time. A continuous debate is under way as to whether the aquaculture industry in general will be able to continue its growth in a sustainable manner. The environmentally-adjusted performance measurements like the ones applied in this essay, facilitate the quantifications to sustain or refute this argument. Decision-makers can also understand the trade-off between the desirable and undesirable outputs to assist them in designing policies to improve current operations and enhance sustainability.

2.4.2 Shadow price of pollutants (marginal cost of pollution abatement)

The shadow price of pollutants can be interpreted as the increase in costs that the production of an additional unit of the output entails (Hailu,2000).

The unit mean shadow price of P and N effluents shown in Table 2.7 are higher for 1994, when less N and P were released, and decrease until reaching a low \$3.6/kg N and \$6.32/kg P in 1998. These mean shadow prices are calculated as the average of the pond estimates of the shadow prices, and not as shadow prices calculated at the mean values of the data. For all years, the standard deviations are small relative to the means, representing that in general there is a good level of uniformity in the observed levels of effluents released by the DMUs in a year.

In this essay, shadow prices of N and P follow the same behavior discussed in other similar studies reported in the last decade for shadow prices of pollutants in different industries (Färe et al., 1993; Coggins and Swinton, 1996; Hailu and Veeman, 2000, Hernandez-Sancho et al., 2000; Reig-Martinez et al., 2001). Decision making units that emit fewer pollutants and are therefore more environmentally-efficient, have higher unitary pollutant shadow prices than inefficient DMUs.

The interpretation of this result is as follows: for firms or ponds with high undesirable emissions, investment intended to cut the volume of effluents would have a relative small cost in comparison with their prospective yields in terms of reduction of pollutants. Conversely, firms that already have reduced pollutant emissions would face a higher marginal cost, if they seek even further reductions in emissions (Hailu and Veeman, 2000; Reig-Martinez et al., 2001). The decreasing values of the shadow prices

(marginal cost of pollution abatement) every year refer to the fact that there has not been significant progress in abatement technology. This again is a reflection of the characteristics of the problem analyzed: the new shrimp production technology introduced after the viral diseases requires adaptation and learning, and the efficient production with less discharge of nutrients was not found in the initial years. When a firm (or decision making unit as pond in this case) is less adapted to minimise the release of residuals, investment intended to cut the volume of effluents would have a relatively small cost in comparison with their prospective yields in terms of reduction of emissions. On the other hand, firms who are already controlling successfully their emissions would face a higher marginal cost in the case of searching for an even higher reduction of waste discharges. For these latter firms, this would be reflected in a higher shadow price for bad outputs (Reig-Martinez et al., 2001). These decreasing marginal costs of pollution abatement also mean that the increasing returns to pollution abatement due to the low rate of pollution abatement for the period of time analyzed are big compared with the marginal cost of abatement brought about by improvements in pollution abatement technologies.

Under the input (and cost) minimization approach followed in this study, the negative sign of the shadow prices for pollutants indicate not an input (and cost) reduction but the marginal extra input (and cost) that at pond level should be put forth in order to maintain the emission of aggregated N and P outflows constant, by means of pollution abatement technology.

Although DMUs face lower unitary shadow prices of N and P pollutants per kg in the years of higher emissions (1997-1998), figure 2.6 and tables C.1-C.4 show that the

cumulated cost is higher (total pond abatement cost) compared to more environmentally-efficient ones (1994).

The economic impact of pollution abatement technology is finally assessed for the semi-intensive farms of the database, assuming firms have not invested in pollution abatement. The analysis evaluates the impact on firms' revenues and profits of investing in pollution abatement costs, assessing total operating costs at different percentages of a firm's revenues. The sensitivity analysis shows that in 1994, when unitary shadow prices of pollutants are higher (Table C.1), the proportion of total pollution abatement costs to revenues is in the range of 5.05% to 14.10%. Taking the worst financial scenario, when operating costs are 75% of total revenues, pollution abatement costs are 20.2% to 56.4% of profit. In 1998, when pollution is at its peak but marginal cost of pollution abatement is at its lowest, this extra input and cost directed to pollution abatement is in the range of 8.71% to 14%, taking the worst financial scenario when total operation costs are 75% of revenues. The implementation of pollution abatement adjustments or technologies is considered economically feasible for the firms.

What is the significance of this evaluation? This research provides a reference point because until now, no estimation of shadow prices of shrimp farming pollutants was available. Assessing pollutant shadow prices in terms of marginal abatement costs and comparing these costs to firm's revenues and profits, provides insights into the firms financial capability to solve environmental impacts. For example, Färe et al. (2000) conducted a study to determine shadow prices and pollution costs in US agriculture, and found that total pollution costs average about 17.5% of crop and animal revenues. He found that in Georgia in 1993 there were negative net revenues indicating that the

revenue from crops and animals was offset by pollution costs. That State in that year wouldn't have been able to solve the pollution problem financially, unless some external government support was provided. The firms examined here have the financial capability to deal with pollution control.

CHAPTER 3

MULTICRITERIA DECISION MAKING (MCDM) MODEL FOR REGIONAL SUSTAINABLE SHRIMP FARMING DEVELOPMENT IN MEXICO

3.1 Introduction

Decisions concerning aquaculture development are affected by several conflicting criteria. Usually the conjoint establishment of social, economic and environmental criteria requires the evaluation of trade-offs among the objectives. For the central planner or decision-maker in charge of evaluating the effectiveness of policies for aquaculture development, multiobjective analysis may be more appropriate than general cost-benefit analysis if the objective is to improve the effectiveness of the policy process itself. Developing a model for evaluating aquacultural public policy is fundamentally a problem of decision science.

Sylvia (1997) discusses the need for the application of models, such as Multicriteria Decision Making (MCDM) models or Decision Support Systems (DSS), which properly reflect the multiobjective and multicriteria features of aquaculture development. With a growing concern about the environmental effects (externalities) of aquaculture, the majority of the models found in the literature for aquacultural policy and planning focus on controlling environmental pollution. Unfortunately, Sylvia's review concludes that economic policy models under MCDM approaches have not yet played a significant role in aquacultural policy development, and if sustainability is incorrectly defined, institutions will not promote socially efficient aquacultural industry growth.

Despite the empirical evidence, modelers in aquaculture economics and planning have not paid much attention to the crucial role that could be given to several objectives

and goals in designing decision making models. Multiple-criteria analysis of aquaculture more realistically depicts the strong motivation of decision makers to seek optimization or satisfaction of several objectives or goals rather than pursue the maximization or minimization of a single one.

The problems posed by multicriteria optimization are raised not only in connection with model design by central government and at the level of a single branch of the national economy, but also in the lower links of management. At the enterprise level, application of multicriteria analysis and decision making is urgent in many cases and influences practical solutions. Enterprises have their basic, strategic, tactical and operative, exogenous and endogenous goals. All these goals and objectives cannot be modeled by a sole global criterion of optimality (Pitel, 1990).

Several techniques are available for handling MCDM problems (Zeleny, 1982; Romero and Rehman, 1989). The application of each of them depends upon the characteristics of the problem, the information available and the goal of the decision-maker when using a MCDM technique. For example, if the situation is one with multiple objectives, then the recommended approach is either multiple objective programming (MOP) or compromise programming (CP), depending on the number of objectives considered.

MOP is usually considered to be the best approach when at most 2 simultaneous objectives are optimized. As the number of objectives increases, the size of the efficient set grows exponentially (El-Gayar and Leung, 2000) thereby overwhelming the planner with a large number of efficient solutions. In this case CP is recommended, because it searches for the best compromise and this solution is presented to the planner, who can

then avoid choosing from a large number of efficient solutions. When the problem is characterized by multiple goals (target values or aspiration levels are known a priori), weighted goal programming is recommended.

Among the few applications of MCDM to aquaculture is the work of Parton and Nissapa (1997) who applied goal programming for aquaculture decision-making in Thailand. A recent special issue of the Journal *Aquacultural Engineering* publishes several papers of MCDM analysis of aquaculture, including work by El-Gayar and Leung (2000) showing an application of multiple objective programming to aquaculture planning in Egypt, as part of an aquacultural DSS, and a paper by Bolte, Nath and Ernst (2000) and Ernst, Bolte and Nath (2000), discussing their experience in developing the softwares POND and AQUAFARM. Finally, El-Gayar and Leung (2001) present a multiple criteria decision-making framework for aquacultural development.

In the case of multi-objective problems, decision makers have the difficult task of analyzing and selecting a few alternatives as solutions to complex problems. A methodology that displays graphic information and solutions would help in making the process easier to interpret and analyze. Politicians also need information presented in a concise and comprehensive way.

Consequently, there is a necessity for developing a methodology that allows MCDM problems, with more than 2 objectives, to be properly conducted and analyzed under multi-objective approaches. This is the philosophy behind the development of the Feasible Goals Method (FGM) and Interactive Decision Maps (IDM) techniques by Dr. Alexander Lotov and his colleagues at the Russian Academic of Sciences in 1994. This graphics-based decision support technique provides information on the outcome of a very

large (or infinite) variety of possible decision strategies, and helps the decision-maker to select the best option. This technique supports the two phases of the decision choice process: decision screening initially, and what-if analysis in the final phase (Fig.3.1).



Fig 3.1 Decision Choice Steps (From Lotov et al., 1999)

Using decision screening, the FGM/IDM technique selects a small number of strategies and subjects them to further detailed exploration and what-if analysis, with both the static and dynamic graphic components included.

The concept of Pareto optimality plays a vital role in economic theory and is also very important for the different approaches within the MCDM methodology, particularly for the multiple objective programming. An efficient or Pareto optimal solution is a feasible one if no other feasible solution can achieve the same or better performance for all the criteria under consideration, and is strictly better for at least one criterion (Romero and Rehman, 1989). An allocation that is Pareto optimal uses society's initial resources and technological possibilities and assumes no alternative way to organize the production and distribution of goods that makes a consumer better off without making some other consumer worse off (Jehle and Reny, 1998).

