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Review

Analysis of production and environmental effects of Nile tilapia and white shrimp culture in Thailand

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ABSTRACT

Two case studies from Southeast Asia are used to analyse production, environmental effects, and economic optimisation of Nile tilapia (*Oreochromis niloticus*) and white shrimp (*Penaeus vannamei*) pond culture. A projection of these data is made for the whole of Thailand. The results are analysed on a regional scale based on site selection using multi-criteria evaluation (MCE).

Farm-scale culture was simulated for (i) tilapia monoculture in Chiang Rai; (ii) shrimp monoculture in Chanthaburi; and (iii) Integrated Multi-Trophic Aquaculture (IMTA) of tilapia and shrimp in Chon Buri. Together, these provinces produced 17,500 tonnes of tilapia in 2012, with a significant proportion exported to North America and Europe.

Growth models for both species were developed, calibrated, and validated, and used to simulate population dynamics of cultivated animals, and sediment diagenesis and eutrophication in ponds. Co-cultivation stimulates nitrogen dissolution (134 kg N cycle^{-1}), which is greater than in tilapia (96 kg N) or shrimp (52 kg N) monoculture, and doubles the NH_4^+ discharge to the environment (10.7 kg in tilapia monoculture, 20.5 kg in co-cultivation). However, eutrophication as a result of shrimp monoculture decreases sharply – chlorophyll emissions fall from 0.17 kg to 0.02 kg. A modelled IMTA scenario including the green seaweed *Ulva* reduced NH_4^+ outflow to 0.32 kg cycle^{-1}. Scaling to the national level, for a 2010 production of 158,293 t y^{-1} (tilapia), and 553,899 t y^{-1} (shrimp), gives calculated emissions of 2,105,118 and 34,904 Population Equivalents (PEQ) respectively. Only part is a negative externality, because rural agro-aqua systems in Thailand reuse discharges in holding ponds, rice culture, etc.

Commercial tilapia and shrimp aquaculture have a value added share of total GDP of 0.38, and value added of 96.24, resulting in indirect impacts of the industry on the Thai economy of $35 million, and the creation of 16,000 additional jobs.

The MCE scenario analysis suggests sustainable expansion is possible for both species. The *highly suitable* class for tilapia would triple in the dry season, but halve in the rainy season. For shrimp the corresponding areas would decrease in both seasons. However, the *suitable* class is two orders of magnitude greater than the current level of tilapia farming, and shrimp could increase tenfold (limited by the rainy season due to low salinity). These projections which are constrained by competing land claims, will be further influenced by socio-economic factors, and would depend upon national or regional policy decisions.

These models, together with economic indicators developed for the aquaculture industry in Thailand, provide an overview of this important contributor to world aquaculture, which has a volume production greater than both the US and EU, and explore some of the lessons that may be learnt worldwide at both the local and national scales.

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1 . Introduction

Carrying capacity and site selection for aquaculture have received increasing attention over the past decade (e.g. Aguilar-Manjarrez and Nath, 1998; Pcbérez et al., 2003; Ross et al., 2013; Silva et al., 2011). This focus has been sharpened by the recent paradigm shift in aquatic food production, when the harvest of cultivated species overtook capture fisheries for direct human consumption (Bostock et al., 2010; Ferreira et al., 2013a). In addition, there is an accepted need to substantially increase the world supply of aquatic foodstuffs (Costa-Pierce, 2002; FAO/NACA, 2012; Godfray et al., 2010) to meet an extra annual demand of 30 million metric tonnes[1] by 2050 – this represents a 25% rise in global production, but effectively corresponds to 50% growth in the aquaculture segment, because capture fisheries have been flatlining for decades (e.g. FAO, 2012; Pauly et al., 1998; Watson et al., 2001).

Policy-makers recognize that aquaculture must expand significantly (e.g. Diana et al., 2013; Godfray et al., 2010), and scientists and managers have been systematically developing (Broch et al., 2013; Cromey et al., 2002; Ferreira et al., 2007; Stigebrandt, 2011; Stigebrandt et al., 2004) and applying (Nunes et al., 2011, Falconer et al., 2013; Saurel et al., 2014; Zhang et al., 2009) the tools needed to evaluate how this expansion can occur in a sustainable manner, using accepted frameworks such as the FAO Ecosystem Approach to Aquaculture (EAA—FAO, 2010).

Although Europe and North America have put in place policies such as the EU aquaculture strategy (2009, http://ec.europa.eu/fisheries/cfp/aquaculture/strategy/index_en.htm) and the U.S. National aquaculture policy (2011, http://www.nmfs.noaa.gov/trade/DOCAQpolicy.htm), the regulatory climate in both regions remains a substantial barrier to aquaculture development. As a consequence, the EU presently imports 74% of its aquatic products, while the U.S. imports 84% (FAO, 2012). This is a liability with respect to job creation and balance of trade, and will tend to become more acute due to the dietary shift promoted in developed countries, which creates higher demand for aquatic products.

Furthermore, the nations or regions where the majority of those products originate, i.e. China, SE Asia, and South/Central America, will internally consume a higher proportion of their production as per capita GDP increases and aquatic products become more generally affordable, thereby constraining exports and further increasing prices in the major import markets.

Most of the cultivated finfish production worldwide takes place in ponds and reservoirs, for species such as carp, tilapia (mostly Nile tilapia, *Oreochromis niloctictus*), and barramundi (*Lates calcifer*). In parallel, a substantial biomass of shrimp (mainly white shrimp, *Penaeus vannamei*) is also reared in pond culture. Despite the fact that 70% of aquaculture takes place on land, in developing nations, the bulk of site selection and carrying capacity studies have been executed for open water systems, mainly in the western world, and typically for bays or estuaries where stocking density is constrained by social carrying capacity (Ferreira et al., 2013b; Inglis et al., 2000; Mckindsey et al., 2006).

This asymmetry between the developed and developing nations occurs for various reasons, including (in the former) higher data availability, access to more sophisticated simulation tools, and greater regulatory and societal concerns about sustainability – it is therefore important that state-of-the-art instruments be used to promote the EAA in the parts of the world where it is most needed, i.e. those with both substantial aquaculture production and growth potential.

Our aim is to contribute to this broader worldwide assessment of both carrying capacity and site selection by analysing one of the major producing countries, the Kingdom of Thailand. This nation is considered an example in SE Asia of proactive development of aquaculture, both in terms of production and in its approach to environmental sustainability (Yamprayoon and Sukhumparnich, 2010). Pond culture of Nile tilapia and white shrimp in Thailand represents a combined annual production of over 770,000 t – overall, inland culture is in excess of 1,000,000 t y^{-1}, roughly the same as the entire E.U. and double that of the U.S. (Table 1). The production data can be normalized on a *per capita* or an area basis (Table 2), and illustrate how these ratios differ by 1–2 orders of magnitude between Asia and Western nations.

Tilapia production in Thailand has been mostly targeted at the domestic market, whereas white shrimp are produced mainly for export (Fig. 1). However, a number of the tilapia farms visited during this work are increasingly focused on export, which required significant changes to culture practice, and approval by international certification bodies (Yamprayoon and Sukhumparnich, 2010). The export destinations for these products (Fig. 1) illustrate the global nature of the market – for both species studied, over 50% of exports are destined for Europe and the United States.

The main objectives of this work are to:

1. Use detailed information for different types of tilapia and shrimp pond culture in Thailand, including cultivation of both species in Integrated Multi-Trophic Aquaculture (IMTA), to evaluate regional production and environmental effects;
2. Perform a regional site selection analysis and use the results to project sustainable aquaculture growth;
3. Determine the ecological and economic impacts of these key segments of aquaculture for the whole of the country;
4. Discuss the results obtained in the context of future development of world aquaculture.

2 . Methodology

2.1 . Overview

Our analysis was developed in the following steps, which will be reviewed in detail below.

1. Assess production and environmental effects at the pond scale for Nile tilapia and white shrimp by means of individual and population models, combined in the Farm Aquaculture Resource Management (FARM) model;

[1] All tonnage is expressed in metric tons (tonnes).

