An Optimal Corrective Tax for Thai Shrimp Farming

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Abstract

"If Thai shrimp farming were taxed, how much should it be?" is the key research question of this paper. The dynamic-constraint optimization model incorporating accumulated nutrient load from farm discharges is applied in the analysis. The model implies some tax has to be imposed on stock externality that is equal to increasing shadow cost of nutrient stock before damage occurs. However, the simulation results show very small shadow costs at the beginning of the paths and indicate that nutrient load in Andaman has a negligible effect on the sea but significant on the Gulf of Thailand. A socially efficient level of production for Thailand would be around 70-80% of private optimal production. The tax regime ensures a higher net gain from trade than at private optimum but it is ambiguous in term of net social welfare.

Keywords: green tax, stock externality, shrimp farming, Gulf of Thailand, Andaman Sea.

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1. Introduction

Shrimp farming involves trade and environmental issues. Although farming techniques are being developed fast, the industry still relies much on exploiting domestic natural-environment for direct inputs of production and as receptacle of farm discharge. Without proper management and policy, a natural resource-based production as such causes resource use conflicts including environmental damages, which are generally seen in most of shrimp producing countries. Meanwhile, almost all of the products are traded; 91% of the world's cultured shrimp find their final markets in the United States, Japan and EU. The pattern of global trade for cultured shrimp is a one-way flow, from developing tropical producer countries to these main markets in the developed world (Clay, 2003).

Implementing non-economic incentive-based policies has long been observed as an inefficient way to mitigate environmental impacts of shrimp farming. This is supported by the discussion of policy choices on such instruments as quantity regulation, process and product standards, technical regulations and certification systems, which are preferred by interest groups (as these tend to create rents) to a market instrument, which is relatively more efficient but generally leaves nothing on the table for them (Anderson, 1992: 221-246).

In this paper, taxation as a "green tax", collected for externalities, is suggested as an alternative policy to be applied to shrimp farming focusing on Thailand's case. Implementing taxation in aquaculture is proposed. In Ecuador, for instance, tax exemption is offered to farmers who treat water effluent while other countries impose tax on farm discharges (Hishamunda and Ridler, 2003: 175). In Thailand, a green tax has not been imposed on aquaculture or to agriculture, although it has been imposed on energy industries (e.g. gasoline). Use of public land for coastal aquaculture is charged a "water fee". However, the rate imposed is not based on environmental costs borne by the society. A green tax is expected to be one way of using the market mechanism to encourage efficient use of resources and good practices, e.g. Good Aquaculture Practices (GAPs) and Code of Conduct (CoC).

Widely known adverse impacts and externalities of coastal shrimp farming in Thailand are: land use change (e.g. mangrove conversion) and release of farm effluent causing nutrient enrichment in coastal waters (FAO/NACA, 1995; Funge-Smith et al., 1998). The accumulation of nutrient in coastal waters may contribute to severe plankton blooms that cause eutrophication, which subsequently affects fishery resources (PCD, 2003).

In principle, externalities can be classified into two types—flow externality and stock externality. The former is caused by the current flow of damage that is directly generated from resource uses. The latter is claimed as damage through stock pollutant at the level beyond natural threshold. The definition is widely applied in fossil fuel literature.[1] For shrimp farming, flow externality that directly affects human welfare would vary by the quantity of shrimp produced, for example, the benefit foregone of wood products by converting mangrove to shrimp farms. On the other hand, the stock externality incurs the shadow cost of cumulative nutrient stock discharged from farms. Nutrient stock also relates to biogeochemical processes of a coastal system to assimilate nutrient load.

Internalizing externalities is the basic principle of a conventional market-based instrument called Pigouvian tax (Baumol and Oates, 1988). If it is only flow externality that exists, in theory, one can relate that marginal environmental cost in static view would be equal to the tax to be imposed. However, in the presence of stock externality, the static Pigouvian tax is modified. Dynamic approach is required in order to present the intertemporal behavior of stock externality which causes long-term damage. Hence, when both flow- and stock externalities exist, the optimal corrective tax covers not only the current cost but the future cost of damage. Pigouvian tax is also stated as first-best environmental policy to be implemented in terms of efficiency criteria (Ulph, 2000). In addition, the tax may be used to reduce the cost of implementation in contrast to

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[1] Fuel consumption generates noise and smoke pollution which are defined as flow externalities. On the other hand, the cumulative CO_2 that causes climate change is defined as stock externality. See Farzin (1996) and Sandal et al. (2003) for examples.

the administrative costs of command-and-control (C&C) policies. Thus, it can reduce pollution in the least cost manner (McMorran and Nellor, 1994).

The main purpose of this paper is to measure an optimal corrective tax for shrimp farming. Internalizing externalities as the main concept of Pigouvian tax is applied as a basis for the analysis where the cumulative amount of nutrient from farm discharge is considered as stock constraint. Although, a dynamic model framework is applied extensively to pollutive consumption, e.g. climate change, the application to pollutive production, e.g. shrimp farming is first introduced to literature. This study is focused on two coastal areas, i.e. the Gulf of Thailand and the Andaman Sea. The adverse effects of nutrient stock, mangrove conversion and abandoned farms as consequences from common farm practices are considered.[2] The result of optimal corrective tax as well as a guideline for implementation is thus suggested based on this scenario. Theoretically, the model shows that some tax has to be imposed on nutrient stock that is the tax equals to increasing shadow cost of its stock even before damage occurs. However, from the simulation results, it turns out that the shadow costs for both coastal sites are very small at the beginning of the paths. The results also indicate that there is a negligible effect of the Andaman nutrient load on the sea but significant on the Gulf. Broadly, the suggestion is that the tax should be imposed on common practice farms. Meanwhile the revenue from the tax may be used to reward good practice farms.

In next section, principle and framework that base the analysis are delineated. This is followed by the review of environmental impacts which provides a guideline for model formulation. The mathematical model is then presented. The numerical results of optimal tax paths, production paths and welfare effect including the results from sensitivity analysis are shown subsequently. The results as well as the implementation guideline are then discussed. The last section is conclusion.

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[2] The term “common farm practices” used throughout this paper means by environmentally unfriendly practices as opposed to good farm practices.

2. Background

Thailand is one of the largest producers of cultured shrimp (including *Penaeus monodon* or Black Tiger and recently *Penaeus vannamei* or white shrimp) in the world next to China. The kingdom contributed 27% of global farm production of 1.09 million tons (FAO Fishstat 2002). The production mainly comes from 23 coastal provinces of both the Gulf of Thailand (eastern side of the peninsula) and the Andaman coast (western side of the peninsula). Department of Fisheries (DOF) reported that in 2002 total farm production was around 264,923 tons from 31,179 farms involved. This comprises 464,881 rai of ponds (74,380 ha).[3] More than 90% is small-scale intensive farms (less than 50 rai). Intensive ponds are stocked with high rate and applied high other inputs especially feed. Feed cost ranges from 40-60% of total cost.

In terms of trade, Thai cultured shrimp had the biggest market share of 25% of world traded value (FAO Fishstat 2002). Food quality and safety is the most common non-tariff barrier applied to Thai shrimp exports. Other non-tariff trade barriers include those related to environmental issues. GAPs and CoC have been promoted recently in Thailand, as voluntary practices, in order to promote environmentally friendly shrimp farming. It includes, among others, not converting mangroves into farms and not polluting receiving waters. Unfortunately, there is no clear market signal to navigate such practices.

A survey in 2000 revealed that 45% of the shrimp farms in one of Thailand's premier shrimp producing provinces (Nakhon Sri Thammarat) were located in ex-mangroves (Tokrisna, 2004). The survey also found that conversion happens although at a lesser extent in new shrimp producing areas. In addition, the attraction to continue to apply common farm practices, which leads to high effluent discharge, remains to be the prospect of getting a high return despite the risks. As Clay (2003: 492) states, "shrimp farmers have simply made too much

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[3] 6.25 rai = 1 hectare (ha)

money doing aquaculture the wrong way for anyone to convince them to change”.

The Thai government has developed a mix of mechanisms to encourage farmers to “change”. These include command-and-control (C&C) instruments and voluntary adoption. C&C instruments however are inefficient, costly and difficult to enforce. The government has included shrimp farm registration as one of the voluntary schemes to promote GAPs and CoC. The same farm survey found that 55% of total representative farmers registered and of this less than half registered because they thought it was useful. Some 45% did not register for lack of information, for fear of being taxed or for lack of perceived additional benefit.