The criterion of Pareto optimality, however, does not insure that an allocation is in any sense equitable. For example, using all of society's resources and technological

capabilities to make a single consumer as well off as possible, with all other consumers receiving a subsistence level of utility, results in an allocation that is Pareto optimal but not one that is desirable on distributional grounds. Nevertheless, Pareto optimality serves as an important minimal test for the desirability of an allocation, since it does, at the very least, ensure no waste in the society's allocation of resources (Mas-Colell et al., 1995).

When analyzing more than two objectives, the evaluation of trade-offs among them is usually necessary to take the final decision. The FGM/IDM methodology includes the broadened set of dominated points (called the Edgeworth-Pareto Hull) in the visual search of a solution for the multi-objective problem. The steps involved in this methodology are depicted in Figure 3.2.

This second essay of the dissertation analyses the sustainable development of shrimp farming in Mexico at a regional level, under a MCDM approach. A multiobjective, deterministic model is developed to analyze trade-offs of shrimp farming development in the northwestern region of the country. The model is static and doesn't include general equilibrium effects.

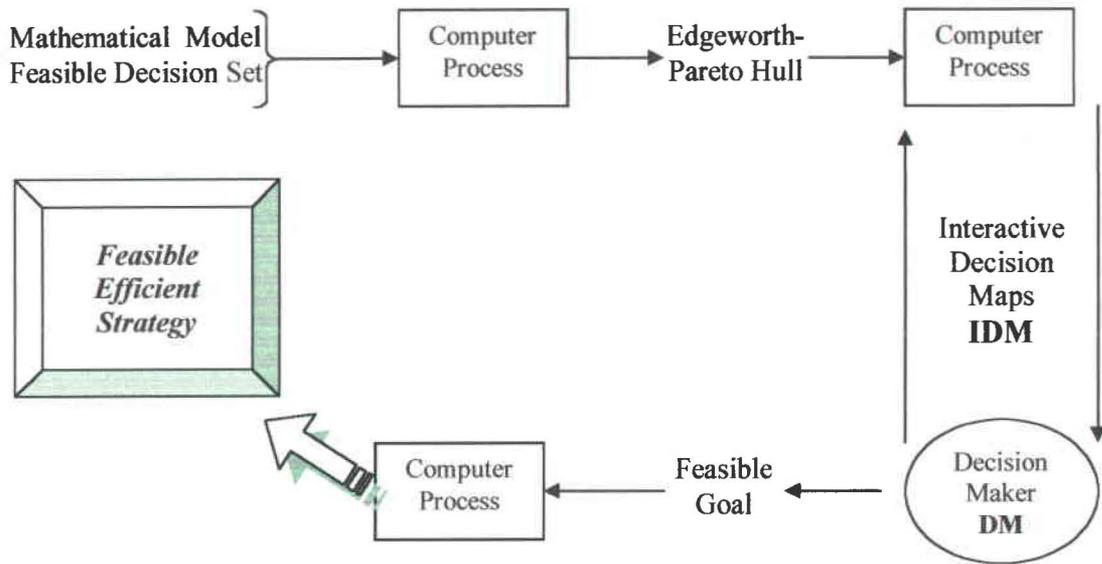


Figure 3.2 Steps in the Feasible Goals Method

3.2 Material and Methods

3.2.1 Secondary source information

Major data sources for the parameters used in the multiobjective model are described in Appendix D, Table D.1. Values of the main parameters in the baseline models are shown in Table D.2.

3.2.2 Mathematical model

An objective is a statement about the desired state of the system under consideration. It indicates the directions of improvement of one or more attributes. Objectives are functionally related to, or derived from, a set of attributes. For any given

objective, several different attributes are necessary to provide complete assessment of the degree to which the objective might be achieved (Malczewski, 1999). Policy objective functions in this essay represent the ones set by the Mexican government, cited in two documents: The National Plan for Development (2001-2006) and the Program of Aquaculture and Fisheries 2001-2006 (CONAPESCA, 2001). These objectives are: generation of employment (E), foreign exchange earnings (XG), increase of economic rents (ER) and promotion of sustainable aquaculture. In this study this last objective is included as pollution minimization, in the form of nitrogen (N) and phosphorus (P) effluent minimization.

The management problem is to determine the combination of shrimp farming production systems (new farms in addition to existing ones) to develop within a five-year period of time (2000-2005) in the northwestern region (3 States: Sinaloa, Sonora and Nayarit, see Annex A), selecting from 3 possible production levels (extensive, semi-intensive and intensive) and two species (Pacific white shrimp *Litopenaeus vanammei* and blue shrimp *Litopenaeus stylirostris*), while at the same time fulfilling the projected market demand (national consumption) and land constraints (Figure 3.3). Since shrimp is a luxury product, its role in the national market is not evaluated in terms of food security, but instead the need to satisfy current consumption levels, including population growth, in the next five-year period. This five-year period begins in 2000 since the latest shrimp production statistics available are from 2000. The MCDM model has four objectives considered in the process of the search for a development strategy:

- Maximize economic rent (ER):

$$Max Z_1 = \sum_{s=1}^3 \sum_{j=1}^3 \sum_{i=1}^2 [(y_{s,i,j} \cdot ep_i \cdot SE_i) + (y_{s,i,j} \cdot lp_i \cdot (1 - SE_i)) - C_{j,i,s}] \quad (15)$$

where

$y_{s,i,j}$ = Shrimp production (kg) of system operating at production intensity level j , with species i and at State s

SE_i = Share of production to the export market

ep_i = export selling price (US \$) of species i (assuming uniform sizes in harvests)

lp_i = local selling price (US \$)

$C_{j,i,s}$ = Total operating costs of a shrimp farm under system j , rearing species i , in State s

- Maximize regional shrimp on-farm employment (E) (in persons):

$$Max Z_2 = \sum_{s=1}^3 \sum_{j=1}^3 E_{j,s} \quad (16)$$

where:

$E_{j,s}$ = Number of persons working in production system j in State s

- Maximize foreign exchange earnings from shrimp exports (XG):

$$Max Z_3 = \sum_{s=1}^3 \sum_{j=1}^3 \sum_{i=1}^2 (y_{s,i,j} \cdot (SE) \cdot ep_i) \quad (17)$$

Since the model assumes zero imports of seed and feed, this objective doesn't reflect a balance of payment's objective but rather reflects simply the interest in maximizing foreign exchange earnings from shrimp exports.

- Minimize total (N+P) pollution discharges (TOTPOLL)¹:

$$\text{Min } Z_4 = \sum_{s=1}^3 \sum_{j=1}^3 \sum_{i=1}^2 (nd_{s,i,j} + pd_{s,i,j}) \quad (18)$$

where:

$nd_{s,i,j}$ = average nitrogen discharge of production in State s with species i , and system j

$pd_{s,i,j}$ = average phosphorus discharge of production in State s with species i and system j

The optimization problem is subject to land availability and national shrimp demand constraints, as follows:

- Land availability: total coastal land available for new farms in the region. Sites with good quality-seawater are assumed to be in enough supply. Expected new area incorporated into shrimp aquaculture per year is 2000 ha. for the States of Sonora and Sinaloa, and 500 ha. for the State of Nayarit.

$$\sum_s L_s \leq TL \quad (19)$$

where:

L_s = Land required for shrimp aquaculture in State s

TL = Total land available for shrimp farming development in the 5-year span

- Market (national) demand: required shrimp production to fulfill with projected shrimp demand in Mexico. See assumptions in the next section for clarification

¹ Nitrogen and phosphorus minimization were initially evaluated as two independent optimization objectives, but the results are identical if N+P is set as the minimization objective. The reason is that, although total N and P discharges (in ton/ha) vary among extensive (E), semi-intensive (SI) and intensive (I) systems, species and States, there is no system where P discharge > N discharge, and always E discharge < SI discharge < I discharge as well. Hence, the environmental objective is set as minimization of total (N+P) discharges.

$$LCons \leq \sum_{s=1}^3 \sum_{j=1}^3 \sum_{i=1}^2 (y_{s,i,j} \cdot (1 - SE_i)) \quad (20)$$

where:

LCons = Local Consumption, projected from historical data
 (1-SE_i) = Share of production to the local market

Figure 3.3 shows the MCDM model developed.

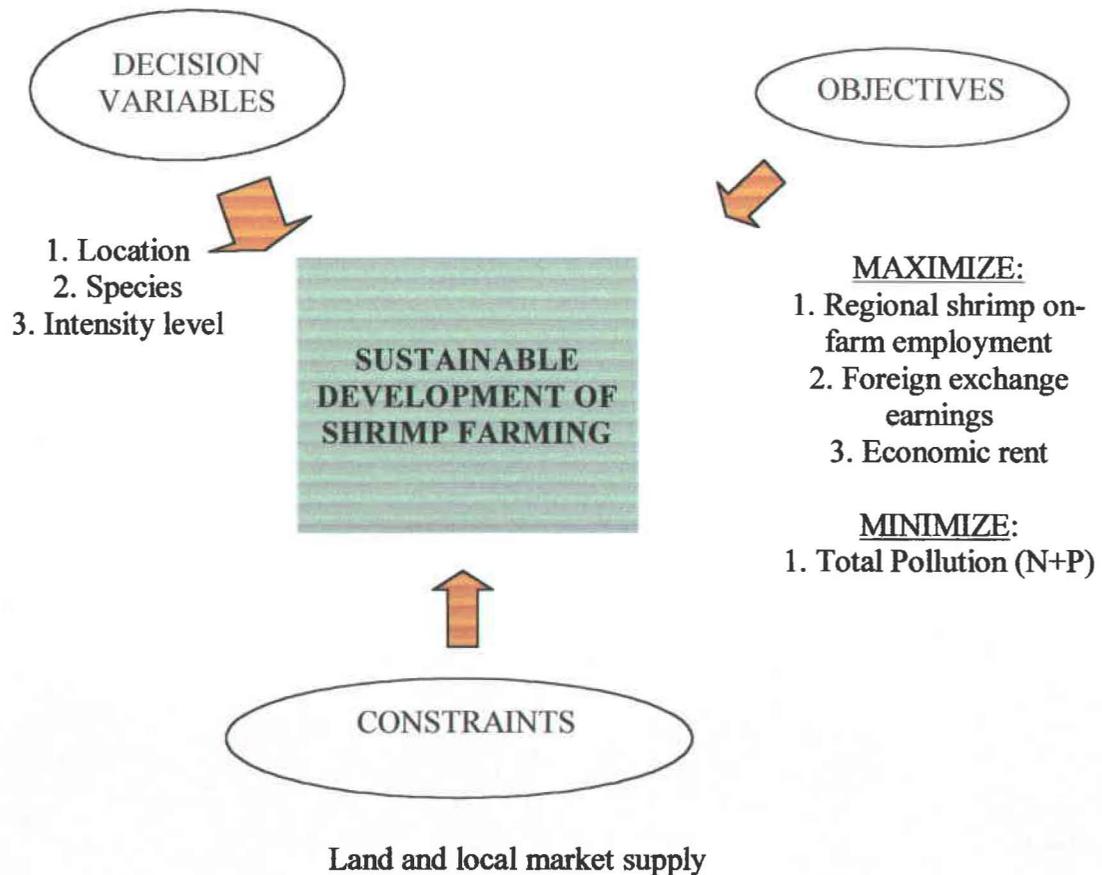


Figure 3.3 Multiple Criteria Decision Making Model for Sustainable Development of shrimp farming in northwest Mexico.

