Aquacultura Indonesiana (2015) 16 (2) : 38-49
ISSN 2477-6939

A STELLA Model for Evaluating the Efficiency of an Integrated Multi-Trophic Aquaculture System (IMTA)

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Abstract

Cicilia Kambey and Ik Kyo Chung. 2015. A STELLA Model for Evaluating the Efficiency of an Integrated Multi-Trophic Aquaculture System (IMTA). ***Aquacultura Indonesiana, 16 (2): 38-49.*** Interest is increasing in Integrated Multi-Trophic Aquaculture Systems (IMTA) that encourage the development of environmentally friendly practices. By combining fed aquaculture with nearby extractive aquaculture, an IMTA can minimize the negative ecological impacts of conventional monoculture farms while expanding their economic base. To evaluate the efficiency of such a system, we applied dynamic STELLA modeling based on nitrogen content. The application of seaweed co-culturing reduced the level of dissolved inorganic nitrogen (DIN) by 20 to 35% over the short term whereas DIN values declined annually by 68 to 88%. When sea cucumber was incorporated into the scheme, the amount of particulate organic nitrogen was decreased by up to 50%. Ultimately, we plan to introduce potential strategic guidelines for IMTA implementation that might improve management and predictive capabilities while enhancing the social acceptability of such a system.

Keywords: IMTA; Modeling; Nitrogen; Seaweed

Introduction

Coastal waters are susceptible to a variety of land and coastal-based pollutants. Their direct discharge from various sectors continues to increase. Extensive aquaculture operations now constitute a major source of nutrient inputs to coastal waters and have become a general concern in environmental systems because an excess of some nutrients can lead to chronic bioaccumulations and eutrophication. One suggested approach to developing a balanced ecosystem is Integrated Multi-Trophic Aquaculture (IMTA), a scheme designed to reuse waste products and reduce the potential for eutrophication (Troell *et al*., 2009; Chopin, 2011; Ren *et al.*, 2012).

Although recently re-introduced, IMTAs are not a new concept but rather they represent the old wisdom of ancient farming that minimizes the effects of nutrient effluents, particularly those from aquaculture activities in coastal waters (Chopin, 2013). Integrated fed aquaculture that involves organic and inorganic extractive organisms is urgently required. One feature of an IMTA is that the waste products from fed-aquaculture species, such as shrimp or finfish, are recaptured and converted into fertilizer, feed, and energy for extractive culture species, such as plants and other farm animals that can eat organic waste. Therefore, an IMTA system not only can be employed to produce valuable crops but can also mitigate the harm of pollutants and help bio-remediate coastal waters. Various aspects of an IMTA system have been studied worldwide, involving different systems and a variety of organisms (Chung *et al.*, 2002; Carmona *et al.*, 2006; Wang *et al.*, 2012; Wu *et al.*, 2015).

Because of the rapid and often uncontrolled expansion of aquaculture, additional efforts are necessary to combat challenges in ecosystem management of these systems. Any IMTA design must consider site characteristics and select organisms that contribute the necessary synergies if one is to understand the entire environmental system (Lamprianidou *et al*., 2015). When knowledge is inadequate for properly preparing an IMTA design, many problems can arise, including inappropriate combinations of organisms (Nizzoli *et al.*, 2005; Navarrete-Mier *et al.*, 2010), or a reduction in water movement that leads to an increase in populations of pathogen bacteria and high mortality rates for the cultured organisms (De Silva, 2012). Therefore, stocking density is an important component of any design (Wu, 1995; Wu *et al.*, 2015). As demand increases for sustainable solutions to environmental and economic problems, new methods must be developed that can predict the outcomes of policy decisions (Costanza and Voinov, 2001).

To generate a sustainable and effective system of aquaculture practice, we used the dynamic STELLA model for simulating the complexities of each IMTA component. In the study described here, we evaluated the efficiency of a model to reduce nitrogen in such systems and promote high productivity by associated components. We focused on a land-based integrated closed system and validated this model using data reported by Shpigel *et al.* (1993), Neori *et al*. (2000), and Schuenhoff *et al*. (2003).