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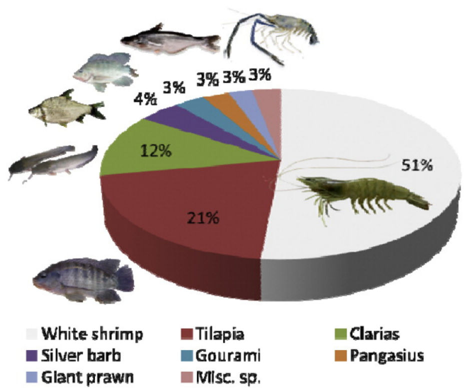
Table 1
Production of inland species and white shrimp in Thailand in 2009 (DOF Thailand).



Common name	Species	Tons y^{-1}
Tilapia	*Oreochromis niloctictus*	221,042
Clarias	*Clarias* sp.	130,064
Silver barb	*Barbus choloensis*	47,231
Gourami	*Trichopodus* sp. *Osphronemus sp.*	34,220
Pangasius	*Pangasius sp.*	30,200
Giant prawn	*M. rosenbergii*	26,785
Misc. sp.	Misc. sp.	32,338
Total inland	Total inland	521,880
White shrimp	*Penaeus vannamei*	553,899

2. Define a geographically representative test region in central Thailand and scale the results for both components (production and environment), and for both species, using pond areas and species distributions obtained from the Thailand Department of Fisheries (DOF) and FAO;
3. Apply a GIS with multi-criteria evaluation (MCE) to determine the suitability ranking for aquaculture of both species within the test area;
4. Compare the pond-level production and environmental effects scaled through DOF and FAO data to the results obtained by combining those dynamic models with the GIS classification;
5. Provide an IMTA analysis at the pond level, for co-culture of shrimp and tilapia, and the potential addition of seaweeds, and scale it to the test area;
6. Calculate the economic value for aquaculture within the test area, and scale it to the political region it contains, based on administrative boundaries;
7. Evaluate the national balance for both types of culture with respect to production, environment, and economics, using DOF and FAO data on aquaculture areas for the two species, broken down by province.

The conceptual framework is shown in Fig. 2: it illustrates the various types of models and how they are combined, and the general data and information flow pattern for the different components of the work. Details on data collection are presented in the relevant parts of the methodology.

In this text, we refer throughout to co-cultivation of tilapia and shrimp as IMTA, with the caveat that since both types of aquaculture are fed, it can also be classified as polyculture. However, in the culture ponds, waste from shrimp culture stimulates primary production, both directly through discharge of dissolved excretory products, and indirectly through diagenesis of particulate organics. As a consequence, there is an increased supply of phytoplankton that enhances the food supply available to tilapia, complementing the pelleted feed.

2.2 . Study area

The study area may be subdivided into three categories, ordered from top to bottom:

1. The entire Kingdom of Thailand, consisting of six broad administrative divisions: Northern (9 regions); Northeastern (19 regions); Central Plain (23 regions); Eastern (8 regions); Western (6 regions); Southern (13 regions). Each of these Level 1 regions or states is divided into a number of Level 2 provinces/districts (e.g. the Chiang Rai region contains 21 districts). Detailed aquaculture data are available in FAO's National Aquaculture Sector Overview (NASO) maps collection Web site a at the district level and include information such as farm types, species, cultivation areas, and production for 2008 (FAO, 2014). These data form the basis for overall upscaling of model results;
2. A regional test area (RTA) in the Central and Eastern parts of Thailand, between longitudes 99° E and 103° E and latitudes 12° N and 15° N (Fig. 3). This test area was defined using drainage basin vector files, downloaded from the Hydro 1K dataset (USGS, 2011), to provide a geographic context for spatial analysis.
The RTA covers an area of 48,319 km^2 and includes the city of Bangkok. This area has a rainy season from May to October and a dry season from November to April (Szuster, 2006). The RTA was used for application of the GIS–MCE and for comparisons with present-day aquaculture, by means of the farm-scale models applied;
3. Aquaculture ponds (i) in the northern area (8 ponds at 3 farms in Chiang Rai province, Pan district) for Nile tilapia culture, and (ii) in the eastern area (25 ponds at one farm in Cholburee province, Phan Thong district), for Nile tilapia and white shrimp culture. Data from ponds in the two areas were used to calibrate and validate individual growth models for both species, and to simulate production and environmental effects at the pond scale.

Table 2
Key ratios for aquaculture production in some different regions/countries.

Country or region	Population	Surface area (ha)	Aquaculture production[a] (kg)	Population ratio (kg per capita)	Area ratio (kg ha^{-1})
China	1,344,130,000	970,700,000	36,734,215,000	27.33	37.84
Thailand[b]	66,790,000	51,312,000	1,075,779,000	16.11	20.97
Thailand	"	"	1,286,122,000	19.26	25.06
EU	503,500,000	441,666,667	1,261,592,000	2.51	2.86
US	313,900,000	982,700,000	495,499,000	1.58	0.50

[a] All aquaculture data from FAO (2012), except Thailand land-based culture (Thailand Dept. of Fisheries, this paper).
[b] Aquaculture data for land-based culture only.

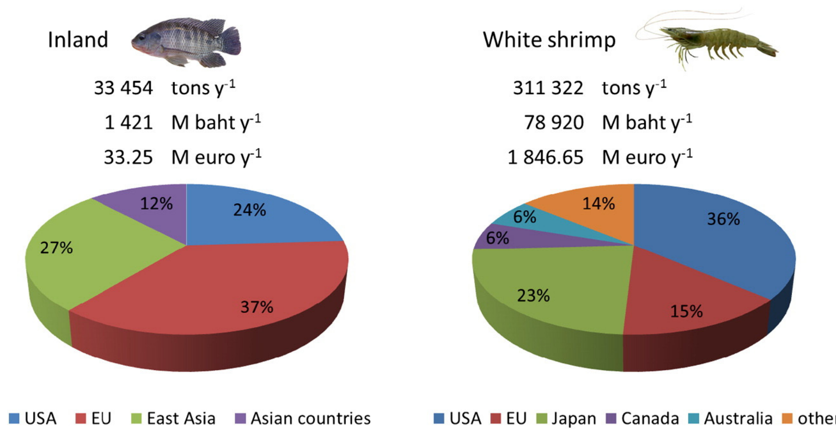


Fig. 1. Export of tilapia and white shrimp from Thailand.

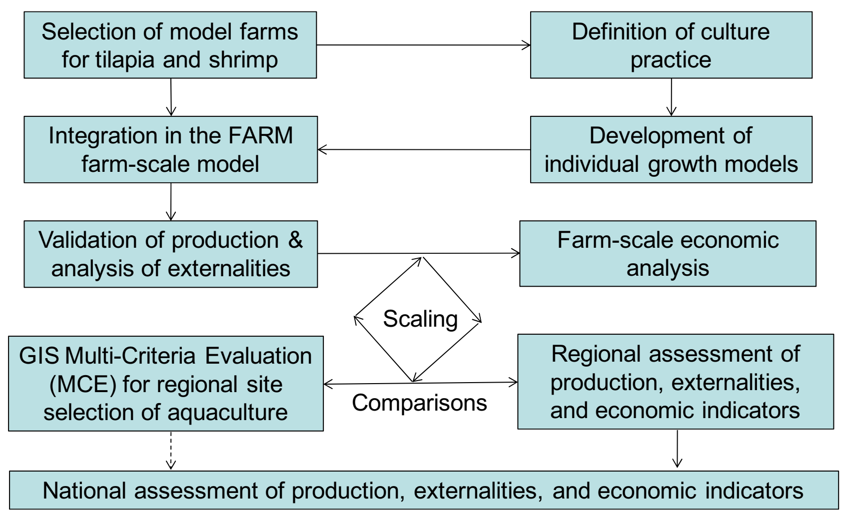


Fig. 2. Modelling framework for examining sustainability.