The underlying assumptions of this model are the following:

1. The northwestern region has different bio-technological parameters for each of the three shrimp production levels (extensive, semi-intensive and intensive), in terms of stocking density, survival rates and annual yields. These parameters differ between white and blue shrimp as well. Blue shrimp is not reared in Nayarit, and Sonora will not develop intensive or extensive systems (based on historical data).
2. Prices of commodities, availability of labor and commercialization costs are assumed fixed within the region, but wage rates differ among the three States. Water quality and sources are homogeneous in the region. Total new land developed for shrimp farming is distributed among the States of Sonora, Sinaloa and Nayarit and the scenario of no land developed in any of the three States is not feasible. The potential for shrimp farming development in each State varies since Sonora and Sinaloa can incorporate up to 2000 ha/year, Nayarit 500 ha/year. Seed and feed are locally supplied (no imports) and there is enough to sustain current farms and the new ones to be established.
3. All resources are available locally, and 90% of the shrimp production goes to the export market (based on current estimations).
4. The annual average per capita shrimp consumption in Mexico in 2000 was 0.54 kg and the share of aquaculture to total local consumption was 6.3%. The future shrimp demand in the local market in the year 2005 is estimated by multiplying per capita human consumption times expected population in that year, projected from a 50 years time series. Maintaining the same percentages for 2005 as in 2000, the extra amount of shrimp that the new farms would need to add up to current share is only 200.25

tons. Hence, more ambitious goals in terms of national consumption are introduced in the baseline models: the share of aquaculture to local consumption is assumed to increase from the 6.3% currently to 13.33% by 2005, with the intrinsic consideration that fisheries will remain stagnant at current yields and therefore aquaculture has to take a more decisive role to supply the local market. For all scenarios, any system that exceeds 4,173 tons for local consumption (the minimum production necessary to keep current per capita shrimp consumption) will allocate to the local market the excess for a fixed amount of 10%. Shrimp demand projections take into account population growth only, but certainly a more complete projection of shrimp demand would be determined by a complex and interactive set of factors. Among them, the estimated supply of capture fisheries, aquaculture and product substitutes (chicken), which will in turn depend on the state of the marine ecosystem and on the human possibilities to manage it. Also, supply and demand responses to changes in real price levels determined by market conditions as well as changes in national (Mexican) and international policies will influence the future outcome.

5. A single-decision-maker process, representing the central planner who is in charge of setting policies for aquaculture development in the country is assumed.

The efficient trade-offs for the four criteria are obtained using FEASIBLE GOALS[®], which allows for the collection of the efficiency frontiers comprising a decision map. Based on these decision maps, trade-offs among objectives are depicted in a very friendly, graphical interface, where the user can analyze and modify the outputs, with a picture of non-dominated but also dominated scenarios. This methodology was developed by Dr. Alexander Lotov and colleagues at the Russian Academy of Sciences,

who have applied it to investigate long-term economic development strategies at country level (Lotov et al., 1992), to analyze ocean waste management decisions (Lotov et al., 1998) and water quality planning (Lotov et al., 1999) among other reported studies. It was also applied by Leung et al. (2001) to evaluate regional economic impacts of fish resources utilization in the Barents Sea.

For comparison and as a preliminary analysis, single-objective optimization policies are evaluated using LINDO[®], independently for the four objectives described.

3.3 Results and Discussion

3.3.1 The baseline model and single-objective optimization

As a preliminary analysis, single-objective optimization was assessed for the industry development, evaluating separately the objectives of Economic Rent (ER), Employment (E) and Foreign Exchange Earnings (XG) maximization, and total pollution (TOTPOLL) minimization. Table 3.1 presents the results for these Baseline cases, for all relevant model variables. The results indicate the following:

- Extensive systems are never supported as part of the industry development, regardless of the policy objective pursued. Since these production systems employ the fewest people among the three, and generate less rent and production, its attractiveness as the system with lower environmental impact is not strong enough to be selected as part of the industry development under individual, independent optimization policies, even under a pollution minimization planning objective. In this later case, although extensive shrimp farms pollute the least,

Table 3.1. Five-year planning (2000 to 2005) optimal solutions for the main model parameters, single-objective optimization.

Variable	Total Pollution Minimization	Economic Rent Maximization	Employment Maximization	Foreign exchange earnings Maximization
F121	200	200	0	200
F122	0	0	200	0
F211	0	0	0	0
F221	118	0	0	0
F231	0	200	0	200
F212	0	0	0	0
F222	0	0	200	0
F232	0	0	0	0
F311	0	0	0	0
F321	0	0	50	0
F331	0	50	0	50
Production	41,730	102,000	57,000	102,000
Rent	159,172	322,524	62,560	322,524
Tot.Poll.	1,395	4,340	3,145	4,340
Local supply	4,173	10,200	5,700	10,200
Foreign	363,552	888,624	417,960	888,624
Employment	5,403	6,150	7,650	6,150
Extensive	0	0	0	0
Intensive	0	250	0	250
Semi-int.	318	200	450	200
Sonora	200	200	200	200
Sinaloa	118	200	200	200
Nayarit	0	50	50	50

$F_{s,j,i}$ number of farms in the State s (1=Sonora, 2=Sinaloa, 3=Nayarit), using production system j (1=extensive, 2=semi-intensive, 3=intensive) and species i (1=white shrimp, 2= blue shrimp)

Production= Total shrimp production (ton)

Rent= Total Economic Rent from industry development (\$000 US)

Tot.Poll= Total nutrient outflows (cumulated phosphorus and nitrogen). (ton)

Local supply= Total shrimp production to national market, to fulfill local projected demand. (ton)

Foreign= Foreign exchange earnings from the industry development (\$ 000 US)

Employment= Total number of new on-farm workers from the industry development.

Extensive= Total number of new extensive shrimp farms established in the region

Intensive= Total number of new intensive shrimp farms established in the region

Semi-int= Total number of new semi-intensive shrimp farms established in the region

Sonora= Total number of new farms in the State of Sonora

Sinaloa= Total number of new farms in the State of Sinaloa

Nayarit= Total number of new farms in the State of Nayarit

total production from an only-extensive-farms scenario doesn't fulfill with one of the constraints, which is the minimum production required to satisfy local demand.

- Total nitrogen and phosphorus discharges, and land available are used to the limit under economic rent and foreign exchange earnings maximization.
- With an economic rent or foreign exchange earnings maximization development strategy, planners would select intensive systems, allocating to them the totality of land in Sinaloa and Nayarit, the two States where intensive systems can be promoted. Total individual production and rent are higher in intensive scenarios compared to the options, and thus is the most attractive option.
- Under an employment maximization development policy, economic rent, total production of shrimp and foreign exchange earnings are at their lowest levels compared to the other single-objective optimization cases. Since semi-intensive systems are more labor-intensive, developing the shrimp aquaculture industry following an employment maximization strategy allocates all available land in the three States to semi-intensive shrimp farms.
- The four single-objective development scenarios each fulfill the minimum shrimp production necessary for national consumption (4,173 tons). Furthermore, developing the industry under ER or XG maximization objectives means higher production levels achieved, allowing to increase total aquaculture share in shrimp supply to the local market from 6.3% currently to 13.33% in 2005. This means that under the assumptions of these baseline models, there will be enough product from shrimp farms in the local market by 2005 to allow per capita consumption to

increase marginally from 0.54 kg in 2000 to 0.6 kg in 2005 for ER and XG maximization development policies.

- Total production is higher and similar with XG and ER maximization, reaching 102,000 tons. in the five years.
- The stronger sustainable development policy of pollution minimization signifies important reductions for the industry growth, in terms of all parameters evaluated. Total economic rent is only 49.5% of the amount under ER or XG maximizations. But total nutrients discharges are only 32% compared to these two single-objective development policies. However, this is at the cost of US \$525 and \$163.3 million reductions in foreign exchange earnings and economic rents respectively, from the baseline models for each of these criteria. Compared to E maximization, this stronger environmental development policy creates 2247 less on-farm jobs.

3.3.2 Multi-objective optimization.

The results of the MCDM model (multiobjective optimization) are presented in Table 3.2, where the objectives of foreign exchange earnings, economic rent and employment maximization and total pollution minimization are simultaneously evaluated.

Interesting results are obtained as outcomes of the MCDM model. Initially, and as expected, the simultaneous optimization of the four objectives means they all have lower values than under the single-objective optimizations, or higher in the case of TOTPOLL

Table 3.2. Five-year planning (2000 to 2005) optimal solutions, multi-objective optimization.

Variable	Economic rent, employment and foreign exchange earnings maximization and total pollution minimization
F121	200
F122	0
F211	0
F221	200
F231	0
F212	0
F222	0
F232	0
F311	27
F321	34
F331	5
Production	57,119
Rent	204,586
Tot.Poll.	2,000
Local supply	5,712
Foreign	497,621
Employment	7,490
Extensive	27
Intensive	5
Semi-int.	434
Sonora	200
Sinaloa	200
Nayarit	66

$F_{s,j,i}$ number of farms in the State s (1=Sonora, 2=Sinaloa, 3=Nayarit), using production system j (1=extensive, 2=semi-intensive, 3=intensive) and species i (1=white shrimp, 2= blue shrimp)

Production= Total shrimp production (ton)

Rent= Total Economic Rent from industry development (\$000 US)

Tot.Poll= Total nutrient outflows (cumulated phosphorus & nitrogen). (ton)

Local supply= Total shrimp production to national market, to fulfill local projected demand. (ton)

Foreign= Foreign exchange earnings from the industry development (\$ 000 US)

Employment= Total number of new on-farm workers from the industry development.