Applying good practices, however, requires high level of farming knowledge, technical skill and investment. Using such technique as reduced water exchange possibly generates production uncertainty and income risk due to the stressful rearing environment (Stanley, 2000; Funge-Smith et al., 1998). Another example is water-recycling system which requires a portion of the production area to be sacrificed for water treatment ponds. These could hamper promoting the practices.

What the above discussion indicates is that C&C and voluntary instruments have been inadequate for mitigating the environmental impacts of Thai shrimp industry.

3. Framework of Analysis

The analysis is based on intertemporal optimization framework of pollutive production of an internationally traded farm product. This section comprises two parts as follows.

3.1. Dynamic Optimization Model

The dynamic-constraint optimization model, commonly applied to pollution management, is found pervasively in natural resource management such as fisheries (see Conrad and Clark, 1987, for instance). Pollution or environmental damages can be induced by either direct or indirect uses of resources through human consumption and production. This model is extensively employed to derive optimal policy for fuel fossil consumption, for example. It provides optimal solutions for consumption, fuel tax, carbon tax and abatement. Farzin (1996) presents the model of climate change which consists of two types of stock externality, i.e. resource stock as the accumulation of oil depletion from extraction; and environmental stock as stock pollutant from oil consumption. This study also assumes irreversible stocks while a number of literature incorporate a decay function to represent reversible stocks (see Sandal and Steinshamn, 1998 for the review).

In this paper, the model is applied to shrimp production which entails the exploitation of coastal resources. The nutrient assimilative capacity of the coastal system is incorporated in the model. Application of dynamic problem in coastal resource is found in the area of transboundary pollution management. Bayramoglu (2004), for example, uses dynamic-game model in the case of nitrogen loads discharged from coastal states that cause eutrophication in the Black Sea. However, non-transboundary pollution is assumed for Thailand's coastal waters.

The analysis throughout is based on assumption that intensive shrimp farming with high water exchange rate (open system)[4] and without prior effluent treatment before discharging is commonly applied. It is called, in this paper, "common farm practices".[5]

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[4] See Funge-Smith et al. (1998) for the description of farming techniques and pond environment.

[5] Although semi-closed or fully closed water exchange systems became popular as a means to deal with disease outbreak, these systems do not guarantee lower nutrient load discharged during harvest. Total effluent loads discharged are not significantly different among the systems (Funge-Smith et al., 1998). Water recycling system is found to be technically possible in deal-

The results of optimal collective tax from this study would be represented as a benchmark taxation based on a "critical" scenario of the industry where no other better practices are considered. Maximized net social benefit is the objective. Externalities in terms of impacts of nutrient stock, mangrove conversion and abandoned shrimp ponds are internalized. Nutrient stock is incorporated via dynamic constraint. Information on the rate of nutrient assimilation and carrying capacity of coastal waters is required. Rough estimations of initial level of nutrient stock and threshold (critical level) are used to indicate the carrying capacity. Follow this setting, the optimization model for shrimp farming can be simulated. Furthermore, the model is also related to international trade where shrimp price is determined. Welfare gain and loss from the trade of pollutive production is also investigated next.

3.2. Trade and Environment

Shrimp farming causes environmental impacts at the local level. Extra production encouraged by gain from trade tends to induce additional environmental damages. In connection with the international trade of cultured shrimp, two questions are raised. First, how much does the producing/exporting country (referred to as Home Country, HC) gain in terms of trade and improved welfare when a green tax is imposed compared to not imposing it? Second, why should the tax be imposed directly at production level instead of at export level? The main framework used for seeking answers to these two questions follows the basis provided by Hoekman and Leidy (1992).

Although Thailand is one of the world leaders of aquaculture shrimp (around one-third of world aquaculture production), its market share is around 7% of total (capture and culture) world shrimp production. It is thus assume that Thai shrimp price is associated with the overall world shrimp price. As a result, a

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ing with environmental problems with respect to farm effluent. However, it may not be economically feasible, as indicated by the finding that only a small number of farms (4%) applied this system. See PCD (2002) for the survey of 668 farms in 2000. The same survey also reports that only 6.5% of farms has effluent-water treatment ponds.

small country case is assumed for the analysis, that is, HC has no influence on the world price, p.

Figure 1 shows a static view of optimal solutions and social welfare effects. Assume that only flow externality is accounted in the first place. Without trade and green tax, private optimum is obtained at production level of oq_1 where domestic demand, D, equals supply, S. With trade, the production is encouraged by a high level of world price (or at least a level that is higher than price in the local market) which raises private optimum up to oq_2. Domestic consumption is oC_p and the remaining volume C_pq_2 is exported. Society gains large producer surplus (*pka*) and consumer surplus (*bip*). But it also bears a larger environmental cost (*akm*).

When externalities are internalized, marginal social cost, S', is generated, i.e. marginal private cost (S) plus marginal environmental cost. At socially efficient level of pollutive production, corrective tax (*js*) is obtained. The tax rate ensures that both private cost and environmental cost generated by polluters' actions are accounted. If HC imposes a green tax at production, and free trade is pursued,[6] the country would unambiguously gain from trade (*cij*). Social welfare is also improved (*jkm*) due to reducing production from oq_2 to oq_2' which consequently reduces pollution and natural degradation. On the other hand, the gain from trade at private optimum (*eik*) does not ensure the offsetting of the environmental cost (*dekm*) when the tax is not in place. As shown later in the numerical results, net welfare and net gain from trade at private optimal production, i.e. the surpluses and the gain from trade over the environmental costs, are compared with the values derived from social optimal production. This analysis is aimed to compare the economic consequences between these two policies within the same society's concern of environmental damage.

As to the second question, figure 1 shows that imposing export tax instead of a direct production tax would decrease the price received by exporters (*p-js*) al-

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[6] Assume that HC is not allowed to set trade policy such as extra export tariff. But only environmental policy, i.e. a green tax can be imposed.

though it gives the same effects in reducing optimal production (from oq_2 to oq_2') and in improving welfare by reducing pollution (jkm). It will increase domestic consumption by C_pC_e. HC will lose part of gain from trade (iuv).[7] In other words, the export tax instrument is less efficient than the production tax by costing more to achieve the same target.

If stock externality is also internalized, the optimal production is lower than when only flow externality is accounted. At each point in time, the optimal production would be reduced to oq_2* where $j's'$ plus $j'j''$ is the modified tax rate that corrects for both flow and stock externalities, respectively. The welfare effects can be measured using the same concept as depicted above. At private optimal production, the welfare loss caused by the environmental damage due to accumulated nutrient load from over-production (the level above the steady state) is also included in the calculation of net welfare and the net gain from trade.

It is clear that imposing a green tax still ensures the gain from trade. Although it is smaller than that without imposing the tax, the producing country's welfare is improved by less pollution. The tax at production is considered throughout the analysis as it generates higher improvement in welfare in terms of trade than the tax at export for the same reduction of pollution and resource degradation.

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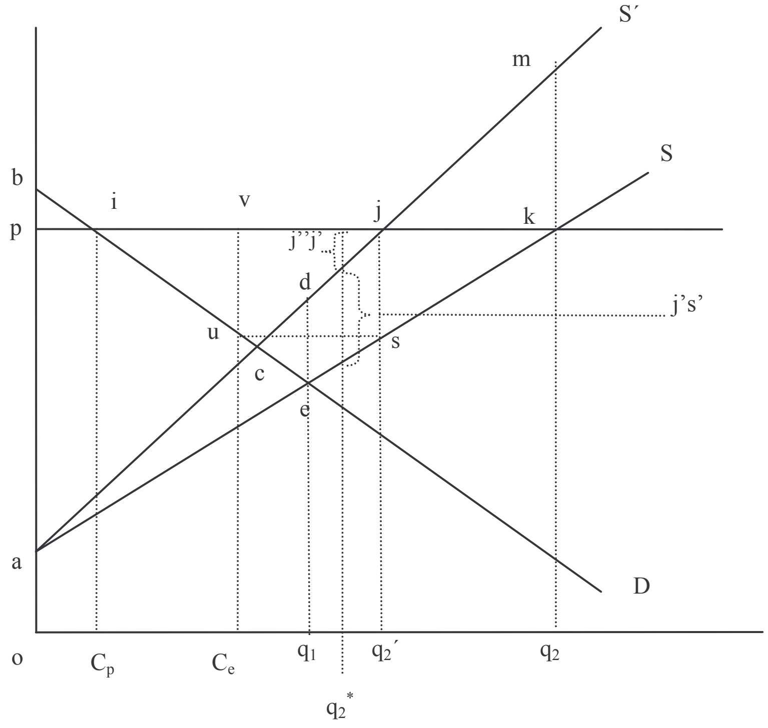
[7] In fact, it could be worse if iuv is greater than jkm. This can be the case especially when elasticity of domestic demand is relatively high.