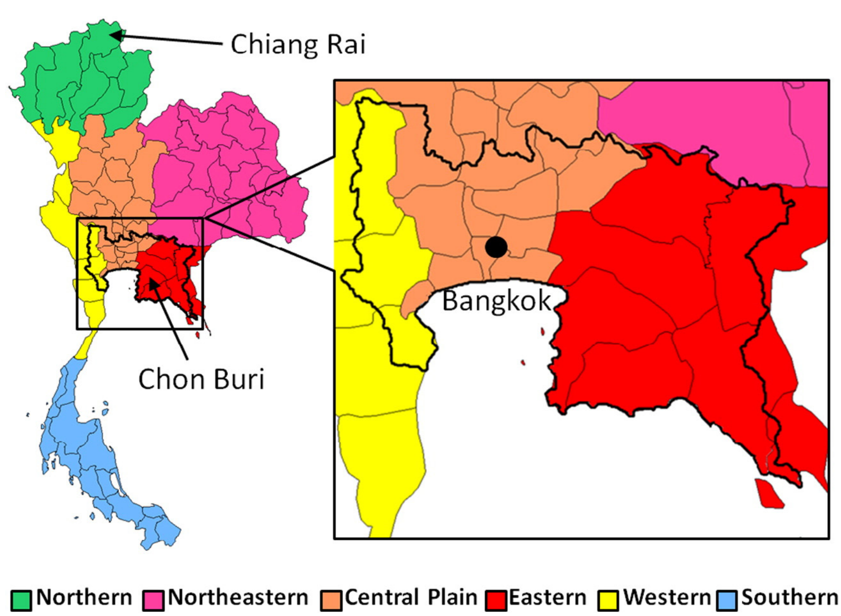


Fig. 3. Regional test area (RTA) in Eastern and Central Thailand for GIS spatial model (green) with administrative borders in black. This region was defined as a hydrological unit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3 . Individual and population models for cultivated species

The 'Aqua' series of models (http://www.longline.co.uk/site/products/aquaculture/) was used to simulate individual growth and environmental effects. The general approach of these models has been previously described for finfish (Ferreira et al., 2012a) and penaeid shrimp (Franco et al., 2006; Zhu et al., 2007). The AquaFish model was extended for Nile tilapia based on equations from Yang Yi (1999) for temperature and dissolved oxygen effects on feeding, and temperature effects on basal metabolic rate; Likongwe et al. (1996) present combined results for the effect of salinity and temperature on feed conversion efficiency (FCR) – these were used to derive a quadratic function to limit the feeding rate based on salinity (Eq. (1)):

$$\sigma = \frac{23.356 + 1.123S - 0.1247S^2}{25.89} \tag{1}$$

$$\sigma = 0 \text{ if } S > 18.9$$

where:

σ : salinity limitation factor $(0-1)$

S : salinity (no units)

Limits in Eq. (1) were obtained from the positive root and first derivative of the equation.

Tilapia length (L) was calculated from biomass (W) following (Eq. (2)) (Gómez-Márquez et al., 2008):

$$W = 0.1207L^{2.469} \tag{2}$$

Gastric evacuation was simulated based on experimental data from Riche et al. (2004). The model additionally incorporates filtration of phytoplankton by tilapia (Eq. (3)) following Perschbacher and Wendell (1993) and Turker et al. (2003).

$$FR = 779.7W\left(1 - e^{(-0.0679\alpha \mathrm{chl})}\right) \tag{3}$$

where:

FR : Filtration rate $\left(\mathrm{mg\ POC\ h^{-1}}\right)$

α : Carbon to chlorophyll ratio (0.05 for C in g and chlorophyll in mg)

chl : Chlorophyll $\left(\mathrm{mg\ m^{-3}}\right)$

A shrimp individual growth model based on Franco et al. (2006), and improved by Zhu et al. (2007), taking into account experimental work on effects of ionic ratios in seawater (Zhu et al., 2004), and dissolved oxygen (Zhang et al., 2006), was modified by applying a net energy balance approach, and calibrated to environmental conditions typical of the ponds selected for this work.

This model had previously been validated for ponds in China where biomass data were available throughout the growth cycle (Fig. 4).

One of the main challenges in validating both individual growth and population models is a reliable description of culture practice. Extensive surveys were carried out during field missions to Thailand; these data, after verification of consistency among farms, were used both to validate growth end-points for individual models and farm-scale modelling of production and environmental effects, carried out with the FARM model. An example of the type of information needed for application of these models is summarized in Fig. 5.

The individual models were used to establish that finfish and shrimp growth could be adequately reproduced, and that the environmental emissions of organic and inorganic materials were appropriately

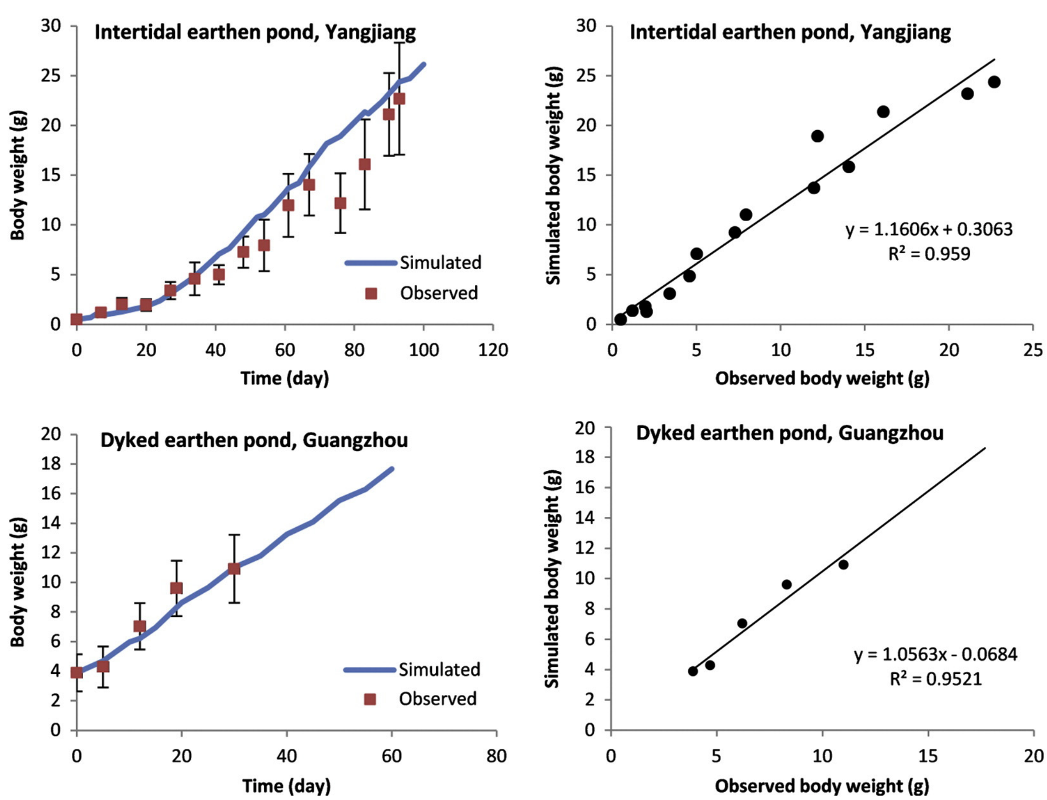


Fig. 4. Validation of the AquaShrimp individual white shrimp growth model in China.

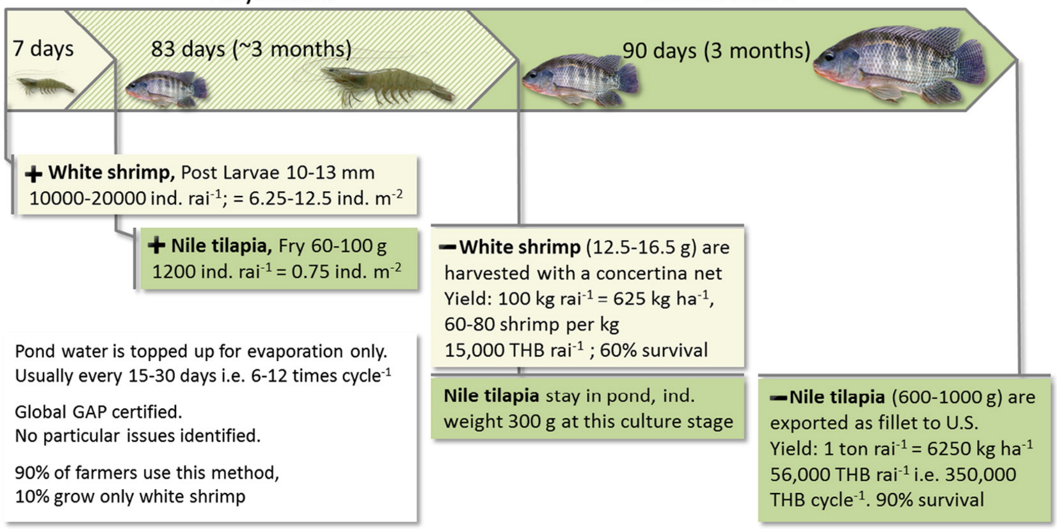


Fig. 5. Culture practice for IMTA in ponds in Chon Buri province, Eastern Thailand.

calculated. Overall mass and energy balances for the species of interest, over the full culture cycle, are extremely helpful for model verification.