Extensive= Total number of new extensive shrimp farms established in the region

Intensive= Total number of new intensive shrimp farms established in the region

Semi-int= Total number of new semi-intensive shrimp farms established in the region

Sonora= Total number of new farms in the State of Sonora

Sinaloa= Total number of new farms in the State of Sinaloa

Nayarit= Total number of new farms in the State of Nayarit

minimization. This reflects the trade-offs that usually are present in solving multicriteria problems and models. Employment comes out as a favored parameter in the development of the industry, with 7,490 new jobs created when 22,500 ha of shrimp farms are developed in the States of Sonora, Sinaloa and Nayarit (just 2.1% less than the single-objective E maximization scenario). The number of new jobs is only second to the total amount when employment maximization was a single-objective policy. Since the semi-intensive systems (the more labor-intensive of the three systems evaluated) are in the majority, with 93% of the total number of farms developed, employment remains strong. Also, the MCDM solution allows 16 extra farms to be created than the total number under the single-objective development policies, although 27 of them are extensive farms supported in the State of Nayarit (see discussion below).

The second interesting result is that blue shrimp farms are not supported at any intensity, and 27 extensive farms are established in Nayarit. Blue-shrimp farms have higher yields but also higher feed conversion rates, which increases operating costs (reducing ER) and total pollution. Hence, all semi-intensive farms are developed with white shrimp.

The 27 extensive farms in Nayarit represent 41% of the total number of new farms to be developed in that State, using 21% of the total 2,500 ha. In the northwest region, Nayarit's farmers achieve the lowest yields among the three States in semi-intensive farms. In order to maximize the economic objectives (ER, XG and E), the optimal solution is based on the semi-intensive systems of Sinaloa and Sonora, highly productive and because land to be developed in these two States is 89% of the total regional. The selection of the combination of systems to be developed in Nayarit is more

influenced by the sustainability objective of the industry development (TOTPOLL minimization), once the minimum production for local consumption is satisfied. Total production of these extensive farms is only 162 tons, 0.28% of the total of the new farms in the region. Jobs created in these farms are only 0.72% of the total. Therefore, selection of these extensive systems is not based on economic criteria or relevance, but rather, once the basic constraints are satisfied and no more land can be developed in Sinaloa and Sonora for ER and XG maximization, Nayarit's development is complementary and has the least impact on the environment. Total production from all Nayarit's systems is 8.8% of the total.

The multi-objective industry development optimization allocates land to a variety of production systems. In Sonora, semi-intensive systems with white shrimp are promoted. Sinaloa will similarly see the development of white shrimp semi-intensive farms only, but in Nayarit white shrimp farms of all three intensities will be created.

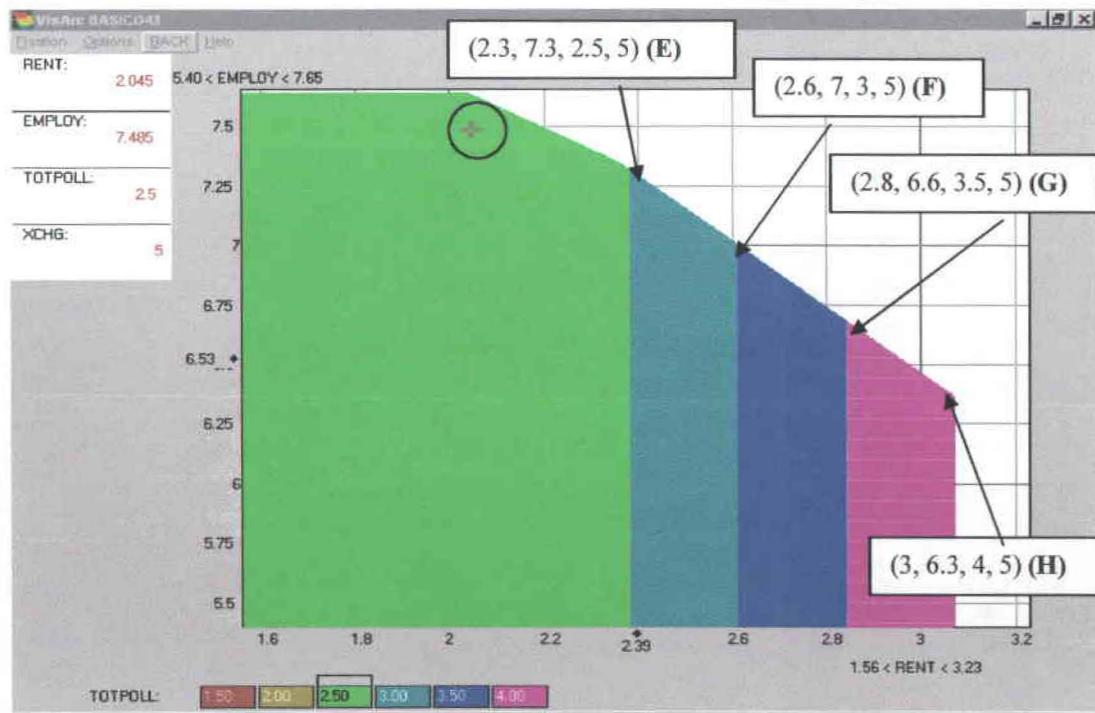
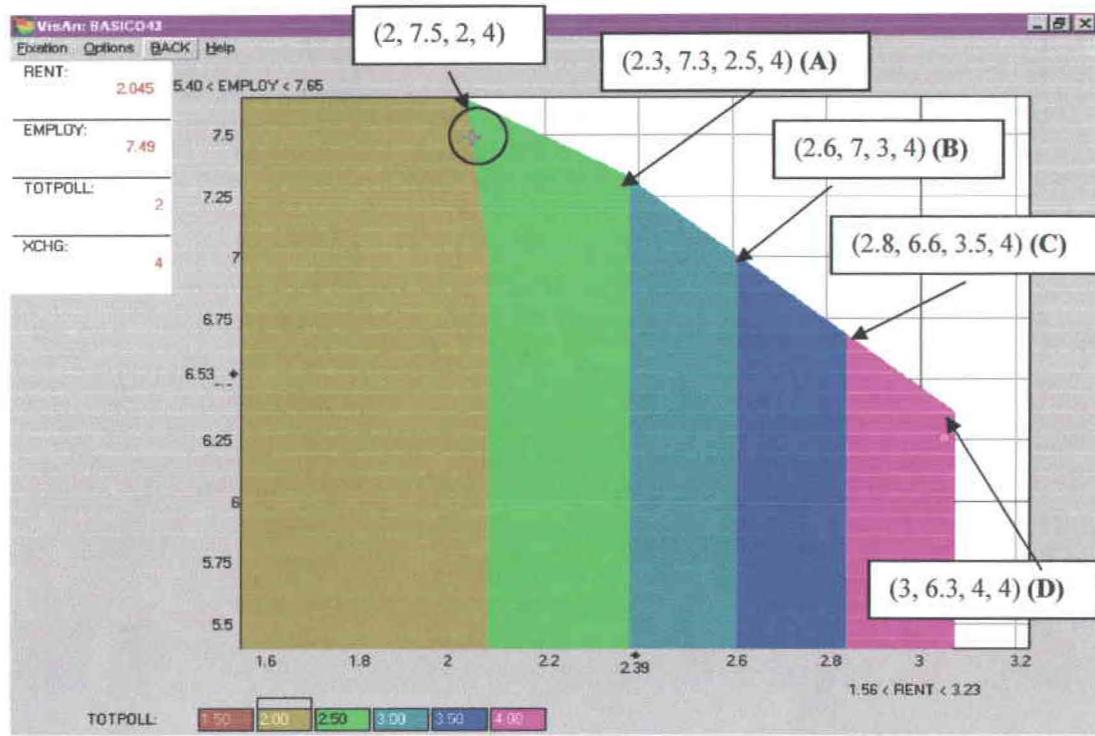
Total production is 56% of the amount reached under single-objective ER and XG maximization, with an important reduction of 54% in total pollutants discharged compared to these two single-objective maximization scenarios.

Total pollution (2,000 tons) is not as low as when the pollution minimization criterion directs the industry development (1,395 tons.). But this multi-objective growth of the industry is much more equilibrated, with a cumulated shrimp production in 2005 of 57,119 tons from the new farms.

The results and trade-offs of the MCDM model can be analyzed graphically, taking advantage of the properties of Feasible Goals[®]. As a first figure, Appendix E, Figure E.1 shows the matrix of decision maps that FG constructs for the efficient trade-

offs among ER, XG, E and TOTPOLL. This matrix allows exploration of the four criteria at once. The decision map corresponding to the model's solution is encircled in Figure E.1., and the cross shows the exact location of the optimal solution. For ease of discussion and interpretation, ER, E and XG are read in the x,y and secondary y axes respectively, and TOTPOLL is depicted as areas of different colors in the decision maps, according to different levels of total P+N discharges. As can be seen, the optimal solution is at the frontier of the 2,000 tons total pollution discharge (light green layer). In order to increase ER, XG or E, the central planner will have to give up having 2,000 tons as maximum effluents, and the feasible results would be read from the dark-green layer (2,500 tons of pollutants) both in the circled decision map or in the decision map above, corresponding to US \$ 500 million as foreign exchange earnings.