Figure 1. Trade, tax and welfare



4. Environmental Impacts of Shrimp Farming in Thailand

This section identifies and describes environmental impacts of shrimp farming. This is used for the model formulation in next section. Economic value losses are reviewed from available studies. These values yield to deriving parameters of environmental cost (see details in appendix).

Shrimp farming in Thailand are generally in two types of location: farming outside mangrove and farming in ex-mangrove. The former case is mostly in ex-agricultural areas such as rice, oil palm and para rubber including abandoned agricultural land. For the latter, although there is no record of the rate of mangrove conversion into shrimp farms when the industry began, it appeared that significant areas of mangroves were cleared (81,136 rai per year) during the period that the shrimp industry was rapidly expanding, from late 1970s to mid 1980s. It started in provinces along the Gulf of Thailand and expanded to those along the coast of the Andaman Sea. However, the record of 1996 shows a lesser extent of destruction (2,292 rai per year). The same year record also reveals that using the 1961 mangrove area as a base, around 18% of that was occupied by shrimp farms and only 45% remained of the original mangrove.[8]

Intensive farming system is widely applied in Thailand. It contributes considerably large share of production compare to that of extensive and semi-intensive farming.[9] For model simulation, coastal shrimp farming both on the Gulf of Thailand and the Andaman Sea are considered. It is assumed that farming outside mangrove does not generate externality, if any, that relates to mangrove. But farming in ex-mangrove obviously causes direct impacts due to mangrove conversion into farms and thus entails mangrove forgone benefits. Both cases, however, cause off-site and on-site impacts in terms of accumulated nutrient from farm discharge and abandoned shrimp ponds, respectively.

Effluent discharged from intensive farms mainly contains nitrogen (N) and phosphorous (P) loadings (Funge-Smith et al., 1998). Satapornvanit (1993) shows that, considering high water exchange in open system, 94.2 % and 91.0% of total N and P inputs in shrimp ponds are from feed, but only 21.0 % of N and 5.8% of P in feed are converted to shrimp. Nutrient losses are mainly in the forms of accumulated sludge (N=38.1% and P=36.2% of total outputs) and water effluent (N=11.5% and P=14.11%). A small amount of nutrient is released from bottom pond washing. Generally, farmers do not dispose the sludge in public canals due to their awareness of self-pollution. Here water effluent dis-

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[8] The areas of cleared mangrove and shrimp farms in ex-mangrove are estimated using Landsat-5 TM data by Charuppat and Charuppat (1997). Total original stand mangrove in 1961 was 2,327,800 rai (372,448 ha).

[9] The number of farms, area, and production of intensive farming increased from 70%, 50% and 90% in 1991 to 90%, 65% and 98% respectively after 1999 (based on DOF statistics).

charged during culture and harvest is considered as source of nutrient load into the watercourse.

Over-enrichment of nutrient loads can contribute to eutrophication in coastal waters with adverse effects on marine resources (PCD, 2003). However, there is a limiting nutrient that bounds to the phenomenon. Based on the traditional redfield ratio[10] of N:P at 16:1, it was deduced that for Thailand's coastal waters, N is most likely to be the limiting nutrient (PCD, 2003).[11] It should be noted that although severe damage has yet to happen in Thailand's coastal waters, it is believed that nutrient load accumulated in the Gulf of Thailand is nearing critical level, indicated by more incidences of red tide occurring recently as reported by PCD (2003). On the other hand, it does not seem to be a sensitive case for the Andaman Sea.

The damage cost function of such limiting nutrient stock can be measured by observing the effects of the phenomenon on social welfare (e.g. fishery resource loss). However, this approach rules out the behavioral and market responses to changes in environmental qualities. It is thus characterized as naïve (Freeman, 2003).

Treatment cost of nutrient is used as a proxy value in this paper. This approach is suggested in literature. Gren et al. (1997), for example, evaluated the cost-effective reduction of nitrogen and phosphorous into a desirable level in order to restore the Baltic Sea. Muir et al. (1999) interpret the costs of reducing salmon farm effluent in Sweden as society's willingness to pay for reducing eutrophication. Brennan (2002) applied the same method to shrimp farming in Queensland. Although this approach is argued that it may provide an overestimated or underestimated value, the relevant studies for the case of Thailand are available. In addition, using effluent treatment ponds is found on the sites even with a small number of farms.

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[10] See more details in Yuan-Huili et al. (2000).

[11] When the ratio of N:P is less (greater) than reafield, then N (P) is the limiting nutrient. This follows the law of minimum (see also Elofsson, 2003).

In case of shrimp farms surrounded by agricultural areas, the environmental issue commonly raised is the dispersion of saline water to adjacent croplands especially rice fields. The issue is very controversial from the scientific point of view, particularly in inland shrimp farming.[12] For coastal shrimp farming, however, the impact of salination of soils is minor since coastal soil *per se* naturally induces the problem. There is also the fact that rice lands along the coasts are less productive than those inland. This physical problem adds to the other economic pressures that encourage the conversion of coastal rice lands to other uses such as shrimp farms and more profitable plantations (e.g. palm oil, papa rubber). Hence this impact is not considered in the analysis.

Impacts of abandoned shrimp farms should also be taken into account. Farms are usually abandoned after five years of continuous intensive operation. According to Towatana et al. (2002) and Towatana et al. (2003), the impacts are: 1) the abandoned ponds are unsuitable for raising shrimp or growing economic crops due to high salinity[13] and high density; 2) without soil reclamation, salt accumulation will be a point source of surface and ground water contamination; and 3) the abandoned pond cannot purify itself without remediation. In the analysis, the reclamation cost of pond bottom soil is used as a proxy value of the environmental cost of shrimp farming outside mangrove.

Mangrove conversion in Thailand entails forgone benefits as presented by Sathirathai (1998). The values are measured in terms of direct use values (i.e. wood and non-wood products) and indirect use values (i.e. coastal protection, carbon sequestration and off-shore fishery linkage). For impacts of abandoned shrimp farm in ex-mangrove, the cost of mangrove rehabilitation is accounted. Data of forgone benefits due to mangrove conversion used in this paper are based on this study. More details are presented in the appendix.

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[12] See Pongthanapanich (1999) for the review.

[13] The result of the electrical conductivity (EC) ranges from 2.41 to 9.48 mS/cm (Towatana et al., 2002).

5. The Model

The standard dynamic optimization model is applied to Thai shrimp farming. The modeling follows the review of impacts above. To simplify the model, only damage caused by nutrient load is corrected as stock externality. Other externalities are accounted as flow externalities which are in turn summed up with private cost to derive social cost. These include environmental costs of abandoned shrimp ponds and mangrove forgone values.

Net social benefit function, *W*, is set as a function of shrimp productions from two sites denoted as Q_1 for ex-mangrove and Q_2 for outside mangrove as well as nutrient stock, *N*.[14]

$$W(t) = W(Q_1(t), Q_2(t), N(t)) \tag{1}$$

The environmental cost due to nutrient stock externality is accounted through damage function defined as *D(N)*. However, the damage exerts only when cumulative stock reaches threshold or critical level, i.e. $N(T) = \hat{N}$ at time *T*. The auxiliaries, *n(t, T)* is thus used to state the time horizon: at the stage when damage has not yet occurred (at $0<t<T$), n=0 and when damage happens (at $T \leq t < \infty$), *n*=1. *W* function can then be expressed:

$$W = pQ_1 + pQ_2 - \int_0^{Q_1} S_1 dQ_1 - \int_0^{Q_2} S_2 dQ_2 - n(t,T)D(N) \tag{2}$$

where *p* is an exogenous constant price; $S_1=S_1(Q_1)$ and $S_2=S_2(Q_2)$ are marginal social costs for farming in ex-mangrove and outside mangrove, respectively.

The continuous free terminal-time model with maximizing discounted net social benefit objective is formulated as follows:

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[14] All variables are associated with time variable, *t*.

$$\underset{Q_1 \geq 0, Q_2 \geq 0}{Max} \int_0^{\infty} e^{-\delta t} W(\cdot) dt \tag{3}$$

s.t.

$$\dot{N} = \beta_1 Q_1 + \beta_2 Q_2 - \theta N \tag{4}$$

Given:

$$N(0) > 0 \tag{5}$$

$$N(T) = \hat{N} \tag{6}$$

Equation (4) is nutrient stock constraint where the first two terms represent the total amount of nutrient load from both culture sites (i.e. ex-mangrove for the first term with the rate of discharge β_1 and outside mangrove for the second term with rate of discharge β_2). The last term is the total amount of the load assimilated by coastal system including nutrient loss during transport to the sea. The rate of total nutrient loss is defined as θ.