Fig. 6 illustrates the mass balance for Nile tilapia, using growth drivers for temperature, salinity, and chlorophyll (for the filter-feeding component) measured monthly by DOF. The individual model shows that an animal grown in a pond over a period of 167 days reaches a biomass of about 750 g, and a length of 34 cm; these values compare well with the reported harvest weight of 700–900 g for farms sampled in Chiang Rai province, and 600–1000 g in Phan Thong district (Chon Buri). The FCR given by the individual model is always lower than for population scale simulations in FARM because uneaten feed is not taken into account. The energy budget helps verify how the model organism partitions catabolism, including the energy devoted to Specific Dynamic Action (SDA) and to locomotion.

The model also allows the determination of other derived parameters such as the Apparent Digestibility Coefficient (ADC) for nitrogen. Our tilapia model gives a value of 83%, at the low end of the range ($\mu = 88 \pm 7\%$) determined experimentally by Moreau (1996).

Pond water quality data from DFO (Kittiwanich, pers. com) were used to drive the individual and population models. DFO makes datasets available through the website: http://www.pcd.go.th/download/en_water.cfm.

2.4 . Site selection models

The availability and suitability of the RTA for future development and expansion of aquaculture was assessed using GIS based models. It should be noted that these site suitability models have been developed

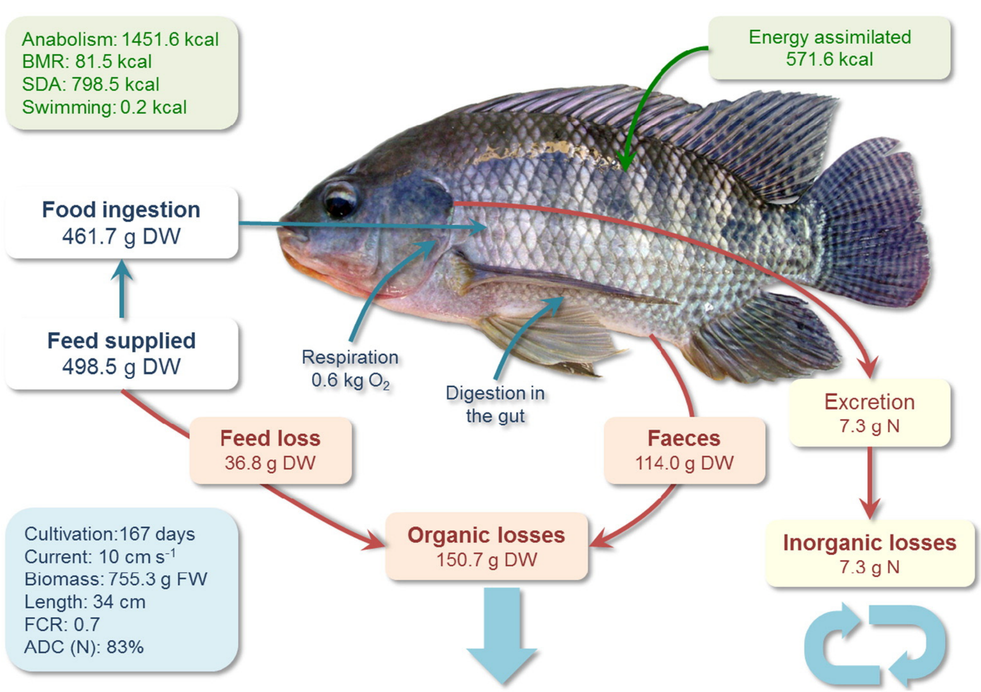


Fig. 6. Mass balance for individual growth of Nile tilapia.

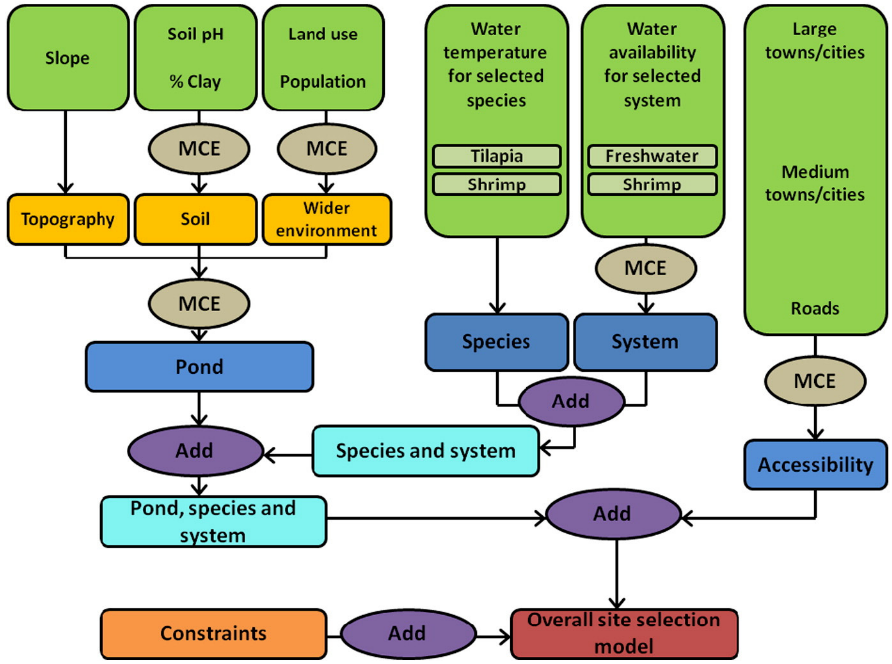


Fig. 7. Structure of site suitability model.

using the optimal values for production and indicate the most suitable areas to locate aquaculture on that basis. The models were designed to help decision makers select areas for development and to identify areas which may be less than suitable and require extra support. The structure of the models is shown in Fig. 7 (Falconer, 2013).

There are four major submodels (Pond, Species, System and Access) which are added together, along with a constraints layer, to produce the final output; the overall site suitability model. The tiered approach represents the key stages in the decision making process when evaluating an area for an aquaculture pond; where are the physical locations a pond could be established (Pond submodel), what species can be farmed within the area (Species submodel), could a sustainable system be established with regard to water availability (System submodel) and is the location accessible to transport networks and urban centres (Access submodel). This study focussed on tilapia and shrimp, however the framework can be used for multiple species and/or areas. Detailed information on model development is provided in Falconer (2013).

Table 3
Model results and measured data for tilapia pond monoculture in Chiang Rai, Thailand.

Variable	FARM model	Farm data
Model inputs		
Seeding density	3.13 fish per m^2 2 rai (3200 m^2) ponds	
Seeding density (kg FW)	801.3	800
Model outputs		
Production		
Total (TPP) (kg TFW)	5115.6	5400
Feed Conversion Ratio (FCR)	1.8	1.69
Environmental externalities		
Outflow of NH_4^+ (kg N)	224.5	–
Outflow of chlorophyll (kg chl)	1.27	–
Profit and loss (USD)		
Income from aquaculture products	8747.69	9234
Total expenditure	7659.5	7388.28
Feed cost	6276.77	6324
Seed cost	969.25	967.7
Energy cost	413.48	96.58
Farm Profit = Income–Expenditure	1088.19	1845.72

3 . Results and discussion

3.1. Farm-scale models

Model results for production, environmental effects, and economic performance of tilapia pond culture are shown in Table 3.