Methods

Model Description

We developed our concept model of IMTA using STELLA software (*isee system*-USA) and integration with *Euler's methods*. The selected running periods for simulation were based on data obtained via field cultivation over 28 d, 58 d, or 12 mo, with DT (delta time) set at 0.25. This model combined fed aquaculture with other extractive aquaculture using data reported by Shpigel *et al*. (1993), Neori *et al*. (2000), and Schuenhoff *et al*. (2003).

The four main components of culture included fed organisms (finfish), suspended filtering feeders (bivalves), inorganic extractive organisms (seaweed), and benthic detrivores (sea cucumber), as recommended by Chopin (2011) (Figure 1). In addition, our land-based system considered co-culturing with abalone because of its high value. In contrast, different combinations of organisms have been used in earlier studies, including finfish/bivalve/seaweed (Shpigel *et al*., 1993), abalone/finfish/seaweed (Neori *et al*., 2000), and short-term cultivation finfish/seaweed (Schuenhoff *et al*., 2003). Each connection in this IMTA model assessed how those components might influence the availability of nitrogen. Furthermore, the IMTA model presented the N-removal process for each extractive organism in terms of its uptake, metabolism, and harvest.

We conducted a literature review (see References in Table 1) to identify the most reasonable and representative parameters to use as our coefficients in developing the model equations (Table 2).

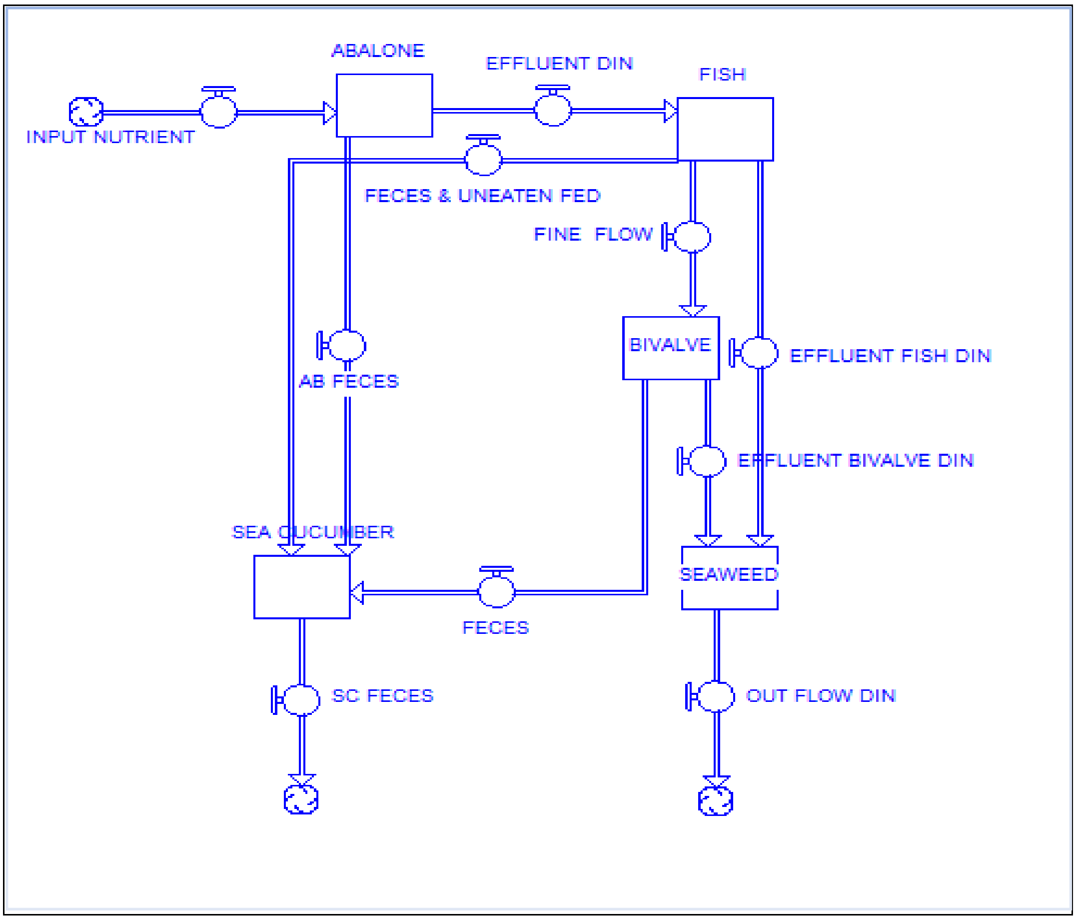

Figure 1. Conceptual model for land-based IMTA bioremediation of excess nitrogen.