Equation (5) and (6), initial stock, $N(0)$, and critical level of stock (threshold), $\hat{N}$ are given. It should be noted that the model is justified only when initial stock level is lower than threshold, i.e. $N(0) < \hat{N}$.

The current Hamintonian is:

$$H = W(\cdot) - \mu(t)(\beta_1 Q_1 + \beta_2 Q_2 - \theta N) \tag{7}$$

where the current shadow price of the stock at instant time t is denoted as $\mu(t)$.

Thus, the first-order conditions are obtained:

$$\frac{\partial H}{\partial Q_1} = p - S_1 - \beta_1 \mu = 0 \tag{8}$$

$$\frac{\partial H}{\partial Q_2} = p - S_2 - \beta_2 \mu = 0 \tag{9}$$

$$\frac{\partial H}{\partial N} = \dot{\mu} - \delta\mu = -nD'(N) + \theta\mu \tag{10}$$

$$\frac{\partial H}{\partial \mu} = \dot{N} = \beta_1 Q_1^* + \beta_2 Q_2^* - \theta N^* = 0 \tag{11}$$

Equation (8) and (9) interpret the optimal pricing of pollutive production where both flow- and stock externalities are internalized.

In (10), $D'(N)=0$ before when the stock reaches threshold at T and $D'(N)>0$ thereafter. Hence, (10) can be rewritten as:

$$(\delta + \theta)\mu - \dot{\mu} = 0 \qquad 0<t<T \tag{12}$$

$$(\delta + \theta)\mu - \dot{\mu} = D'(N) \qquad T\leq t<\infty \tag{13}$$

Assume linear damage functions $D(N)=vN$ where v is marginal damage cost.[15] Thus $D'(N)=v>0$ at T and thereafter. Substitute v in (13) then solve (12) and (13). This obtains:

$$\mu^*(t) = \frac{v}{\delta + \theta} e^{-(\delta+\theta)(T-t)} \qquad 0<t\leq T \tag{14}$$

$$\mu^*(t) = \frac{v}{\delta + \theta} \qquad T\leq t<\infty \tag{15}$$

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[15] Using linear parameterization has the advantage of yielding exact solutions for the steady-state optimal paths, which provides insight for policy implication (see the proof in Farzin, 1996).

$\mu^*(t)$ is the shadow price of nutrient stock which represents the tax amount to be imposed on an additional unit of stock externality. (14) gives an insight that even if the stock has not reached threshold to cause damage, it entails an increasing external cost with the growth rate of $e^{-(\delta+\theta)(T-t)}$ because of accumulated nutrient. The tax rate becomes stable through time when the stock reaches threshold as shown in (15).

Solving for optimal production paths, (14) and (15) are substituted in (8) and (9) where it is defined that $S_1=a_1+b_1Q_1$ and $S_2=a_2+b_2Q_2$. These give the results:

$$Q_1^*(t) = \{p - a_1 - \beta_1 \frac{v}{\delta+\theta} e^{-(\delta+\theta)(T-t)}\}/b_1 \qquad 0<t\leq T \qquad (16)$$

$$Q_1^*(t) = \{p - a_1 - \beta_1 \frac{v}{\delta+\theta}\}/b_1 \qquad T\leq t<\infty \qquad (17)$$

$$Q_2^*(t) = \{p - a_2 - \beta_2 \frac{v}{\delta+\theta} e^{-(\delta+\theta)(T-t)}\}/b_2 \qquad 0<t\leq T \qquad (18)$$

$$Q_2^*(t) = \{p - a_2 - \beta_2 \frac{v}{\delta+\theta}\}/b_2 \qquad T\leq t<\infty \qquad (19)$$

The results in (16)-(19) show that optimal productions decrease until they reach steady state. However, solving for the optimal paths also requires information of T. Use (5), (6) and (11) to formulate (20):

$$\hat{N} = N_0 + \int_{t=0}^{T} \{\beta_1 Q_1(t) + \beta_2 Q_2(t) - \theta N(t)\} dt \qquad 0<t\leq T \qquad (20)$$

Substitute (16) and (18) in (20). Then, derive (20). This will obtain (21) which is used to solve for T. Use T to derive optimal production paths in (16) and (18).

$$\hat{N}-N_0=\frac{\beta_1}{b_1}(p-a_1)T+\frac{\beta_2}{b_2}(p-a_2)T-\frac{\theta}{2}(\hat{N}^2-N_0{}^2)$$
$$-(\frac{\beta_1{}^2}{b_1}+\frac{\beta_2{}^2}{b_2})\frac{v}{(\delta+\theta)^2}\left[1-e^{-(\delta+\theta)T}\right] \tag{21}$$

6. Numerical Results

The model in previous section is applied to shrimp farming on two coastal sites, i.e. the Gulf of Thailand (G) and the Andaman Sea (A). On each site, there are two sub-sites of farming, i.e. ex-mangrove (G1 and A1) and outside mangrove (G2 and A2). Data and parameter description is presented in the appendix. It is used to obtain a base case scenario that serves as the basis for sensitivity analysis.

6.1. Base Case Scenario

Results from base case, at shrimp price of 190 THB/kg,[16] are illustrated in table 1. The model gives the results of total optimal shrimp production at social optimum (when externalities are internalized or a green tax is imposed) of 182,370 tons (from 341,688 rai) at initial time (t_0) and 165,172 tons (from 309,246 rai) at steady state ($T \leq t < \infty$).[17] Around 77% 6% 11% and 6% of total production are from G1 G2 A1 and A2, respectively. In comparison, the optimal shrimp production from private optimum (no taxation in place) is 231,460 tons (from 436,718 rai). It implies that in order to obtain social efficiency the overall productions should be reduced by around 20% at t_0 and 30% at steady state. Farming in ex-mangrove areas both on G and A should be decreased in higher proportion than in outside mangrove. Production from G should be reduced more than from A for all sites.

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[16] 40 THB = 1 USD.

[17] At steady state, nutrient stock reaches critical level (i.e. zero net change of stock) thus optimal production and optimal tax become stable from $t=T$ and thereafter.

The social optimal path entails total optimal tax corrected for both flow- and stock externalities in the range of 28.41-53.93 THB/kg for shrimp farming in ex-mangrove area and 1.71-19.00 THB/kg in outside mangrove. It turns out that only at steady state there is a substantial tax to be imposed on nutrient stock of 14.57 THB/kg for G and 16.54 THB/kg for A. On the other hand, it is close to zero at the beginning of the path. Total tax revenue obtained would be 6,472 and 7,976 million THB/year at initial period and steady state, respectively.

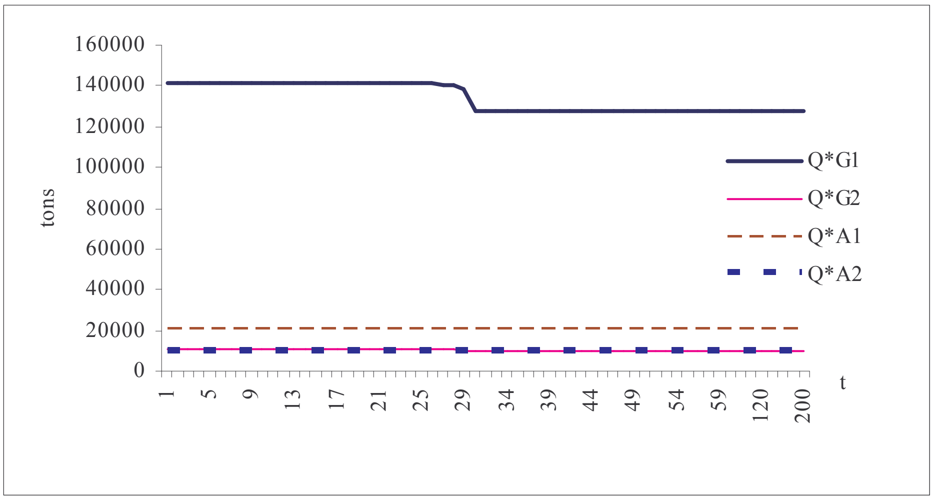
The result also shows that at social optimum both production- and tax paths reach steady state in 30 years for G but 150,696 years for A. In comparison, at private optimum, nutrient stock will reach threshold in 23 years for G and 132,589 years for A. It can be implied that the carrying capacity of G is a sensitive factor for shrimp farming in the area while it is not likely to be the case for A. The optimal paths from social optimum are presented in figure 2.