Figure 3.4a&b show the Pareto optimal trade-off curves for the decision map corresponding to the MCDM model solution. Since the optimal solution lies on the border between the two decision maps at the bottom of Figure E.1, both are analyzed. The edges of each of the colored layers (blue, green, red) represent the efficient frontier for each pollution level, and the respective foreign exchange earnings, employment and economic rent can be read from the axes. Point labels in this figure have the following notation: [x axis (ER, \$00 million), y axis (E, 000 jobs), criterion in layers (TOTPOLL, 000 ton), and constant criterion (XG, \$00 million)] and are rounded up. So for example, the circled point in Figure 3.4a (2.04, 7.5, 2.0, 4.98) corresponds to the optimal MCDM solution with values of US\$ 204.586 million economic rent, 7,490 new jobs, 2,000 tons of total pollutants discharged and \$497.621 million in foreign exchange earnings.



**Fig. 3.4. MCDM optimization: trade-offs between economic rent and employment
 a) fixed XG at \$ 400 million; b) fixed XG at \$ 500 million**

How the trade-offs among the three economic objectives (ER, XG and E) are affected by the fourth, environmental objective (TOTPOLL) in the decision maps is analyzed as follows. In figure 3.4a, for a fixed total foreign exchange earnings at \$ 400 million, if the central planner wants to move from the optimal solution and increase ER, he would be giving up jobs and pollution. Reading along the frontier for each of the colored layers and passing from the optimal solution to the point A increases ER in \$33.4 million and decreases employment by 165 jobs: an average \$202,424 in economic rent is gained for each job lost. Although this figure looks high, the complete evaluation of this scenario in terms of gains and losses must consider what the color layers are showing: there is an extra 500 tons of pollutants discharged into the environment as well. Therefore, the economic benefit in the form of Economic Rent gain by reducing employment has as counterpart the 500 extra tons of pollutants that will be discharged to the environment.

A larger ER (passing from A to B) yields a \$56.4 million increase in ER as compared to the optimal solution and a loss of 485 jobs. Further increases in ER to points C and D results in \$79.4 and \$102.4 million increases and 805 and 1,125 fewer jobs, respectively. In the last scenario, point D, total pollutants discharged doubled, to a total of 4,000 tons. If a planner wants to evaluate the similar trade-offs among ER, E and TOTPOLL while keeping XG constant at \$500 million (Figure 3.4b), he has to initially give up 500 tons in pollution contamination (there is no light-green layer in 5.2b).

Shrimp farming intensification (developing the shrimp farming industry supporting intensive systems mainly) will always come at the expense of employment reductions and pollution increments, based on the characteristics of the production

systems used to generate this model. In coastal areas where fishermen need an economic activity to compensate for declining fishery yields, policies that favor less intensification of shrimp farming seem plausible, and the semi-intensive system appears to be a logical choice. However, the resulting social benefit in coastal areas does not include direct on-farm jobs only. The income effects are multiplied through the marketing channel for the entire shrimp farming industry and increase in ER and XG generate more wealth directly and indirectly.

CHAPTER 4

EXTENDED JOINT ANALYSIS OF RESULTS, AND POLICY IMPLICATIONS.

The results of the three main topics of this dissertation (traditional and environmentally-adjusted production performance measurements of shrimp farms, shadow prices of pollutants and pollution abatement costs, and the MCDM model to assess sustainable shrimp farming development in Mexico) have already been thoroughly discussed from methodology to results in the two previous chapters. This chapter will extend the discussion to the policy implications of these results by presenting a broader perspective of the advantages of periodically deriving production performance measurements, both traditional and environmentally-adjusted.

4.1 Role of Productivity and Efficiency in Strategic Policy Planning

Callens and Tyteca (1999) conclude that in the majority of cases, sustainable indicators have been developed mainly at the macro level, i.e. the state or country level. However, firms have a central role in human activities and development and therefore play an important part in the attainment of sustainability goals. The indicators of sustainability that were assessed in the first essay of this dissertation have a “bottom-up” focus that starts with the individual production systems. By comparing firms it is possible to detect which ones are the laggards, what the reasons are for lagging (e.g. which are the factors for unsustainability) and hence what the possibilities are towards improvement.

The basic unit of analysis for understanding competition is the industry. The industry can be analyzed using aggregated data or, as is the case of this study, individual firms can be examined to determine their productivity and efficiency.

An industry is a group of competitors producing products or services that compete directly with each other. A strategically differentiated industry encompasses products and services sharing similar sources of competitive advantage. For example, many aquacultural industries in the world market produce products that share customers, technologies and distribution channels. But all these industries have their own unique elements that contribute to their competitive advantage, and this advantage is lost or won at the industry level. In addition, in industries like shrimp farming in Mexico, with three different production intensities, different climates that limit effective annual production time, and a production process characterized by a large degree of risk and uncertainty, the competitive advantage is affected at the farm level. Firms, through competitive strategy, seek to define and establish an approach to compete in their industry, which is both profitable and sustainable.

Productivity and efficiency play a major role in strategic policy planning for the aquaculture and shrimp farming industry, and for the farm owner or manager. Central planners and producers must be aware of the productivity and efficiency levels of their operations and understand how these performance indicators change. Competitive advantage at industry level comes out of the way firms organize and perform discrete activities. Firms gain competitive advantage from conceiving new ways to conduct activities, selecting new procedures or technologies, or different inputs. Firms must

sustain a competitive edge over time by providing higher quality products and services, or producing more efficiently. This translates directly into productivity growth.

For the industry's planning purposes, important contributions of productivity and efficiency measurements are:

- Both the individual's welfare and the nation's economy depend upon productivity and effectiveness in which resources are used.
- Intersectoral, intrasectoral, regional and intrafirm comparisons and analysis can be performed using the indicators, with the possibility to incorporate performance trends when analyzing time series data.
- Since differences in productivity and efficiency might reflect differences in farm sizes, research and development and extension spending, and other factors, the proper approach that government and/or public and private sectors can use to develop and implement improved operations and results can be determined.
- Factors that cause change over time can be identified. Output can be enhanced with improved inputs at similar costs, which reduces costs per unit of output. However, improvement in the quality of inputs may be beyond the farmer's control but the on-farm use of these inputs can be improved.
- International competitiveness can be improved. The shrimp export market is competitive and Asian countries have achieved huge production levels at low operation costs, and developing the industry in Mexico hinges on improved efficiency and productivity.

- The assessment of productivity and efficiency assessed at various times and under various conditions facilitates economic sensitivity analysis to determine the impacts of each of these policies and of alternative ones.
- Evaluation of the dynamics of both TFP and TE helps to assess future scenarios. Economic evaluations with other sectors of the national economy can be carried out, such as the relation between productivity and the GNP growth rate.
- As future challenges occur such as the viral diseases outbreaks, an understanding of how to ease the transition to another technology can be gained. The industry and the government can support the process if they expedite training and transmission of knowledge, in order to ensure a quicker, more efficient response.

It is my strong belief that, as is the case with other industries in other countries, productivity and efficiency evaluations and reports must be produced systematically for the aquaculture industry in Mexico. Governments, business and academic communities would benefit from periodical reports of economic/environmental indicators relating economic issues to the industry's development. However, with this empirical application in mind, it is necessary to evaluate the easiness of the Distance Function methodology and compare it with other approaches reported in the literature.

DEA-based methodologies used to estimate production performance indicators on a regular basis are simple to calculate, and applicable for small sample sizes. Communicating the results in an easy to understand manner remains a challenge. The interpretation of shadow prices is more complicated using an output approach than under the approach used in this dissertation (input-oriented), and the methodology is still under

discussion. Another advantage of estimating TFP and TE by the Input Distance approach presented in this dissertation is that cost/price information other than shrimp price is not required. However, the estimation of TE is sample-specific and nothing can be concluded about the relative efficiency unless TFP is estimated, whose TE component is a ratio of two individual's (independent years) TEs. For efficiency calculation purposes, the data of next year cannot be directly incorporated in the actual calculations, without affecting the efficiency scores of the previous years. Comparing farms from different regions is a fundamental problem. A solution is to develop a meta-frontier production function like the one developed by Gunaratne and Leung (1996) and Sharma and Leung (2000). When the difference in technology among production units is included in the analysis, Battese et al., (2002) have developed the methodology for stochastic estimations, including technology gaps. However, all of these techniques are data-intensive requiring data not readily available.

Reinhard (2000) compares ease of estimation for SFA, DEA and distance functions, to assess their potential uses in producing periodical reports of productivity and efficiency. While he favors SFA, this methodology represents single-output technologies, and required that Reinhard modeled the detrimental pollutants as inputs. In doing so, he changed the whole approach from cost minimization to revenue maximization.

The benefits from having annual reports of TE and TFP for the shrimp farming industry, government and development banks in Mexico will certainly assist their decision-makings at the farm and industry levels. Specifically:

1. TE scores: The TE score is a benchmark to the performance measure, since the farmers then know how they deviate from the best management practices. More importantly, the frontier can be characterized, so internal analysis at firm level could occur. Planners could use TE scores to identify potential sector improvements. Most importantly, the response in terms of education and training necessary to younger and/or non-expert farmers to catch-up with efficient ones in a short period of time can be evidenced. Development banks would be more interested in funding training courses. Since TE differences also result in managerial differences within farms, the training should not be constrained to just the technical level.
2. Productivity Indexes and TC scores: intertemporal comparison is important since it provides elements for analyzing the dynamics of industry growth. As demonstrated in this dissertation (see Figure 4.3), the analysis of a partial productivity score (yields) gives an incorrect assessment of inputs used to obtain a set of outputs. The managerial tool behind the annual growth in yields was an increased use of inputs. If only yields are analyzed, the desired sustainability-related objective of a more efficient use of resources and achievement of higher productivity cannot be evaluated. Equally important is the analysis of the transition from one technology to the other after the viral diseases, with the decomposition of TFP into TE and TC provides unique elements for analysis during times of crisis in the industry. TFP estimations, decomposed into TC and TE, show that the government response to assisting farmers could be improved by incorporating new technology with a better use of inputs during the transition

period. Since viral outbreaks are recurrent, efforts to learn from these results and to be prepared at industry level is important.

3. Environmentally-adjusted TE and TFP: The focus of the dissertation was to estimate these indicators and compare them to the traditional ones. The analysis concludes that in the “normal” year without diseases, shrimp farmers can be as efficient using traditional indicators as they are using environmentally-adjusted ones. Second, if a technology change makes use of more production inputs per unit of desirable output, the score (both TFP and TE) is correctly reduced. For farmers and government planners interested in sustainable development of the industry, this will provide them with information for adjustments.