The model is able to reproduce the harvestable biomass ($\Delta = -5\%$), and the slightly higher Feed Conversion Ratio (FCR) reflects this difference. The economic performance for the farm is underestimated by the model ($\Delta = -40\%$), partly because the simulated biomass yield is a little lower, but principally due to lower costs for aeration. FARM also determines the negative externalities associated with the activity, which in this case correspond to emissions of over 200 kg of dissolved nitrogen and over 1 kg of chlorophyll, or about 50 kg of particulate organic carbon (POC).

Fig. 8 (top) shows the full mass balance for a 167 day cycle, aggregated for an area of 8 rai[2] (12,800 m^2), i.e. four identical culture ponds. The total harvestable tilapia biomass is 22,943 kg (about 39 t ha^{-1} y^{-1}), and the dissolved and particulate waste drives a net primary production (NPP) of 102 kg N. If the phytoplankton filter-feeding is switched off in the model[3] the harvestable biomass falls to 18,591 kg, the NPP doubles (212 kg N $cycle^{-1}$), and the resulting emission of chlorophyll increases by a factor of 5.

Table 4 shows the financial structure of a typical tilapia farm in Thailand. As a rule these are family-operated smallholdings, as is the case also for shrimp farms (mean area of 0.3 ha, FAO/NACA, 2012), and therefore have reduced labour costs – in this case study, only 5% of the total expenditure. The remaining costs are feed, seed, and energy for aeration. Cost estimates range from 74% of revenue (Table 4) to 87% of revenue (Table 3, model).

Fig. 8 (bottom) shows a similar analysis for shrimp farming. As in the simulation for tilapia, detailed environmental driver data, a validated individual growth model, and harvest data were used to gauge the model performance. The simulated harvest of 4376 kg $cycle^{-1}$ is higher than

[2] The rai is the Thai unit for area, equivalent to 1600 m^2.
[3] Results not shown.

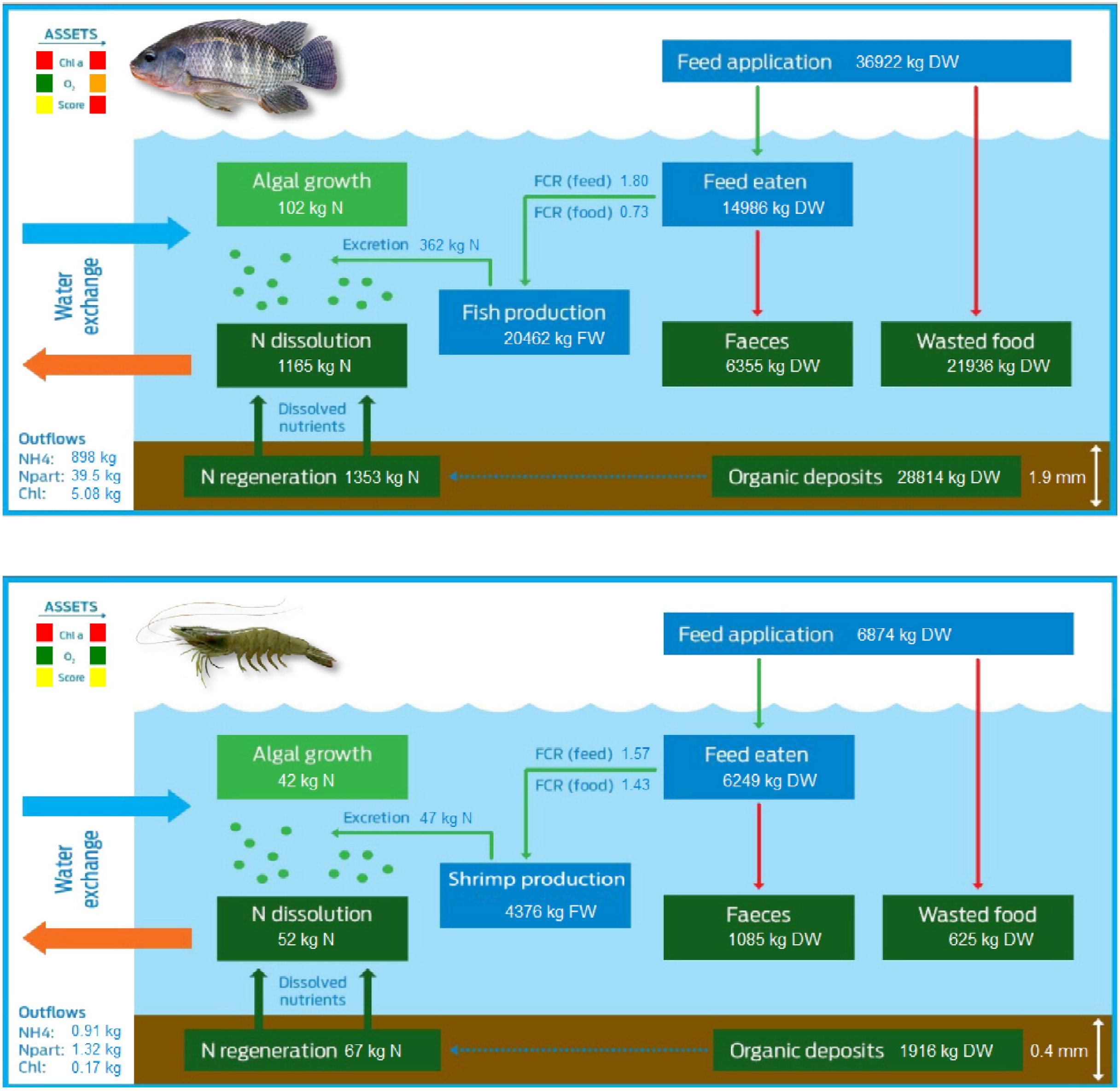


Fig. 8. Mass balance for pond culture. Top: Nile tilapia pond monoculture in Chiang Rai; bottom: white shrimp pond monoculture in Chanthaburi.

the declared production of 4000 kg. The FCR is about 20% higher in the model (1.57), which is within the margin of error for simulations of this nature, given the uncertainties in the measured data.

In parts of central Thailand, such as Chon Buri province, tilapia and shrimp are co-cultivated (Fig. 5), providing a double crop grown both as polyculture (the two species are artificially fed) and IMTA (tilapia yield is enhanced by microalgal production partly driven by shrimp waste products, and POC from tilapia provides food for benthic invertebrates eaten by shrimp).

Fig. 9 shows a simulation of this co-culture (top), together with a hypothetical addition of macroalgae (bottom), which would shift the system towards IMTA. The model uses the culture practice shown in Fig. 5, but the environmental drivers available were the same as used for the standard shrimp monoculture, based on DOF data from Chanthaburi.

Table 4
Financial structure of a typical tilapia (pond) farm in Thailand.

Economic indicators	USD
Labour (household)	82.8
Labour (seasonal)	54
Total labour	136.56
Total expenditures	2274.35
Total revenue (income)	3064.32

For a typical monoculture cycle, the modelled 2.5 rai (4000 m^2) farm produces 3317 kg of tilapia, valued at 4140 USD. Fig. 9 (top) represents the simulated mass balance for the first stage of the culture i.e. 81 days of shrimp co-cultivation. An additional harvest of about 4 tonnes of shrimp is obtained, a significant financial boost to the farmer, because shrimp farmgate prices are three times higher than for tilapia – total revenue becomes 18,277 USD.

The co-cultivation has both environmental costs and benefits. There is an increase in particulate organic sedimentation and diagenesis, resulting in a change in nitrogen regeneration from 137 kg N (for the 81 day simulation) to 200 kg N. Co-cultivation thus stimulates nitrogen dissolution (134 kg N), which is greater than in tilapia (96 kg N) or shrimp (52 kg N) monoculture, and consequently doubles the NH_4^+ discharge to the environment (10.7 kg in tilapia monoculture, 20.5 kg in IMTA).