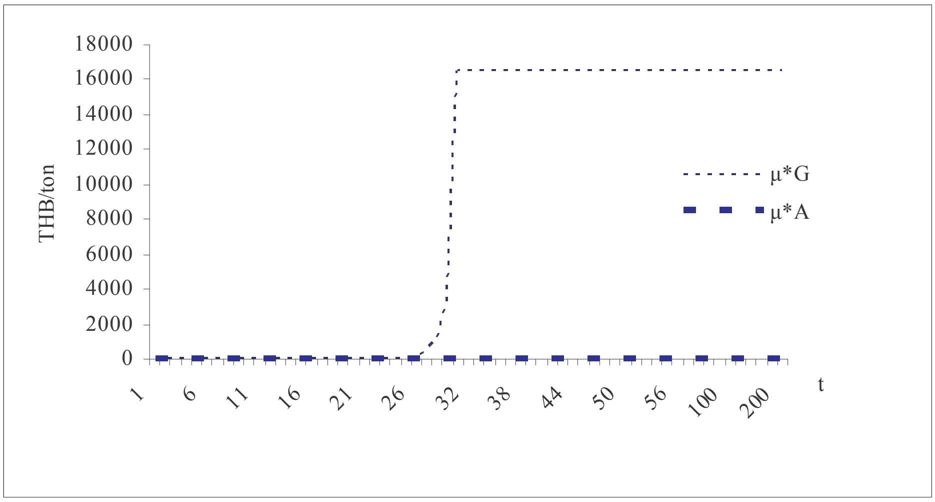
With private optimum and no consideration of environmental values, the society considerably benefits in terms of social welfare (producer- plus consumer surplus) of 28,304 million THB/year and gain from trade of 18,748 million THB/year. While at social optimum, both the surpluses of 19,758 million THB/year and gain from trade of 14,517 million THB/year (at steady state) are relatively smaller. It turns out that at private optimum both benefits also offset environmental costs, i.e. net welfare and net gain from trade are still positive after environmental costs are considered. In addition, net welfare at initial time is higher at private optimum than at social optimum. This contrasts in the steady state, which shows that society will benefit more from social optimal policy than from private optimal policy, i.e. 1,787 million THB/year higher in net welfare. In terms of net gain from trade (with consideration of environmental costs), social optimal policy also gives higher benefits than at private optimal policy through times, i.e. 1,133 million THB/year higher at initial time and 4,974 million THB/year higher at steady state.

Table 1. Optimal policies from base case scenario categorized by sites

	G1		G2		G1+G2		A1		A2		A1+A2		Total (G1+G2+A1+A2)	
	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**
Production: Private optimum														
Qp* (tons)	185,849	**185,849**	10,677	**10,677**	196,525	**196,525**	24,778	**24,778**	10,156	**10,156**	34,934	**34,934**	231,460	**231,460**
Qp* (rai)	371,697	**371,697**	21,353	**21,353**	393,050	**393,050**	30,973	**30,973**	12,695	**12,695**	43,668	**43,668**	436,718	**436,718**
Production: Social optimum														
Qs* (tons)	141,126	**127,545**	10,507	**9,496**	151,633	**137,041**	20,682	**18,928**	10,055	**9,202**	30,737	**28,130**	182,370	**165,172**
Qs* (rai)	282,252	**255,090**	21,015	**18,992**	303,267	**274,083**	25,852	**23,660**	12,569	**11,503**	38,421	**35,163**	341,688	**309,246**
Changes														
Qp*-Qs* (tons)	44,723	**58,303**	169	**1,180**	44,892	**59,484**	4,096	**5,850**	101	**954**	4,197	**6,804**	49,089	**66,288**
Qp*-Qs* (rai)	89,445	**116,607**	339	**2,361**	89,784	**118,968**	5,120	**7,313**	127	**1,192**	5,247	**8,505**	95,031	**127,473**
% of Qp*	24%	**31%**	2%	**11%**	23%	**30%**	17%	**24%**	1%	**9%**	12%	**19%**	21%	**29%**
Taxes														
Stock: μ* (THB/ton-shrimp)	0	**16,543**	0	**16,543**			-	**14,579**	-	**14,579**				
Flow: f* (THB/ton-shrimp)	41,368	**37,387**	2,726	**2,464**			28,419	**26,009**	1,714	**1,568**				
μ*+f* (THB/ton-shrimp)	41,368	**53,931**	2,726	**19,007**			28,419	**40,588**	1,714	**16,147**				
Total tax revenue (million THB)													6,472	**7,976**
Welfare: Private optimum														
1 CS+PS													28,304	**28,304**
2 Net welfare													22,949	**18,968**
3 Net gain from trade													13,524	**9,543**
Welfare: Social optimum														
4 CS+PS													19,897	**19,758**
5 Net welfare													21,033	**20,754**
6 Net gain from trade													14,656	**14,517**
Changes														
7 =4-1													- 8,407	**- 8,546**
8 =5-2													- 1,916	**1,787**
9 =6-3													1,133	**4,974**

Figure 2. Optimal paths (production for above and tax on nutrient stock externality for below)





6.2. Sensitivity Analysis

Change in shrimp price (other parameters remain constant) significantly affects the results in terms of magnitude but other intuition remains the same as base case. Increasing price will certainly stimulate a higher production level which consequently increases social welfare, gain from trade and tax revenue both in private- and social optimum. This also leads to a shorter period to attain steady state (e.g. 22 years for G with a 30% increase in price compared to 30 years in base case) However, when price increases social optimal policy results in increasing net gain from trade over that from private optimum but not in terms of the surpluses and net social welfare.[18] The interpretation is in opposite direction when price decreases. Details are presented in tables 2 and 3.

Change in damage cost of nutrient stock results in hardly any change from the base case at the beginning of the path. But there is a notable change in steady state: increasing damage cost will decrease optimal production at social optimum and more tax revenue will be obtained. The latter is obviously due to increasing tax on nutrient stock, not on flow externalities. Decreasing production consequently reduces net welfare and net gain from trade in social optimum. It also gives the same effect to private optimum as environmental costs are accounted in measuring net welfare and net gain from trade although private optimum production remains intact. However, the higher damage cost, the better changes of net benefits (net welfare and net gain form trade from social optimum over those from private optimum) the society would gain, if social optimal policy is taken into action.

Increasing the social discount rate will induce higher production at steady state. This also contributes to higher net welfare and net gain from trade in both private- and social optimum. On the other hand, it reduces the corrective tax of stock externality which subsequently decreases overall tax revenue.[19] This is because the decreasing shadow cost of nutrient stock overwhelms the increasing flow of external costs. However, all results do not show significant change from base case at the beginning of the time path.

Furthermore, as shown in the model above, one can expect the same effect when nutrient assimilation rate increases except that change in the latter parameter will also significantly affect terminal time. Experimentally, slight increase of assimilation rate, for example, from 97 to 98%, will dramatically increase the period to attain steady state, i.e. 47,111 years for G and longer for A. In contrast, only a slight decrease in the assimilation rate, which in consequence

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[18] See the section of framework of analysis for the theoretical ground.

[19] See also equation (14) and (15).

makes $\hat{N} - N_0$ close to zero, would move the steady-state period close to zero for G but still a very long period for A. A similar effect occurs when other parameters that relate to the carrying capacity of the coastal water are changed. For example, decreasing nutrient load concentration (β), increasing water volume (as sink), or increasing proportion of allowable threshold level for shrimp sector also indicates, as seen in case of increasing assimilation rate, that the effect of nutrient stock for both G and A is negligible. In addition, a lower load concentration enables society as a whole to enjoy a bigger net welfare as well as a net gain from trade in both private- and social optimum, as seen in table 2.