Frontier analysis locates at the frontier different DMU, even though the production processes are not similar. Thus, multiple answers (farms or ponds on the frontier) provided by the frontier analysis indicate that an optimal decision-making unit may exist in several forms, corresponding to different ways of organizing and managing the unit.

4.2 Pollution abatement in shrimp farming: environmental regulation or self-enforcement

In the environmental economics literature, the terms pollution control and environmental regulation are often used synonymously. However, these terms differ and this difference has policy implications: pollution is often related to material waste and inefficiency of the production process and, consequently the firm is expected to have an

interest in reducing pollution even if it is not regulated. Environmental regulation may be but one of a number of reasons why firms control pollution.

The introduction of a pollution abatement device or technology usually involves changes in the production process. Jorgensen and Wilcoxon (1990) identify three different response categories of environmental regulations:

1. The firm substitutes less polluting inputs for more polluting ones;
2. The firm changes the production process to reduce emissions; and
3. The firm invests in pollution abatement devices.

Clearly the first two are pollution prevention methods, and the latter is an “end-of-pipe” measure. The first response depends on the level of substitutability of inputs, and is likely to be the least disruptive of the three possible responses. For shrimp farming, this choice is represented by the substitution of high-protein feeds by others with low fishmeal content, with testing on low-protein feeds for biotechnological feasibility at commercial level being conducted for years¹. In addition, the first response doesn’t imply an extensive reorganization of the production process as the other two options. Finally, a high degree of substitutability between inputs implies low costs of environmental regulation, and vice versa (Hetemaki, 1996).

The second response to pollution control takes the form of reduced or zero water-exchange farms, and polyculture systems that incorporate as a secondary or third relevant organism whose biological characteristics contribute to the reduction of the pollutant discharged to the environment. For example, molluscs or algae reared in the effluents of

¹ Protein requirements are species-specific. Scientific papers continuously report results of bioassays that test modifications in feeds for commercial species. See recent articles by Kureshi and Allen Davis (2002) for *Litopenaeus vannamei* and Millamena et al. (1999) for *L. monodon*, among others.

shrimp ponds, which take up organic matter, P and N compounds otherwise released. Martinez and Seijo (2000) have economically assessed alternative water exchange and aeration rates in semi-intensive systems in Mexico. Zero-exchange, superintensive systems have also been tested in Belize, with very successful results (McIntosh, 1999; Boyd and Clay, 2002).

The second response, however, if implemented in existing enterprises is very costly and involves the redesign of production methods and infrastructure. Training and the inevitable learning curve are needed to adopt the new production process. The effects on productivity are not obvious: productivity may be increased if there is a net reduction of inputs due to a more efficient production process. On the other hand, if more inputs are required for a given level of good output, this would have a negative impact on productivity.

The last approach is to invest in abatement technology, i.e. in the use of special devices to treat wastes after they have been generated. The polyculture system described in the previous paragraph is a combination of the second and third responses to pollution control. End-of-pipe abatement is usually criticized since it is preferable to prevent pollution. However, this approach is often the only option for firms that have to meet newly imposed standards.

The steps that the shrimp farming industry is taking towards internally achieving sustainable production need to be recognized. These three responses are already being undertaken in several parts of the world, even without regulations being strictly enforced. However, evaluation and economic feasibility under different geographical and socioeconomic conditions remains unknown. From the economics point of view, the

pollutant shadow price estimations of Chapter five and the further sensitivity analysis of the effect of pollution abatement costs on firm's profits and revenues, demonstrate that the extra cost from reducing pollutants are well within the margins of financial feasibility of shrimp farms, at least for the ones characterized in this study.

A final consideration related to pollution abatement and environmental regulations is discussed in the framework of the effect of environmental regulation on the production efficiency of farms. The *Porter hypothesis* (Porter and van der Linde, 1995) has as central argument that properly designed environmental standards can trigger innovation and production efficiency gains that lead to absolute advantages over non-regulated firms. To date, published reports have presented elements for and against this theory. Bjorndal and Salvanes (1995) undertook the only work applied to aquaculture, and the authors concluded that potential gains from deregulation may be substantial for the Norwegian fish farming efficiency. Therefore, no conclusive results can be provided for generalization. Currently, the question of whether environmental regulations, if enforced, would benefit the aquaculture industry depends on specific case-study considerations.

CHAPTER 5

CONCLUSIONS AND SUGGESTED FUTURE WORK

5.1 Conclusions

Planning the development of shrimp aquaculture in Mexico involves decision-making processes at both firm and industry levels. Both farmers and central/regional planners strive to have production carried out in the most efficient way, achieving higher productivity. Farmers and planners will be better able to achieve sustainable growth of the industry if they incorporate more economic and environmental elements, of the production process into analysis.

At firm level, environmentally-adjusted production performance measurements (technical efficiency TE and total factor productivity TFP) were estimated in this dissertation and were lower than traditional ones, since the farms and ponds were increasing their emission of nutrients in discharged water. However, in 1994, operating with a known species and after many years of expertise, farmers' performance at pond level was equally efficient when the score is adjusted for the input directed to the production of pollutants. Thus, the shrimp farmers were capable of operating in an environmentally-efficient manner.

Another important conclusion is the confirmation of the value of total factor productivity performance measurements (TFP), since a partial productivity estimation (yield) shows an opposite result of what the situation was when diseases outbreaks hit the industry, and how the adjustment process took effect. This was more evident with environmentally-adjusted TFP and TE. Therefore, given the objective of sustainable

shrimp aquaculture, the environmentally-adjusted estimations obtained in this dissertation provide a stronger, more complete picture of production performance.

Taking advantage of the division of Total Factor Productivity (TFP) into technical efficiency (TE) and technological change (TC) components, a specific analysis of sources of productivity growth can be conducted. When applied to a case study like the one conducted in this dissertation for shrimp farms in Mexico in 1994, 1996-1998, insights can be gleaned about a critical event like a disease outbreak in the industry, the adoption of a new technology (rearing blue shrimp) and the consequent transition from one species (white shrimp) to the other (blue shrimp). The analysis of this case study showed that the ponds sustained, on average, their relative distance to the best scenario (TE), possibly as a result of a good communication and dissemination of the adjustments among them. However, a quicker response in the form of research was needed to develop or improve production techniques which make better use of inputs to generate a fixed amount of outputs. The new knowledge need not be a technological breakthrough, but a more active role by the government in assisting farmers to learn the technology and adopt it at a faster pace may be needed. This requires, as prevention for future disease occurrences, that plans are set in place to cope with emergencies and to prepare the industry for a faster, technical response.

A final conclusion of the first essay is that the implementation of pollution abatement is economically feasible. Spending on pollution abatement technology has double benefits by reducing environmental impacts from operations and being more efficient in the use of inputs to generate desirable outputs (shrimp).

Several implications and uses of the environmentally-adjusted indicators in terms of growth and environmental impacts exist. Firstly, the input-based Malmquist index of productivity growth that appropriately credits the producer not only for increases in marketable or desirable output but also for the production of improved environmental quality through less emission of pollutants, provides a more robust evaluation of sustainable growth. Sustainable productivity growth, evidenced not only by the traditional TFP index but also by the environmentally-adjusted one, means that from the social point of view this productivity improvement is stronger than what the conventional indicator indicates, because pollutants are reduced or controlled in a better way. Secondly, if the application of environmentally-adjusted TFP index shows consistently lower scores compared to traditional TFP along several years, then implementation/enforcement pollution abatement technologies and/or increased training and technology transfer in order to achieve productivity growth in a sustainable way may be needed. Traditional TFP measures can underestimate or overestimate the production performance of firms or industries, from a social point of view. From the firm's perspective, if there is an enterprise which is already spending on pollution abatement technology, the environmentally-adjusted indicator may be the means to be credited for doing so, achieving higher productivity and/or efficiency. Government policies seeking to reward environmentally-friendly production systems by means of subsidies or tax credits¹, would find in the environmentally-adjusted indicators a correct production performance measurement.

¹ Used also as policy measures to effectively discourage the use of environmentally detrimental production technology.

The MCDM model tested trade-offs of the sustainable development of shrimp farming in northwest Mexico. The solution shows a scenario where the industry generates in a five-year period foreign exchange earnings (XR) and economic rent (ER) to the amount of US \$ 497.6 and 204.5 million respectively, creating 7,490 jobs and discharging 2,000 tons of combined N and P pollutants.

Despite many critics to the intensification (to intensify production systems) of the industry, the opposite, supporting only extensive systems, is clearly not a sustainable planning solution. An alternative strategy is to distribute production and land among all five different kinds of production systems. The growth of the shrimp aquaculture industry in Mexico, since its creation, has been supported by semi-intensive systems and not by intensive or super-intensive ones. Under the assumptions and characteristics of this study, the results of the MCDM model confirm the expectations that semi-intensive systems will support the industry's sustainable growth.

5.2 Recommendations and Future Work

This research generates the need for a number of further studies. Direct quantifications of pollutants discharged from shrimp farms correlated with production data is needed, in order to alleviate imprecise estimations of N and P outflows calculated using Mass Balances. An interdisciplinary research project in Mexico in the future could focus on this research objective. A few direct quantifications of pollutant emissions from shrimp farms in Mexico exist, but data are not published or made available as yet and are very small in sample size.

Another recommendation is to apply the methodology demonstrated in this dissertation to a longer time series of data. The application and usefulness of the performance indicators has already been discussed for producers and planners in Mexico. It would be fruitful to apply the same methodology to other sectors of the aquaculture industry in Mexico (tilapia, oyster, bullfrog) in future endeavors.

The methodology selected for measurement of environmentally-adjusted performance indicators (Distance Function Approach), although considered robust and provided reliable results, is only one of several possible ways to obtain these measurements. One of the main modifications or additions would be to eliminate the deterministic characteristic of the performance measurements generated in this study.