Table 1. Variables and coefficients used as components in STELLA model.

Variable	Description	Value	Unit	Reference
SGR *fish*	Maximum growth rate of fish	0.45-1	% /d	Cotton *et al.,* 2003; Le Ruyet *et al.*, 2004
SGR *Ab*	Maximum growth rate of abalone	1.33	% /d	Neori *et al.*, 2000
SGR *Bv*	Maximum growth rate of bivalve	0.6	% /d	Shpigel *et al.*, 1993
SGR *Sw*	Maximum growth rate of seaweed	1.67	% /d	This study
SGR *Sc*	Maximum growth rate of sea cucumber	0.85	dimensionless	Ren *et al.,* 2012
e DIN *fish*	Ratio excretion DIN of fish	45-49	Percentage	Lamprianidou *et al.*, 2015; Islam, 2005
e DIN a*b*	Ratio excretion DIN of abalone	37	Percentage	Neori *et al.*, 2000
e DIN b*v*	Ratio excretion DIN of bivalve	25	Percentage	Shpigel *et al.*, 1993
e DIN s*w*	Ratio excretion DIN of seaweed	25	Percentage	This study
δr fish	Mortality of fish	0.05	/yr	Neori *et al.*, 2000
δr ab	Mortality of abalone	0.15	/yr	Neori *et al.*, 2000
δr bv	Mortality of bivalve	0.17	/yr	Shpigel *et al.*, 1993
δr sw	Ratio of seaweed discarded	0.0047	/d	Neori *et al.*, 2000
d fish	Feces of fish	10	Percentage	Islam, 2005
d ab	Feces of abalone	26	Percentage	Neori *et al.*, 2000
d bv	Feces of bivalve	26	Percentage	Neori *et al.*, 2000
d sc	Feces of sea cucumber	20	Percentage	Nelson *et al.*, 2012
Un ffish	Uneaten pellet of fish	20	Percentage	Islam, 2005
F PON	Fine particle suspended	3	Percentage	Buschmann *et al.*, 2009
Wf	Water flow	0.8	dimensionless	(estimated)
SW exp.	Seaweed exported	19-20	Percentage	(estimated)
Remov.Eff	Removal efficiency of seaweed	75	Percentage	This study
absorption SC	Sea cucumber absorption	70	Percentage	Nelson *et al.*, 2012
FE bivalve	Filtration efficiency	0.8	dimensionless	Shpigel *et al.*, 1993

Table 2. Equations used to calculate values of component variables in IMTA system.

Description	Equation
1. Abalone	*d Abalone = Ab (t-dt) +(Ab nutrient- Ab harvest- Ab DIN – Ab mortality- Ab feces) x dt*
2. Bivalve	*d Bivalve= Bv (t-dt) +(Bv nutrient- Bv harvest- Bv DIN – AB mortality- Bv feces) x dt*
3. Fish	*d Fish = Fish (t-dt) +(feed flow- Fs mortality- Fs harvest – Fs feces-DIN released) x dt*
4. Seaweed	*d Seaweed= Seaweed (t-dt) +(DIN Input- Nutrient DIN output-Sw discarded-Sw harvest-Swexported)x dt*
5. Sea cucumber	*d Sea cucumber = Sea cucumber (t-dt) +(Absorption-Sc harvest- Sc feces) x dt*
6. Abalone nutrient N	*seaweed x SW exp.*
7. Abalone harvest	*Abalone x SGR ab*
8. Ab DIN	*Abalone x eDIN ab*
9. Ab mortality	*Abalone* x *δr ab*
10. Ab feces mucus	*Abalone x d ab*
11. Feed flow	*(Initial Feed +Ab DIN) x Fish/ Init (Fish)*
12. Fs mortality	*Fish x δr fish*
13. Fs harvest	*Fish x SGR fish*
14. Fs feces	*Fish x d fish*
15. Fish DIN released	*Fish x e DIN fish*
16. DIN input to seaweed*	*(Fish DIN released +*Bivalve DIN) x water flow*
17. Seaweed harvest	*Seaweed x SGR Sw x Converter*
18. Seaweed discarded	*Seaweed x δr sw*
19. Seaweed exported**	*Seaweed x SW exp.*
20. Sea cucumber uptake	*Total PON x absorption SC*
21. Sea cucumber harvest	*Sea cucumber x SGR Sc*
22. Sea cucumber feces	*Se cucumber x d sc*
23. Total organic (PON)	*uneaten feed+ Ab fecesmucus +Bivalve fecesmucus +Fs feces*
24. Bivalve nutrient N	Fine PON x FE Bivalve
25. Bivalve harvest	Bivalve *x SGR Bv*
26. Bivalve DIN	Bivalve x *e DIN bv*
27. Bivalve mortality	Bivalve x *δr bv*
28. Bivalve feces mucus	Bivalve *x d bv*
29. Sensitivity Analysis	{V (1.1 *p*) – V (0.9 *p*)}/V (*p*) 0.2