Table 2. *Optimal policies from sensitivity analysis (summary of all sites)*

I. Price	p=247 THB/kg (inc. 30%)		p=228 THB/kg (inc. 20%)		p=209 THB/kg (inc. 10%)		**p=190 THB/kg (base case)**		p=171 THB/kg (dec. 10%)		p=152 THB/kg (dec. 20%)	
	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**
Qs* (tons)	256,088	**237,942**	231,369	**213,494**	206,786	**186,222**	182,370	**165,172**	158,170	**141,404**	134,250	**118,005**
% dec. from Qp*	17%	**23%**	18%	**24%**	20%	**26%**	21%	**29%**	23%	**31%**	26%	**35%**
Total tax revenue (million THB)	9,709	**12,229**	8,612	**10,783**	7,531	**9,363**	6,472	**7,976**	5,438	**6,629**	4,438	**5,332**
Welfare:												
1 CS+PS (private)	43,399	**43,399**	37,930	**37,930**	32,898	**32,898**	28,304	**28,304**	24,147	**24,147**	20,428	**20,428**
2 Net welfare (private)	36,220	**31,213**	31,359	**26,690**	26,935	**22,608**	22,949	**18,968**	19,400	**15,769**	16,288	**13,013**
3 Net gain from trade (private)	25,375	**20,367**	20,985	**16,317**	17,035	**12,708**	13,524	**9,543**	10,453	**6,822**	7,825	**4,550**
4 CS+PS (social)	31,858	**31,711**	27,438	**27,293**	23,451	**23,309**	19,897	**19,758**	16,776	**16,640**	14,084	**13,952**
5 Net welfare (social)	33,072	**32,778**	28,629	**28,339**	24,617	**24,332**	21,033	**20,754**	17,876	**17,604**	15,141	**14,878**
6 Net gain from trade (social)	26,587	**26,440**	22,175	**22,030**	18,198	**18,055**	14,656	**14,517**	11,550	**11,414**	8,877	**8,745**
7 =4-1	-11,540	**-11,688**	-10,492	**-10,637**	-9,447	**-9,589**	-8,407	**- 8,546**	-7,372	**-7,508**	-6,345	**-6,476**
8 =5-2	-3,148	**1,565**	-2,729	**1,649**	-2,318	**1,724**	-1,916	**1,787**	-1,524	**1,835**	-1,147	**1,865**
9 =6-3	1,212	**6,072**	1,190	**5,713**	1,163	**5,348**	1,133	**4,974**	1,094	**4,592**	1,052	**4,196**

II. Damage cost due to nutrient stock (*v*)	inc.50 %		inc.20 %		**base case**		dec.20 %	
	t_0	**T**	t_0	**T**	t_0	T	t_0	**T**
Qs* (tons)		**156,572**		**161,732**		**165,172**		**168,611**
% dec. from Qp*		**32%**		**30%**		**29%**		**27%**
Total tax revenue (million THB)		**8,562**		**8,224**		**7,976**		**7,710**
Welfare:								
1 CS+PS (private)		**28,304**		**28,304**		**28,304**		**28,304**
2 Net welfare (private)		**16,767**		**18,104**		**18,968**		**19,808**
3 Net gain from trade (private)		**7,342**		**8,679**		**9,543**		**10,384**
4 CS+PS (social)		**19,584**		**19,697**		**19,758**		**19,808**
5 Net welfare (social)		**20,406**		**20,632**		**20,754**		**20,855**
6 Net gain from trade (social)		**14,343**		**14,456**		**14,517**		**14,567**
7 =4-1		**-8,720**		**-8,607**		**- 8,546**		**-8,496**
8 =5-2		**3,638**		**2,527**		**1,787**		**1,046**
9 =6-3		**7,000**		**5,776**		**4,974**		**4,184**

Table 2. (continued)

III. Social discount rate (δ)	12 %		10 %		**8% (base case)**		6 %	
	t_0	**T**	t_0	**T**	t_0	T	t_0	**T**
Qs* (tons)		**165,801**		**165,492**		**165,172**		**164,838**
% dec. from Qp*		**28%**		**29%**		**29%**		**29%**
Total tax revenue (million THB)		**7,929**		**7,952**		**7,976**		**8,001**
Welfare:								
1 CS+PS (private)		**28,304**		**28,304**		**28,304**		**28,304**
2 Net welfare (private)		**19,123**		**19,047**		**18,968**		**18,885**
3 Net gain from trade (private)		**9,698**		**9,622**		**9,543**		**9,460**
4 CS+PS (social)		**19,768**		**19,763**		**19,758**		**19,752**
5 Net welfare (social)		**20,774**		**20,765**		**20,754**		**20,743**
6 Net gain from trade (social)		**14,527**		**14,522**		**14,517**		**14,512**
7 =4-1		**-8,536**		**-8,541**		**- 8,546**		**-8,551**
8 =5-2		**1,651**		**1,718**		**1,787**		**1,859**
9 =6-3		**4,829**		**4,900**		**4,974**		**5,052**

IV. % of load concentration (β-kg N/ton shrimp produced)	**base case (β_G=5.9142; β_A=6.6308)**		75 % of base case		50 % of base case		25 % of base case	
	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**
Qs* (tons)		**165,172**		**169,471**		**173,771**		**178,071**
% dec. from Qp*		**29%**		**27%**		**25%**		**23%**
Total tax revenue (million THB)		**7,976**		**7,641**		**7,279**		**6,889**
Welfare:								
1 CS+PS (private)		**28,304**		**28,304**		**28,304**		**28,304**
2 Net welfare (private)		**18,968**		**20,015**		**21,028**		**22,006**
3 Net gain from trade (private)		**9,543**		**10,590**		**11,603**		**12,581**
4 CS+PS (social)		**19,758**		**19,819**		**19,862**		**19,889**
5 Net welfare (social)		**20,754**		**20,876**		**20,963**		**21,016**
6 Net gain from trade (social)		**14,517**		**14,578**		**14,622**		**14,648**
7 =4-1		**- 8,546**		**-8,485**		**-8,441**		**-8,415**
8 =5-2		**1,787**		**861**		**-65**		**-990**
9 =6-3		**4,974**		**3,988**		**3,019**		**2,067**

Table 3. Optimal taxation (THB/ton) from sensitivity analysis for various sites

	G1		G2		A1		A2	
	t_0	**T**	t_0	**T**	t_0	**T**	t_0	**T**
Base case								
Stock: μ*	0	**16,543**	0	**16,543**	0	**14,579**	0	**14,579**
Flow: f*	41,368	**37,387**	2,726	**2,464**	28,419	**26,009**	1,714	**1,568**
μ*+f*	41,368	**53,930**	2,726	**19,007**	28,419	**40,588**	1,714	**16,147**
P=247 THB/kg (inc.30%)								
Stock: μ*	0	**16,543**	0	**16,543**	0	**14,579**	0	**14,579**
Flow: f*	44,005	**40,825**	2,737	**2,539**	29,639	**27,751**	1,718	**1,609**
μ*+f*	44,005	**57,368**	2,737	**19,082**	29,639	**42,330**	1,718	**16,188**
P=228 THB/kg (inc.20%)								
Stock: μ*	0	**16,543**	0	**16,543**	0	**14,579**	0	**14,579**
Flow: f*	43,253	**39,844**	2,734	**2,518**	29,296	**27,261**	1,717	**1,598**
μ*+f*	43,253	**56,387**	2,734	**19,061**	29,296	**41,840**	1,717	**16,177**
P=209 THB/kg (inc.10%)								
Stock: μ*	0	**16,543**	0	**16,543**	0	**14,579**	0	**14,579**
Flow: f*	42,383	**38,711**	2,730	**2,494**	28,894	**26,688**	1,715	**1,584**
μ*+f*	42,383	**55,254**	2,730	**19,037**	28,894	**41,267**	1,715	**16,163**
P=171 THB/kg (dec.10%)								
Stock: μ*	0	**16,543**	0	**16,543**	0	**14,579**	0	**14,579**
Flow: f*	40,167	**35,822**	2,721	**2,426**	27,847	**25,192**	1,712	**1,548**
μ*+f*	40,167	**52,365**	2,721	**18,969**	27,847	**39,771**	1,712	**16,127**
P=152 THB/kg (dec.20%)								
Stock: μ*	0	**16,543**	0	**16,543**	0	**14,579**	0	**14,579**
Flow: f*	38,724	**33,940**	2,714	**2,379**	27,146	**24,190**	1,709	**1,523**
μ*+f*	38,724	**50,483**	2,714	**18,922**	27,146	**38,769**	1,709	**16,102**
***v* inc. 50%**								
Stock: μ*	0	**24,815**	0	**24,815**	0	**21,868**	0	**21,868**
Flow: f*	41,368	**35,397**	2,726	**2,333**	28,419	**24,804**	1,714	**1,496**
μ*+f*	41,368	**60,212**	2,726	**27,148**	28,419	**46,672**	1,714	**23,364**
***v* inc. 20%**								
Stock: μ*	0	**19,852**	0	**19,852**	0	**17,494**	0	**17,494**
Flow: f*	41,368	**36,591**	2,726	**2,411**	28,419	**25,527**	1,714	**1,539**
μ*+f*	41,368	**56,443**	2,726	**22,263**	28,419	**43,021**	1,714	**19,033**
***v* dec. 20%**								
Stock: μ*	0	**13,235**	0	**13,235**	0	**11,663**	0	**11,663**
Flow: f*	41,368	**38,184**	2,726	**2,516**	28,419	**26,491**	1,714	**1,597**
μ*+f*	41,368	**51,419**	2,726	**15,751**	28,419	**38,154**	1,714	**13,260**
***δ*=12%**								
Stock: μ*	0	**15,938**	0	**15,938**	0	**14,045**	0	**14,045**
Flow: f*	41,368	**37,533**	2,726	**2,473**	28,419	**26,097**	1,714	**1,574**
μ*+f*	41,368	**53,471**	2,726	**18,411**	28,419	**40,142**	1,714	**15,619**
***δ*=10%**								
Stock: μ*	0	**16,235**	0	**16,235**	0	**14,307**	0	**14,307**
Flow: f*	41,368	**37,462**	2,726	**2,469**	28,419	**26,054**	1,714	**1,571**
μ*+f*	41,368	**53,697**	2,726	**18,704**	28,419	**40,361**	1,714	**15,878**
δ=6%								
Stock: μ*	0	**16,864**	0	**16,864**	0	**14,861**	0	**14,861**
Flow: f*	41,368	**37,310**	2,726	**2,459**	28,419	**25,962**	1,714	**1,566**
μ*+f*	41,368	**54,174**	2,726	**19,323**	28,419	**40,823**	1,714	**16,427**