On the other hand, tilapia provide an effective top-down control of primary symptoms of eutrophication (sensu Bricker et al., 2003), with a

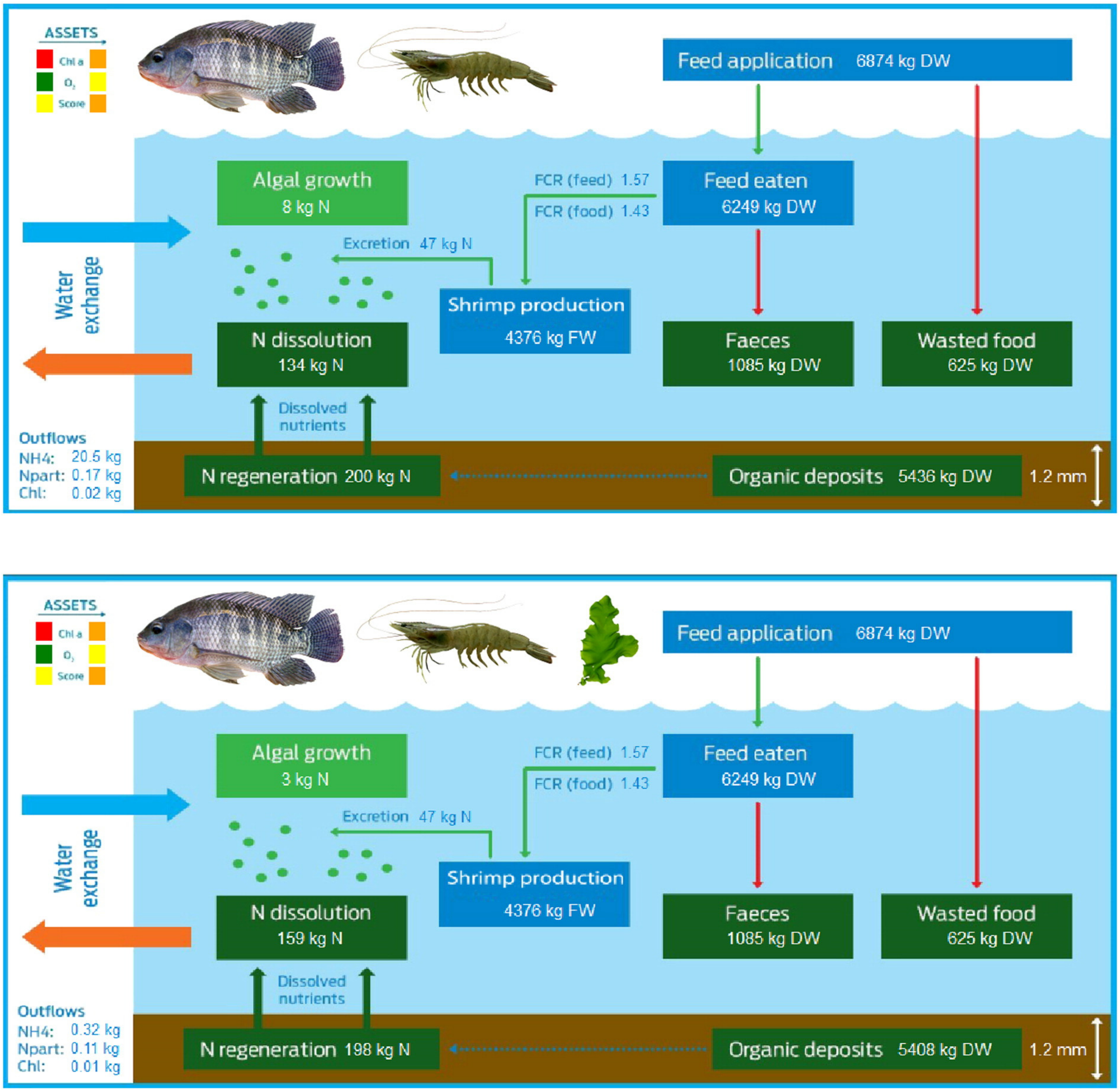


Fig. 9. Mass balance for pond culture. Top: Integrated Multi-Trophic Aquaculture of tilapia and shrimp in ponds, Chanthaburi; bottom IMTA of tilapia and shrimp, with macroalgae added.

decrease in NPP from 42 kg N in shrimp monoculture to 8 kg N in IMTA. Emissions of chlorophyll drop from 0.17 kg to 0.02 kg as a consequence of this reduction.

A final scenario with the addition of seaweeds was simulated in FARM by adding *Ulva* to the culture setup, at a density of 50 ind. m^{-2}. Seaweeds remove the dissolved nitrogen in the outflow (nutrient

Table 5
Modelled environmental externalities from tilapia pond monoculture scaled to Thailand.

Region	Tilapia harvest ($t\ y^{-1}$)	Primary production ($t\ N\ y^{-1}$)	Ammonia outflow ($t\ N\ y^{-1}$)	Algal outflow ($kg\ chl\ y^{-1}$)	Equivalent outflow (PEQ[a])
Northern	36,004	179	1580	8939	478,810
Northeastern	42,981	214	1886	10,671	571,597
Central plain	16,500	82	724	4096	219,430
Eastern	32,957	164	1446	8182	438,294
Western	21,296	106	935	5 287	283,206
Southern	8556	43	375	2 124	113,781
Total	158,293	789	6947	39,299	2,105,118
RTA[b] (355 km^2)	96,064	479	4216	23,849	1,277,547
RTA *highly suitable*					
Dry season (914 km^2)	247,304	1233	10,853	61,397	3,288,862
Rainy season (135 km^2)	36,527	182	1603	9068	485,773

[a] Population-Equivalent = 3.3 kg N y^{-1}.
[b] Estimated production from current area for tilapia cultivated in ponds.

Table 6
Modelled environmental externalities from shrimp pond monoculture scaled to Thailand.

Region	Shrimp harvest ($t\ y^{-1}$)	Primary production ($t\ N\ y^{-1}$)	Ammonia outflow ($t\ N\ y^{-1}$)	Algal outflow ($kg\ chl\ y^{-1}$)	Equivalent outflow (PEQ)
Central plain	170,975	1641	36	6642	10,774
Eastern	41,143	395	9	1598	2593
Western	43,063	413	9	1673	2714
Southern	298,718	2867	62	11,605	18,824
Total	553,899	5316	115	21,518	34,904
RTA[a] (291 km^2)	319,820	3070	67	12,424	20,154
RTA *highly suitable*					
Dry season (198 km^2)	217,654	2089	45	8465	13,716
Rainy season (39 km^2)	42,871	411	9	1665	2702

[a] Estimated production from current area for shrimp cultivated in ponds.

uptake: 218 kg N, or 298 PEQ y^{-1}) and the simulated farm provides a combined crop of 4 t shrimp, 1 t tilapia, and 8 t seaweed for a 81 day cycle, with practically zero discharge.

Inorganic extraction by seaweeds has the twin effect of sharply reducing the NH_4^+ effluent discharge from 20.5 kg to 0.32 kg, and halving the microalgal emissions. Presumably the latter benefit occurs because seaweeds outcompete phytoplankton for dissolved nutrients, in a similar way to what is observed at the bay scale in Sanggou Bay, China, where the kelp *Saccharina japonica* mops up dissolved nutrients from IMTA of Japanese seabass, Pacific oyster, and Chinese scallop (Xiao et al., 2007).

3.2 . Upscaling to the national level

3.2.1 . Environmental effects

Tilapia production in ponds is higher in the north of Thailand, and the national harvest for 2010 is 158,293 t y^{-1}. The environmental externalities simulated for tilapia and shrimp pond monoculture were scaled up to all of Thailand (Tables 5 and 6): based on the pond-scale simulations, this corresponds to an aggregate emission of 6947 t N y^{-1}, or 2,105,118 PEQ, about a third of the population of Bangkok.

White shrimp aquaculture is located mainly in the central and southern parts of the country, due to its dependence on brackish or saline water. The total production of 553,899 t y^{-1} corresponds to a lower nitrogen emission, equivalent to 34,904 PEQ y^{-1}. Although shrimp production is 3.5 times greater than that of tilapia, the total outflow of nitrogen from shrimp ponds is 60 times lower than for tilapia – this reflects differences in the culture practice, since water renewal in shrimp ponds is an order of magnitude lower than for tilapia culture. In contrast, the outflow of algae is lower for tilapia ponds, partly because phytoplankton drawdown due to filter-feeding by the fish (Northcott et al., 1991; Perschbacher and Lorio, 1993) is simulated in the model.