In terms of the theoretical robustness and weakness of Fare's Distance Function approach to environmentally-adjusted productivity estimations, readers are directed to Smith (1998) and Weaver (1998) for a succinct but interesting discussion. According to both authors, the methodology falls short as an important consideration, which is the inclusion of consumers and other costs of pollution and environmental values in the

firm's productivity estimation. This methodology has made little progress in explaining the tasks associated with adapting what is known about consumers' values for environmental quality to meet the needs of productivity measures that would account for pollution reduction. Fare and Grosskopf (1998) have shown a simple inclusion of the consumer component in the model. More effort in the future among the academic community should be directed towards this goal.

The multiobjective model developed needs to incorporate more information of the socioeconomic kind. Other strong assumptions of the model should be relaxed as information is accounted for, like seed supply in Mexico. Passing from a static model to a dynamic one is also an important task that requires attention in the near future.

As discussed before, the selection of Feasible Goals[®] to conduct the multiobjective optimization was based on the favorable visual features of the application. This will benefit the interaction with decision-makers and planners in Mexico, who will be incorporated in future exercises, improvements and updates of the model. Future work should also incorporate risk in the model and evaluate regional development according to the weight and effect of aquaculture (shrimp farming) activities on the regional/national economy.

Finally, biosecurity –and its costs- must be evaluated in both the economic evaluation of firm's performance and the decision-making model, considering experiences in recent years with diseases.

APPENDIX A

LOCATION MAP OF THE MAIN STATES PRODUCERS OF SHRIMP BY AQUACULTURE IN MEXICO

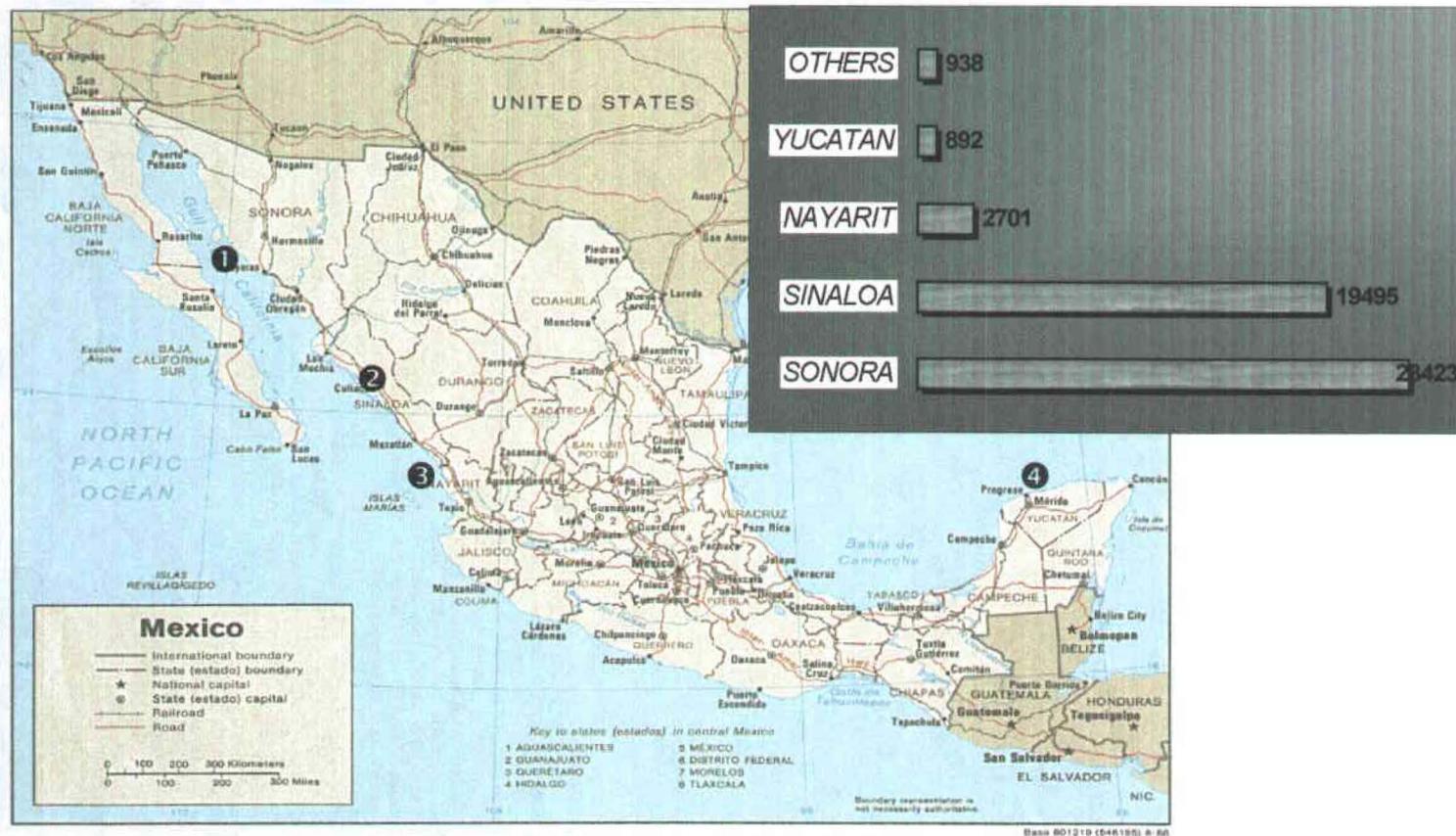


Fig. A.1. Geographical location of the 4 main States producers of shrimp by aquaculture in Mexico, and their total production (metric tons) in 2001: 1) Sonora 2) Sinaloa 3) Nayarit 4) Yucatán. (Source: SAGARPA,2002).

APPENDIX B

PARAMETERS OF TRANSLOG INPUT DISTANCE FUNCTION

Table B.1 Estimated parameters of the Input Distance Function without undesirable outputs, for 1994.

α_4	0.215	α_{46}	-0.24	α_{77}	-0.105	α_{tt}	0.226
α_5	-0.1	α_{47}	-0.09	β_{11}	-0.578	α_{4t}	0.32
α_6	-0.002	α_{55}	0.0047	γ_{41}	0.06	α_{5t}	-0.43
α_7	0.29	α_{56}	0.012	γ_{51}	0.124	α_{6t}	-0.34
β_1	-0.58	α_{57}	0.021	γ_{61}	0.111	α_{7t}	0.257
α_{44}	0.17	α_{66}	0.014	γ_{71}	0.1	β_{1t}	-0.25
α_{45}	-0.56	α_{67}	-0.15	α_t	0.332	α_0	15.25

Table B.2 Estimated parameters of the Input Distance Function with undesirable outputs, for 1994.

α_4	0.593	α_{44}	0.398	α_{45}	-0.309	α_{tt}	0.374
α_5	-0.101	α_{46}	-0.018	β_{11}	-0.457	α_{4t}	0.313
α_6	-0.012	α_{47}	-0.001	α_t	0.548	α_{5t}	-0.381
α_7	0.64	α_{55}	0.0304	α_0	19.548	α_{6t}	-0.293
β_1	-0.417	α_{56}	0.094	γ_{43}	-0.044	α_{7t}	0.359
β_2	0.168	β_3	-2.08	β_{12}	0.077	β_{13}	-0.385
β_{22}	0.123	β_{23}	0.356	β_{33}	0.671	β_{1t}	-0.471
α_{57}	0.034	α_{66}	0.047	γ_{61}	0.147	β_{2t}	0.168
α_{67}	-0.016	α_{77}	-0.057	γ_{72}	-0.238	β_{3t}	-2.084
γ_{41}	0.102	γ_{42}	-0.532	γ_{71}	0.131	γ_{51}	0.241
γ_{52}	0.142	γ_{53}	0.045	γ_{63}	-0.208	γ_{62}	0.126
						γ_{73}	-0.589

APPENDIX C

EFFECT OF POLLUTION ABATEMENT SHADOW COST ON FIRM'S REVENUES AND PROFITS

Table C.1. Sensitivity analysis: effect of pollution abatement technology on firm's revenues and profits. 1994

Farm	Average Abat.Cost	shrimp price (USD/kg)		9.68	If Operation costs are % of Revenues			
		Total Farm Abat.Cost	Direct shrimp Revenues		0.3	0.45	0.6	0.75
				% AB to R ¹	% AB to P ²	% AB to P	% AB to P	% AB to P
1	-13.6253	55,525.87	464,494.80	11.95%	17.08%	21.73%	29.89%	47.82%
2	-5.9801	52,583.73	965,589.68	5.45%	7.78%	9.90%	13.61%	21.78%
3	-15.8352	43,115.03	329,149.04	13.10%	18.71%	23.82%	32.75%	52.40%
4	-10.9531	107,564.72	762,909.84	14.10%	20.14%	25.64%	35.25%	56.40%
5	-7.2542	137,424.12	1,554,811.28	8.84%	12.63%	16.07%	22.10%	35.35%
6	-11.1185	40,975.15	713,570.88	5.74%	8.20%	10.44%	14.36%	22.97%
7	-11.9480	46,230.36	915,031.04	5.05%	7.22%	9.19%	12.63%	20.21%
Aver.	-10.9592	69,060.00	815,080.00	9.18%	13.11%	16.68%	22.94%	36.70%

1 Percentage of pollution abatement cost to revenues

2 Percentage of pollution abatement cost to profits, for different levels of operation costs: revenues ratios

Table C.2. Sensitivity analysis: effect of pollution abatement technology on firm's revenues and profits. 1996

Farm	Average Abat. Cost	shrimp price (USD/kg)		9.68	If Operation costs are % of Revenues			
		Total Farm Abat. Cost	Direct shrimp Revenues		0.3	0.45	0.6	0.75
				% AB to R ¹	% AB to P ²	% AB to P	% AB to P	% AB to P
1	-9.1658	99,523.49	2,124,256.64	4.69%	6.69%	8.52%	11.71%	18.74%
2	-9.0753	45,783.49	1,060,434.32	4.32%	6.17%	7.85%	10.79%	17.27%
3	-9.0511	18,275.59	555,390.00	3.29%	4.70%	5.98%	8.23%	13.16%
4	-9.4161	62,296.15	1,336,662.80	4.66%	6.66%	8.47%	11.65%	18.64%
5	-9.0876	52,571.21	1,211,926.32	4.34%	6.20%	7.89%	10.84%	17.35%
6	-10.2485	47,856.76	1,319,480.80	3.63%	5.18%	6.59%	9.07%	14.51%
7	-9.7596	10,491.39	236,530.80	4.44%	6.34%	8.06%	11.09%	17.74%
8	-10.0681	6,049.35	150,717.60	4.01%	5.73%	7.30%	10.03%	16.05%
Aver.	-9.4840	42,856.00	999,425.00	4.17%	5.96%	7.58%	10.43%	16.68%