7. Discussions

The analysis for numerical results, however, is limited by the lack of direct information on carrying capacities, nutrient transport loss, and assimilation. Knowledge and information from natural science studies that can throw a better light on site-specific data would allow a more precise economic valuation of impacts and enable the development of more accurate marine biogeochemical parameters. This study also found that the numerical results are very sensitive to biogeochemical parameters, which could cause extremely varied interpretation of the results (as discussed later). On the other hand, the valuation data only affect the scale of the results.

The tax rate on nutrient stock externality relies on the overall damage generated by the whole industry that employs the same coastal system as sink for discharges. Again, damage occurs only when total accumulated load reaches threshold, i.e. more than the carrying capacity of the sink to assimilate nutrient load. In addition to the theoretical model, the tax imposed on farm discharge should then be equal to shadow cost of nutrient stock generated by the whole industry. For implementation, although farm discharge concentration and volume differ by farms, the same tax rate to be imposed on discharge from all individual common practice farms is suggested. This scheme is valid by assuming that the farms that remain operating are efficient and cost effective. More specifically, they have no motivation to generate higher effluent, which implies higher feed cost, other than to improve yield. It is supported by the fact that the higher the yield the higher the FCR and *vice versa* as seen from the survey reported by PCD (2002). Higher discharge due to improving yield can then be captured by this tax regime since it is collected per unit of output.

It is important that the tax should be fully imposed regarding individual farm's externalities generated. Practically, it is suggested that instead of monitoring the levels of externalities (e.g. load concentration) acquiring information on sources of externalities generated by individual farms should be sufficient for tax implementation. The tax can be broadly divided into several items: first, "discharge tax" should be imposed on common practice farms but not on farms that are certified as CoC or GAPs farms; second, "mangrove tax" will be charged to the farms located in ex-mangrove (which can be identified from remote sensing data, for instance); third, "abandoned farm tax" may be considered as precautionary tax and social insurance[20] due to the uncertainty of impacts. Furthermore, for the last two items, taxing per unit of area (rather than per ton of production) is a direct approach to be corrected on the impacts.

Although in theory the tax rate is varied before steady state, the simulation results show that constant tax rate can be applied. For the Gulf, the steady-state tax should be applied due to the very limited carrying capacity of the Gulf as indicated by the short terminal time it requires to reach the critical level of nutrient load. In fact, the steady state becomes very close to initial time ($T\approx0$) when assimilation rate slightly decreases. On the other hand, it is unlikely to be the case for the Andaman Sea. This implies that nutrient load has a negligible effect on Andaman but the effect is significant on the Gulf. Thus initial tax rate, i.e. a zero discharge tax, can be applied in Andaman area. Nevertheless, it should be cautioned that the analysis covers only the nutrient stock effect in the sea, not in public canals which can be polluted by high density of farms.

Following the above tax formation and applying the results of steady state policy for the Gulf but initial time policy for the Andaman, the benchmark tax rates and optimal production to be imposed are calculated as follows:

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[20] See Mathis and Baker (2002) for details of these instruments.

Items	The Gulf & ex-mangrove	The Gulf & outside mangrove	Andaman & ex-mangrove	Andaman & outside mangrove	Total
1. Mangrove tax (THB/rai/yr)	14,316	0	17,412	0	
2. Abandoned farm tax (THB/rai/yr)	4,377	1,232	5,323	1,371	
3. Discharge tax (THB/ton)	16,543	16,543	0	0	
Production (tons)	127,545	9,496	20,682	10,055	167,778

Note: The tax items 1 and 2 are based on average yields of 0.5 and 0.8 ton/rai/yr for the Gulf and Andaman, respectively.

This suggestion is based on the results from base case scenario. It should be noted that the steady-state results of the Gulf in base case are not different from the case when $T \approx 0$ as assimilation rate slightly decreases.

Implementing taxation as suggested requires farm registration. Recently, in 2004, the procedure becomes automatic by the governments' requirement of a "movement document" needed to bring products to the markets as part of the requirement on product traceability by export markets. Administration and implementation costs should also be further explored as to whether these additional costs will offset the revenue from taxes.

Although the paper focuses on a tax regime, good farm practices such as those prescribed under the CoC and GAPs should be encouraged as options for pollution management. As the results show, if shrimp industry themselves can reduce overall load concentration to at least 50% lower than the present level (as assumed in base case), private optimal policy could be seen as more economical as well as politically acceptable than social optimal policy since it will give higher net social welfare gain (i.e. the society as a whole would enjoy large surpluses with less pollution!). Although net gain from trade at social optimum is still higher in this case, it may not be necessary to introduce this policy since environmental values accounted in net gain from trade are not tradable in the market, unlike total gain from trade, which is obviously seen. However, the above suggestions would be reversed if the overall nutrient load concentration continues to remain as high as today's load (again as assumed in base case). It is due to the fact that, for a long-term perspective, the social optimal policy contributes higher net social welfare and, clearly, a net gain from trade. Nonetheless, the society's perception and concern on benefits from environmental improvement is necessary in order to promote tax regime. Imposing the taxes may induce farmers to seek for cost-reducing farm management and technologies, compliance with good practices, which may contribute to long-run competitive advantage in world market. "If Thai shrimp farming were taxed as such, would it make farmers' behavior change?" would then be another research question.

Last but not least, it should be remarked that the model applied in this paper cannot cover the problem of competing land use. Integrating the issue in the analysis may provide different insight of information on optimal production for shrimp farming in coastal area with which generally involves land use conflicts.

8. Conclusion

An optimal corrective tax for Thai shrimp farming can be derived from standard dynamic-constraint model where the tax is modified from the static view by incorporating accumulated nutrient stock in the sea as constraint. Environmental effects generated in terms of cumulative nutrient build-up in coastal waters, mangrove conversion and abandoned farms are internalized.

The model shows a conventional outcome of increasing optimal tax path but decreasing optimal production path before it attains a steady state. It implies some tax has to be imposed on stock externality that is equal to increasing shadow cost of nutrient stock before damage occurs.

However, the simulation results in most cases show that the shadow costs for the two coastal areas of Thailand are very small (nearly zero) at the beginning of the paths. The results also indicate that nutrient load in Andaman has a negligible effect on the sea but significant on the Gulf of Thailand. This paper thus suggests applying the steady-state tax policy to shrimp farming on the Gulf and the initial tax policy on Andaman. That is the tax would be imposed on farm discharge of around 16.54 THB/kg for the Gulf but zero discharge tax for Andaman. Mangrove tax would be 14,316 and 17,412 THB/rai/year for the Gulf and Andaman, respectively. Abandoned farm tax would be 1,232-5,323 THB/rai/year depending on culture site. The overall production (at private optimum) should be reduced by 20-30% in order to obtain a socially efficient level for Thailand. Farming in ex-mangrove areas both on the Gulf and Andaman should be decreased in higher proportion than in outside mangrove. Production from the Gulf should be reduced more than from Andaman for all sites. The tax regime ensures a higher net gain from trade than at private optimum but it is ambiguous in terms of net social welfare. However, in the long run net welfare and net gain from trade from social optimum are higher than those from private optimum.

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10. Appendix
Data and Parameters

Ideally, the optimal policy should not be uniform since the factors involve in the model—private costs, environmental damages and ecological system (e.g. thresholds, assimilation) are different by farm practices and natural-environments. Empirically, the analysis here is simplified that is in order to determine a green tax as a benchmark for the whole industry, homogeneous common farm practices are assumed for all farms. Nevertheless, since the coastal-water systems differ by locations thus the parameters are divided broadly into two main sets, i.e. for the Gulf of Thailand (G) and for the Andaman Sea (A). In the case when data is limited, some indicators are used to base the calibration of unknown parameters. Mainly data during 1990s is used because of its availability and also for consistency. In addition, better practices were not yet initiated during that period while common farm practices were widely applied. The details of data and parameters used in the analysis are depicted as follows.