Although these environmental losses are high, reflecting the concerns associated with fed aquaculture (e.g. Burford and Williams, 2001; Lacerda et al, 2006), their actual effects should be placed in the context of the tight coupling of rural activities in Thailand – much of the waste is recycled either within the aqua-system or in agriculture, whereas the remainder is not directly recycled:

(i) part of the discharge is stocked in other ponds for natural water quality improvement and then re-used in aquaculture;
(ii) part of the discharge is used in agri-aqua, e.g. for rice cultivation;
(iii) the remaining pond water is drained into rivers and canals, and corresponds to the true environmental externalities of pond aquaculture in Thailand, resulting in nutrient enrichment, and consequent eutrophication effects.

Further work is needed to evaluate the proportion of waste that is typically re-used, in order to assess the economic and environmental costs of tilapia and shrimp farming.

Eutrophication effects are more clearly visible in cage culture of tilapia in rivers, a practice that is increasingly regulated. In reservoirs, a spatial limit of occupation of 0.5% of the total surface area is imposed for cage culture of tilapia, aimed at protecting water resources and combating the spread of diseases e.g. caused by *Aeromonas* sp. (Cai et al, 2004).

As for all cultured species, the production of tilapia and shrimp fluctuates interannually (Rico et al., 2013) due to market constraints, disease, and other factors – the environmental externalities of culture will change accordingly. An example of such challenges is the impact of Early Mortality Syndrome (EMS) on shrimp production throughout SE Asia; like other diseases, EMS can only be simulated as a stochastic event, but in the case of Thailand the proportion of infected stock in 2013 has already fallen by 44% with respect to 2012, largely due to DOF programmes centred on improvement of hatchery sanitary conditions, broodstock management, quality post-larvae (PL) production, PL screening, and shrimp farm management. Different scenarios can be modelled to project changes in externalities due to events such as EMS.

3.2.2 . Economic impacts

Freshwater tilapia and shrimp aquaculture in Thailand production in 2010 (Table 7) amounted to 194,787 tonnes and 553,899 tonnes respectively with a total value of $25 million. In 2010, the total areas in production of freshwater inland aquaculture of tilapia and shrimp were 71,990 and 50,388 ha respectively. Commercial tilapia and shrimp aquaculture employ approximately 400,000 to 650,000 labourers. While output from this subsector in quantity and value is small compared to the country's total fish production, data from the National Accounts of Thailand, 2012, reflects an increasing trend in production and value over the past two decades. In addition, the current production and revenues reflected only represent the direct economic effects to the country of Thailand from tilapia and shrimp aquaculture. Based on

Table 7
Direct and indirect economic impacts scaled to Thailand.

Direct indicators	Value
Total revenue (10^6 USD y^{-1})	253.27
Total expenditure (10^6 USD y^{-1})	187.98
Labour income (10^6 USD y^{-1})	10.4
Percentage labour	5.5%
Direct job creation[a]	400,000–650,000
Indirect indicators	
VAD ratio	0.38
Value added (10^6 USD y^{-1})	96.24
Indirect job creation determined from revenue (64 per 10^6 USD)	16,209
Total revenue (10^6 USD y^{-1})	349.51
Additional expenditure for internalization of 2,105,118 PEQ @ 30 USD (10^6 USD y^{-1})[b]	21.05
Gross profit (10^6 USD y^{-1})	65.29
Profit taking into account externalities (10^6 USD y^{-1})	44.2

[a] Direct jobs considered (household + harvest): 500,000.
[b] Assuming 1/3 of PEQ correspond to the externality, the rest being internalized in the agri-aqua-system.

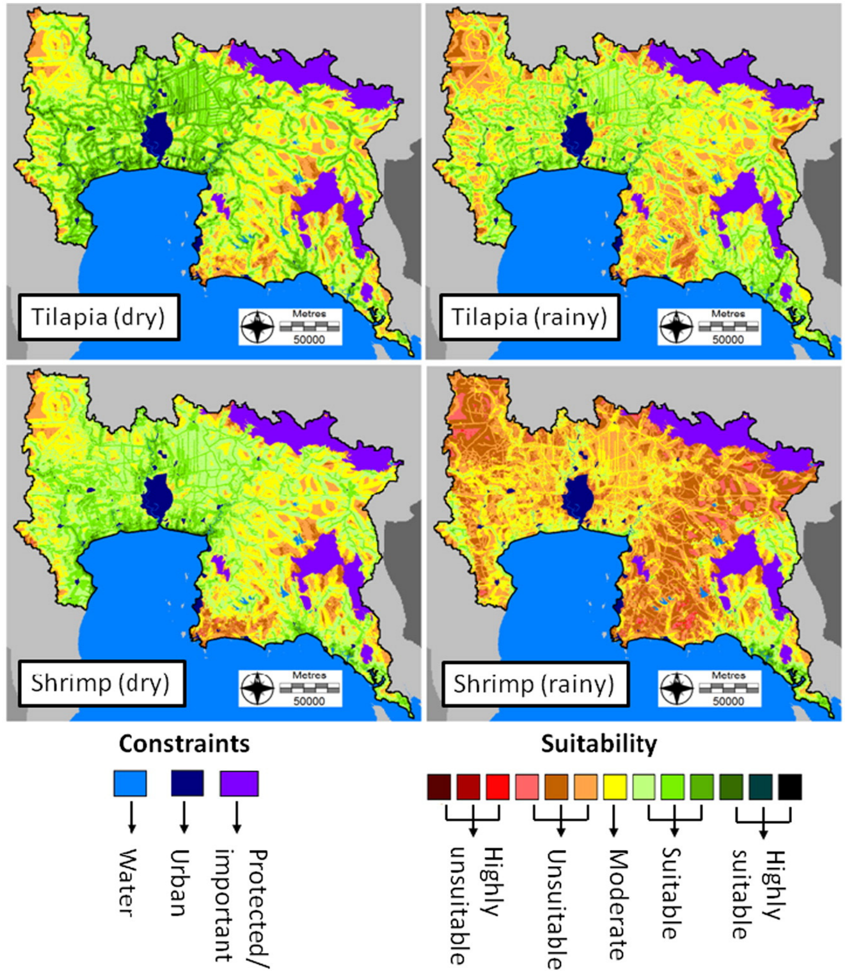


Fig. 10. Site suitability models for tilapia and shrimp monoculture in the dry and rainy seasons. Large water bodies in which ponds cannot be constructed are shown as WATER.

estimates derived from expert elicitation and Thailand data sets we were able to estimate the indirect effects and employment impacts. Because Thailand does not have a national Input/Output model such as the United States IMPLAN, these estimates were based on algorithms presented in Hishamunda et al. (2009).

Our analysis suggests that commercial tilapia and shrimp aquaculture have a value added share of total Gross Domestic Product of 0.38, and value added of 96.24, resulting in indirect impacts of the industry to the Thailand economy of approximately $35 million, and the creation of approximately 16 thousand additional jobs.

3.2.3 . Site suitability models

The results of the site suitability model for the RTA are shown in Fig. 10. The suitability for tilapia decreases in the rainy season, largely due to higher temperatures which are outside the optimal range for production.

There is also a decrease in the availability of suitable or highly suitable areas for shrimp production in the rainy season—however, the coastal area in the southeast of the RTA remains suitable in both seasons. The model indicates there are significant areas available for inland shrimp culture, although the local regulations would have to be consulted prior to development as the Thai government has placed a moratorium on shrimp farming in many inland locations (Roy et al., 2010).

Fig. 11 shows the areas that are suitable or highly suitable for both tilapia and shrimp. As in Fig. 10, there are more suitable areas for the culture of both species in the dry season than in the rainy season. Nevertheless, there is the potential for year-round production in suitable or highly suitable areas across the RTA; particularly in the southeast as highlighted in Fig. 11A and B.

Table 8 shows the area covered by each category.

3.2.4 . Comparison of present and potential aquaculture in the regional test area

The RTA includes 23 provinces and 198 districts. The current farm areas are 355.04 km^2 for tilapia and 290.94 km^2 for shrimp (DOF personal communication). There are 15 IMTA farms covering 0.63 km^2 (394 rai) in Panthong District, Chonburi Province, working with DOF staff in order to reduce production costs.