1 Percentage of pollution abatement cost to revenues

2 Percentage of pollution abatement cost to profits, for different levels of operation costs: revenues ratios

Table C.3. Sensitivity analysis: effect of pollution abatement technology on firm's revenues and profits. 1997

	Average Abat.Cost	shrimp price (USD/kg)		9.68	If Operation costs are % of Revenues			
		Total Farm Abat.Cost	Direct shrimp Revenues		0.3	0.45	0.6	0.75
				% AB to R ¹	% AB to P ²	% AB to P	% AB to P	% AB to P
1	-7.9737	86,647.82	3,192,222.00	2.71%	3.88%	4.94%	6.79%	10.86%
2	-7.4777	45,647.39	1,307,545.36	3.49%	4.99%	6.35%	8.73%	13.96%
3	-7.7757	68,835.07	1,825,831.92	3.77%	5.39%	6.85%	9.43%	15.08%
4	-8.1162	37,275.66	1,100,286.88	3.39%	4.84%	6.16%	8.47%	13.55%
5	-8.1012	52,913.19	1,665,473.04	3.18%	4.54%	5.78%	7.94%	12.71%
6	-7.9694	111,712.11	3,287,531.28	3.40%	4.85%	6.18%	8.50%	13.59%
7	-7.6238	6,938.92	244,807.20	2.83%	4.05%	5.15%	7.09%	11.34%
8	-7.3915	59,646.98	1,675,637.04	3.56%	5.09%	6.47%	8.90%	14.24%
9	-7.0035	44,115.51	1,099,657.68	4.01%	5.73%	7.29%	10.03%	16.05%
Aver	-7.7147	57,081.00	1,710,999.00	3.37%	4.82%	6.13%	8.43%	13.49%

1 Percentage of pollution abatement cost to revenues

2 Percentage of pollution abatement cost to profits, for different levels of operation costs: revenues ratios

Table C.4. Sensitivity analysis: effect of pollution abatement technology on firm's revenues and profits. 1998

	shrimp price (USD/kg)			9.68				
	Average Abat. Cost	Total Farm Abat. Cost	Direct shrimp Revenues	If Operation costs are % of Revenues				
				0.3	0.45	0.6	0.75	
				% AB to R ¹	% AB to P ²	% AB to P	% AB to P	% AB to P
1	-6.5075	-44,131.37	1,739,350.80	2.54%	3.62%	4.61%	6.34%	10.15%
2	-6.7005	-25,242.76	1,159,693.04	2.18%	3.11%	3.96%	5.44%	8.71%
3	-6.3602	-42,971.98	1,361,143.52	3.16%	4.51%	5.74%	7.89%	12.63%
4	-6.4136	-67,949.75	2,164,070.48	3.14%	4.49%	5.71%	7.85%	12.56%
5	-6.4502	-37,997.43	1,229,069.60	3.09%	4.42%	5.62%	7.73%	12.37%
6	-6.6045	-16,724.15	747,354.08	2.24%	3.20%	4.07%	5.59%	8.95%
7	-6.3820	-42,841.17	1,619,996.40	2.64%	3.78%	4.81%	6.61%	10.58%
8	-6.3593	-60,120.90	1,847,350.56	3.25%	4.65%	5.92%	8.14%	13.02%
9	-6.3069	-126,495.87	3,989,563.60	3.17%	4.53%	5.76%	7.93%	12.68%
10	-5.9786	-57,451.70	1,792,765.04	3.20%	4.58%	5.83%	8.01%	12.82%
11	-5.8564	-53,070.55	1,508,463.44	3.52%	5.03%	6.40%	8.80%	14.07%
Aver	-6.3563	-52,273.00	1,741,711.00	2.92%	4.17%	5.31%	7.30%	11.68%

1 Percentage of pollution abatement cost to revenues

2 Percentage of pollution abatement cost to profits, for different levels of operation costs: revenues ratios

APPENDIX D

DATA DETAIL, MULTI-CRITERIA DECISION-MAKING MODEL

Table D.1. Major data sources for the parameters and calculations used in the multiobjective model.

Parameter	Source
Farm cost structure and incomes, by production system, State and species	Primary source: farm data and direct communications with shrimp farmers in Mexico
Nitrogen and Phosphorus discharges, and correspondent TE values	Paez-Osuna et al. (1997 and 1999) and calculated in this Dissertation
Employment figures	Primary source: farm data and direct communications with shrimp farmers in Mexico
Export prices	Ocean Garden Inc. August 2002
Local prices (Mexico)	Sistema Nacional de Informacion de Mercados (National System of Markets Information). August 2002
Objectives and recent year's shrimp development (ha./State/year)	Ocean Garden Inc. (various years), Hernandez-Cornejo and Ruiz-Luna (2000), and Development Plans for the States of Sinaloa (1999-2004), Sonora (1999-2003) and Nayarit (2001-2005)
Food Security (seafood and shrimp consumption in Mexico)	Annual Fisheries and Aquaculture Data, CONAPESCA
Shrimp industry data	Annual Fisheries and Aquaculture Data, CONAPESCA

Table D.2. Values of main parameters for MCDM model.

Parameter	Value
Land for shrimp farming development by State (ha.)	
Nayarit	2,500
Sonora	10,000
Sinaloa	10,000
Average yield by system, State and species (kg/ha/year)	
Y121	2.7
Y122	2.7
Y211	0.3
Y221	2.5
Y231	6
Y212	0.25
Y222	2.5
Y232	5.5
Y311	0.3
Y321	2
Y331	6
Export price (USD/kg)	
White shrimp	9.68
Blue shrimp	8.00

$Y_{s,j,i}$ average yields of farms in the State s (1=Sonora, 2=Sinaloa, 3=Nayarit), using production system j (1=extensive, 2=semi-intensive, 3=intensive) and species i (1=white shrimp, 2= blue shrimp)

APPENDIX E

MCDM MODEL, FEASIBLE GOALS.

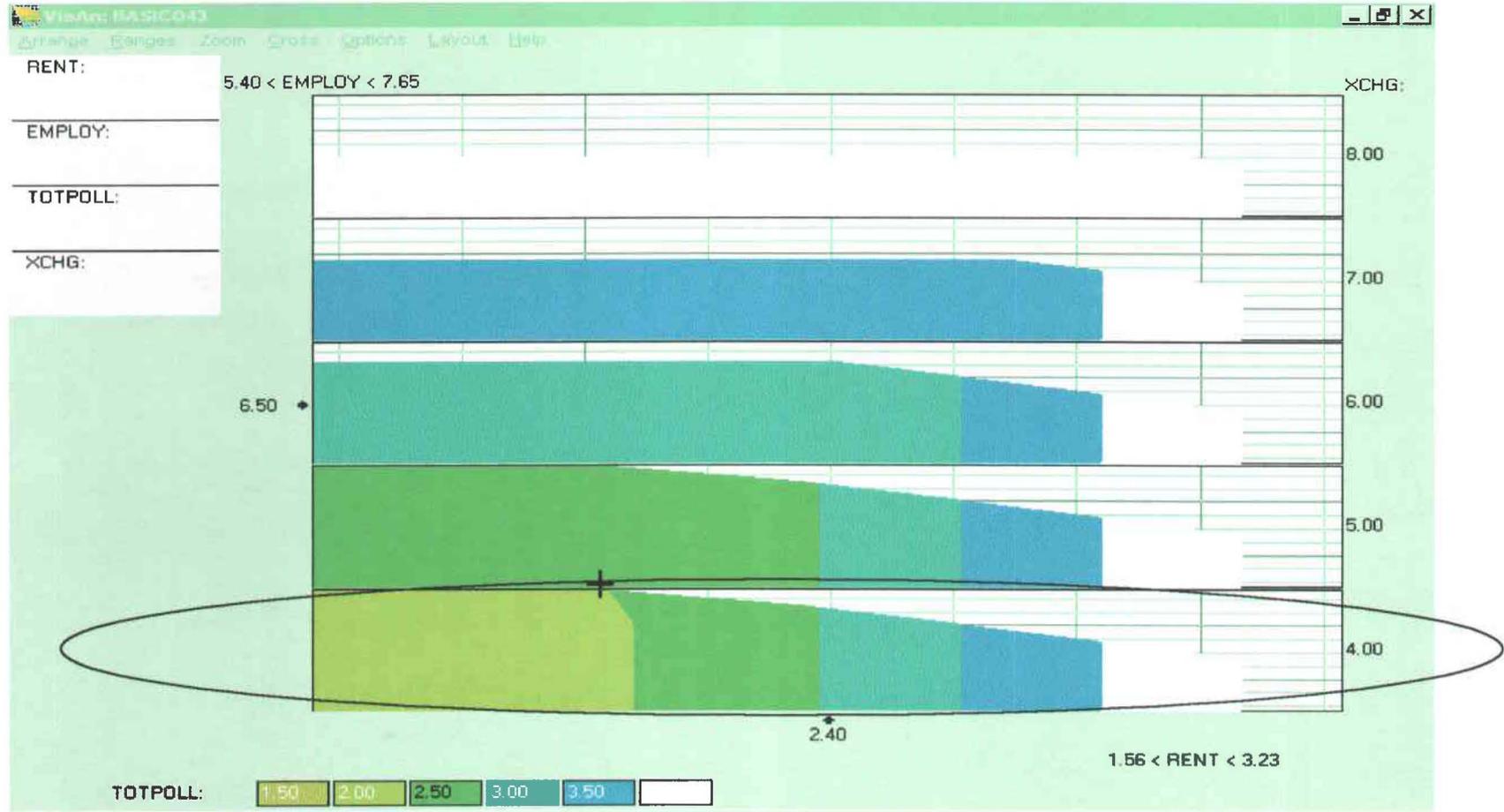


Fig. E.1. Matrix of efficient decision maps, MCDM model solution.

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