Shrimp price

Although Thailand is the second world leader of aquaculture shrimp (around one-third of world aquaculture production), the market share of the product is only 7% of total world shrimp production (capture plus culture). It is thus justified to assume that Thai shrimp price is associated with the overall world shrimp price. A small country case for Thai aquaculture shrimp is thus assumed for the analysis. The average price (p) of around **190 THB/kg** is used in the analysis of base case. It is calculated based on wholesale prices of raw shrimp from various sizes during 1990-1999 (data from Fish Marketing Organization).

Marginal private cost

The marginal private cost function of Thai shrimp $MC=18{,}090+0.7427Q$ (unit in THB/ton) is obtained from Thavornbutr (2000). It was estimated by using DOF statistics during 1988-1997 and applying two-stage least square method in order to solve simultaneous equations model of demand and supply. The supply function obtained was reduced in a simple form as a function of price and then adjusted by the error term.

The function represents aggregated function. The supply function of each production site can then be derived from its share from the aggregated function. The calibration is done by using shrimp farm areas in ex-mangrove in 1996 reported by Charuppat and Charuppat (1997). They were 386,525 and 32,211 rai for G and A, respectively. Total area of shrimp farms for the whole kingdom in the same year reported by DOF was 454,148 rai; around 90% was from G side and the remaining 10% was from A side. From here, the area of shrimp farms for each site can be calculated. Converting the areas into production using the average yields of 0.5 ton/rai/year for G and 0.8 ton/rai/year for A (assuming the same yield in both ex-mangrove and outside mangrove), the proportion of production for each site can be obtained. Use each proportion to calibrate the marginal private cost function for each site. This results the slope of each function of **0.9250 16.1016 6.9380 and 16.9264** (assuming the same intercept) for the Gulf and in ex-mangrove (G1), the Gulf and outside mangrove (G2), Andaman and in ex-mangrove (A1) and Andaman and outside mangrove (A2), respectively.

Treatment cost of shrimp farm effluent

Treatment cost of farm effluent is used for the estimation of unit cost *v* (unit in THB/kg-N) which is represented as a proxy value for damage cost of eutrophication due to nutrient load. According to PCD (2002), treatment costs are varied by farm sizes from 5.9 to 7.7 THB/kg-shrimp harvested or around 7,000 THB/ton-shrimp in average. Data of effluent load from intensive farming in Thailand reported by PCD (1996) is used to convert this cost into cost per unit of nutrient load. It turns out that producing one tone of shrimp (intensive system) generates 5.9142 and 6.6308 kg of nitrogen per year for G and A. Note that nitrogen in the forms of ammonium (NH_4-N), nitrite (NO_2-N) and nitrate (NO_3-N) is considered as a limiting nutrient (see environmental impacts section). Thus, $\boldsymbol{v_G}$**=2,944** and $\boldsymbol{v_A}$**=2,314 THB/kg-N**.

Forgone benefits of mangrove

Forgone benefits of stand mangrove in Surat Thani, Southern Thailand (in the case of mangrove-dependent village) studied by Sathirathai (1998) and Sathirathai and Barbier (2004) are used as proxy value of environmental cost of mangrove conversion. Direct use value from wood and non-wood products (e.g. fish, honey) of 1,938 THB/rai/year was presented (Sathirathai, 1998). Indirect use consists of forgone values of mangrove services in terms of coastal protection, carbon sequestration and off-shore fishery linkage. Values of carbon sequestration and off-shore fishery linkage reported are 341 and 272 THB/rai/year (Sathirathai, 1998).[21] Cost per unit of shoreline stabilization was used as proxy for the estimation of value of coastal protection function. The physical cost of shoreline protection of 746,669 THB/rai or 61,035 THB/rai/year (at project period, t, 50 years and discount rate, r, 8%) was estimated (Sathirathai and Barbier, 2004). However, the study stated that only 30% of this replacement cost represents the demand for shoreline stabilization. This is as claimed by the Harbor Department that the same proportion of Thailand's coastal areas is prone to experience the erosion and thus may require such investment. Therefore, this turns out that the coastal protection value contributed by stand mangrove is 18,310 THB/rai/year. The same proxy value is applied to both G and A area.

Hence, total forgone benefits of mangrove are **41,722 and 26,076 THB/ton of shrimp produced** for G and A, respectively (again assuming shrimp yields of 0.5 ton/rai/year for G and 0.8 ton/rai/year for A). This proxy value excludes biodiversity, option and nonuse values.

Restoration cost of abandoned shrimp farms in ex-mangrove

According to Sathirathai and Barbier (2004), the costs of the rehabilitation program of abandoned shrimp ponds in ex-mangrove run by Royal Forestry Department is 52,736 TBH/rai for initial investment and 755 THB/rai for annual maintenance. The annuity value of the program is 6,378 THB/rai/year (t=15,

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[21] The fishery linkage value used is from the case of price demand elasticity of fishery products of -2 in open-access situation. Note that the values are varied in the range of 133-440 THB/rai/year as a result of different elasticities assumed (from -10 to -0.1).

r=8%) or **12,756** and **7,972 THB/ton** for G and A, respectively. These are used as proxy values for environmental costs of abandoned shrimp farms in ex-mangrove.

Reclamation cost of abandoned shrimp farms outside mangrove

According to Kantangkul (2002), Land Development Department estimated that the reclamation cost of abandoned shrimp ponds is 9,296 THB/rai or 1,385 THB/rai/year (t=10, r=8%). The costs per unit of production are **2,770** and **1,731 THB/ton** for G and A, respectively. These are used as proxy values for environmental costs of abandoned shrimp farms outside mangrove.

Marginal Social Cost

S'_{G1} and S'_{A1} are represented as marginal social costs of shrimp farming in ex-mangrove and S'_{G2} and S'_{A2} for outside mangrove for each coastal area. Each of the functions comprises its MPC and its marginal environmental cost in terms of forgone benefits of mangrove (for G1 and A1) and cost of abandoned shrimp farm (for all sites). From the marginal private cost functions presented above, the private optimal productions of 185,849 10,677 24,778 and 10,156 tons for G1, G2, A1 and A2 respectively (at *p*=190 THB/kg) are obtained. Marginal social cost function of each site can then be obtained by adding total unit cost of externalities at each of the level of private optimal productions. This results the slopes of **1.2181 16.3610 8.3121** and **17.0968** for S'_{G1} S'_{G2} S'_{A1} and S'_{A2}, respectively (at the same intercept as MPC).

Nutrient-related parameters

- Rates of N discharged from intensive shrimp farms during grow-out and harvesting period for G and A are **5.9142 (β_G) and 6.6308 (β_A) kg-N/ton-shrimp/year** (see also the above section of treatment cost of shrimp farm effluent).

- Rate of N net loss due to transport and assimilation within the coastal system is assumed around **97%** for both G (θ_G) and A (θ_A) as base case. Since there is no direct information available, the decreasing rate of N concentration during transport from inland to the sea is used as an indicator. Here data of concentrations varied by distances from inland to the Gulf of Thailand is used for the estimation.[22]

- Initial loads of N from shrimp farms accumulated in coastal waters are around **427,105 and 90,077 kg-N** for G ($N(0)_G$) and A ($N(0)_A$). Data of the rate of N discharge and the rate of N loss (as described above) together with shrimp production is used for the estimation. The load from 1986 (when intensive farming was promoted) to 2002 is accounted.

Data of N threshold concentration is not available. However, it is inspected that red tide occurred occasionally in G. Concentration of N measured during red tide is thus used as an indicator. It should be noted that N concentration threshold should be higher that that measured during red tide. However, due to data limitation the maximum concentrations found when red tide happened are used to base the calculation. They were 10.167 2.286 and 1.673 µmole/l for amonia, nitrite and nitrate, respectively (PCD, 2003, table 2.2-10). Water volumes of G and A (1,600 and 1,000 kilometers of shoreline) within 3 kilometers from the shore and 3 meters deep in average are used together with the N concentrations above in order to reckon total critical loads of N for G and A. In addition, it is assumed that threshold level for shrimp farming alone is around 15% of total critical load (as base case). It is calculated based on the share of GDP from shrimp farming compare to other sources of loading (i.e. agriculture, livestock, industry and domestic waste). This results the N thresholds for shrimp farming of **427,170 and 266,981 kg-N** for G ($\hat{N}_G$) and A ($\hat{N}_A$), respectively.

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