Suitable culture areas during the dry season for tilapia, shrimp, and both species combined, cover 55 to 60% of the RTA (without constraints such as urban area, large water bodies, or protected areas) (Table 8, Fig. 10). During the rainy season, the suitable area for tilapia aquaculture remains about 48% of the RTA, while shrimp and both species in IMTA cover only 12% of the RTA (Figs. 10 and 11). The highly suitable areas for all combinations represent a small percentage, between <0.1% and 2% (Table 8). There is a high potential to increase the current farm areas for both culture of tilapia and shrimp as they only represent 0.8 and 0.7% of the RTA. The combined culture of both species is also very promising as it covers less than 0.01% of the RTA (Table 8).

The MCE scenario analysis indicates optimum site suitability as well as potential scope for sustainable expansion of aquaculture for both

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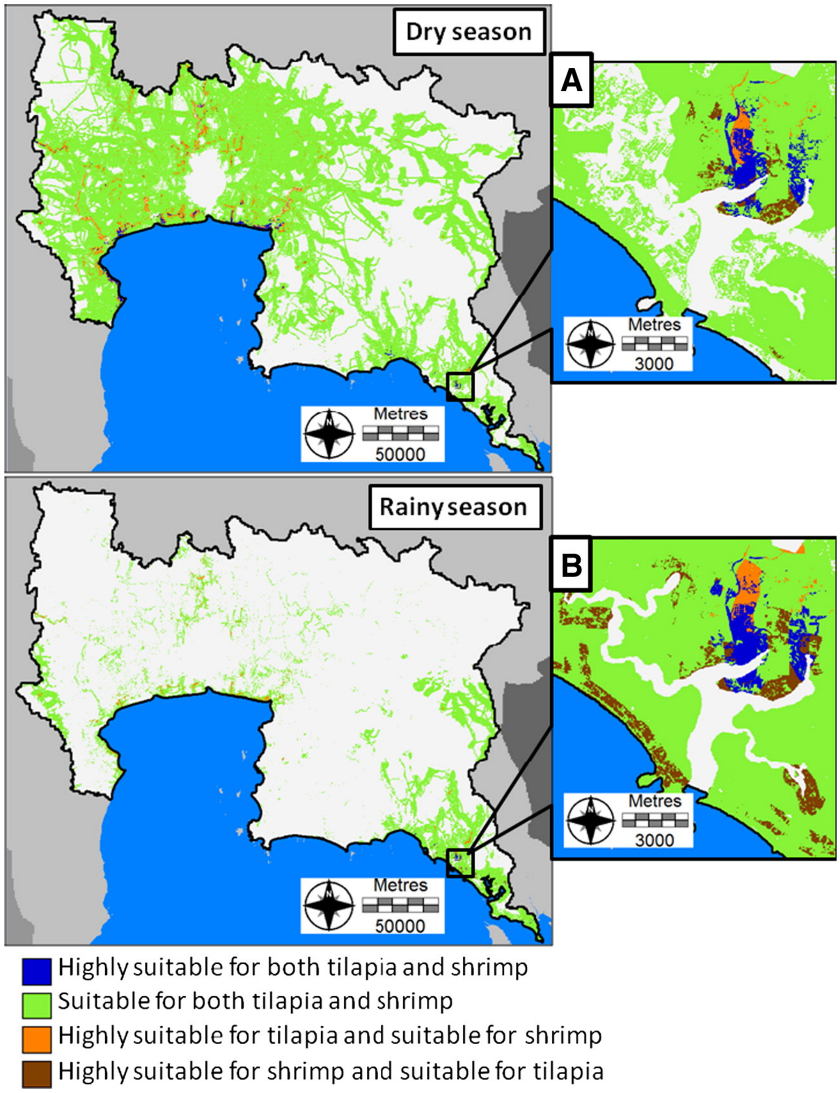

Fig. 11. Suitable and highly suitable areas for tilapia and shrimp aquaculture, combined, in the regional test area (RTA). The zoomed boxes A and B show further detail in key areas.

species. The *highly suitable* class for tilapia could triple in the dry season, but would halve in the rainy season. For shrimp the corresponding areas would decrease in both seasons. However, the *suitable* class is two orders of magnitude greater than the current level of tilapia farming, and shrimp could increase tenfold (limited by the rainy season due to low salinity). Clearly, any proposed expansion of aquaculture would depend upon policy decisions with respect to land uses. The expansion potential reported herein is based on environmental and infrastructural determinants at a regional scale, with the necessary caveat that the availability of space for new aquaculture is dependent also on competing land claims, which may be substantial, and further site-specific analyses.

The potential tilapia RTA classified as *highly suitable* for the dry season is 2.5 times higher than the current area (Table 8). The environmental externality for this scenario would be 3.3×10^6 PEQ, which corresponds to a 60% increase of the calculated ammonia outflow for the whole country (Table 5). However, during the rainy season, the *highly suitable* area is 2.5 times smaller than the present area, which would reduce environmental externalities by 23% (Table 5).

In the RTA, at least a third of the current shrimp ponds are not in *highly suitable* areas, according to the MCE model (Table 8). If shrimp ponds were located only in the *highly suitable* areas, there would be a 30% reduction of environmental externalities to 13,713 PEQ during the dry season, and almost 90% during the rainy season, to 2702 PEQ (Table 5).

4 . Conclusions

At the local level, the approach and results obtained in this work increase awareness of the comparative performance of different types of aquaculture, both single-species and in co-cultivation, and, more broadly, reduce the information gap that exists across different regions of the world. At the global level, we hope that this national-scale assessment, which goes well beyond production per se (see e.g. Costanza

Table 8
Seasonal analysis of areas of suitability for tilapia and shrimp culture in the Regional Test Area (RTA).

	Tilapia		Shrimp		IMTA	
						
Area (km^2)	Dry	Rainy	Dry	Rainy	Dry	Rainy
Suitable area	25,387	20,206	24,617	5408	23,447	5246
% of RTA[a]	*60.1*	*47.8*	*58.3*	*12.8*	*55.5*	*12.4*
Highly suitable area	914	135	198	39	163	12
% of RTA	*2.2*	*0.3*	*0.8*	*0.1*	*0.4*	*<0.1*
Current area cultivated	355.04		290.94		0.63	
% of RTA	*0.8*		*0.7*		*<0.01*	

[a] RTA minus constraints such as urban area, water supply, or protected areas.

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et al., 2014) may contribute to more integrated planning, as we look forward to another 40 years of aquaculture.

The world debate on aquaculture is fuelled by a global food shortage, informed (and sometimes misinformed) by special interest groups (Little et al., 2011), and coloured by the fact that both Europe and North America now import 80–90% of their aquatic products.

By comparison to the major world aquaculture producers (90% comes from Asia, 60% from China – FAO, 2012), greater concerns exist in Europe and North America with respect to sustainability (Ross et al., 2013), resulting in more stringent legislation and better governance. Consequently, the developed world largely imports aquatic products from emerging economies, and exports jobs and negative externalities.

Due to the social and economic limitations, knowledge and modern research measures on sustainable development of aquaculture have not been widely applied in developing countries so far. After decades of fast growth in aquaculture, more and more severe environmental problems (e.g. pollution, diseases, water shortage etc.) have occurred in these countries, particularly in SE Asia including China, which are the major producers.

Despite recent developments such as the US NOAA Aquaculture Initiative in 2011, and the European Maritime Fisheries Fund, both of which promote aquaculture growth, it is difficult to envisage significant changes in production in these regions over the next decade, due to a combination of territorial constraints, both for land and inshore waters, legislative barriers, and social opposition.

Given the extremely skewed distribution in world aquaculture production, the paradox is that Western nations in general have far more sophisticated tools to assess sustainability, and much greater resources to calibrate and validate models (see review in Ferreira et al, 2012b). As a consequence, the relevant scientific literature often refers to study sites and production levels that are not representative of the global aquaculture panorama; however they exemplify the application of models and other tools that address spatial aspects, production, environmental, and economic outcomes of alternative cultivation strategies, and integrated catchment and coastal zone management – the challenge therefore lies in making that knowledge available to stakeholders in the world's great producing nations, in order ensure that aquaculture growth is sustainable, and to avoid boom and bust events, which not only play havoc in a globalized market, but are also responsible for substantial social costs.

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