*if incorporated with bivalves.

**if incorporated with abalone.

Cultured Organisms

For the fish component, we modeled feed as the main input of N into the system while fish excretion was the main output of dissolved inorganic nitrogen (DIN). Feces from the fish were modeled as the main output of particulate organic nitrogen (PON). The harvesting period for finfish (Neori *et al*., 2000; Shpigel *et al*., 1993; Schuenhoff *et al*., 2003) was simulated at the end of the culturing period. As fertilizer for inorganic food production, the DIN from fish is useful for seaweed culture. The selection of bivalve organisms that are cultured in a land-based IMTA system can vary according to culturing purposes.

For example, Schuenhoff *et al.* (2003) did not include bivalves in their short-term system. Neori *et al.* (2000) did not use filter feeders but substituted co-culture with abalone, which was fed approximately 20% of the harvested seaweed. Shpigel *et al.* (1993) used oysters and clams as filter feeders in the IMTA system. Fine particles that formed from uneaten feed and fish feces were also modeled as variables that influenced bivalve growth.

As an autotroph, seaweed has an important role in IMTA because it is the final extractive organism that can take up DIN and reduce the amount of nitrogen in a system. For example, *Ulva* served as the bioremediation species in models by Shpigel *et al.* (1993) and Schuenhoff *et al.* (2003) while Neori *et al.* (2000) used both *Ulva* and *Gracilaria*.

The IMTA model was completed by incorporating sea cucumber as an extractor of large-particle organic components. As such, these organisms remove PON from fish and bivalve waste. For our model, we estimated the initial number of sea cucumbers to predict the absorption of PON. That is, an increase in sea cucumber biomass was calculated as being equivalent to the amount of PON removed from the system. We also modeled the feces of sea cucumber as an additional variable for N inputs.

Simulation Model

While emphasizing nitrogen removal in our land-based IMTA model, we assumed that the physical parameters reflected ideal culturing conditions, e.g., appropriate levels for light intensity, temperature, pH, salinity, and oxygen. Uptake of DIN by the seaweed component was limited by the rate of water flow. This dimensionless variable was modeled here as ranging from 0.1 (fastest flow) to 0.8 (moderate) to 1.0 (steady). Overall, we discounted the processes of nitrification and denitrification, assuming here that all of the N from fish waste was distributed homogenously in the system and was available for uptake. This allowed us to focus only on the bioremediation capacity of each organism, i.e., their ability to take up N and increase the amount of harvested biomass.

The abalone/finfish/seaweed/sea cucumber system of Neori *et al.* (2000) produced a fed-release value over their 12-mo culture period of 3.918 g N and a Feed Conversion Ratio (FCR) value of 2.0, whereas the 12-mo finfish/bivalve/seaweed/sea cucumber system of Shpigel *et al.* (1993) had a fed-release value of 1226 kg N and an FCR value of 3.0. Whereas Neori *et al.* (2000) considered the amount of dissolved nitrogen taken up by *Ulva* and *Gracilaria*, Shpigel *et al.* (1993) and Schuenhoff *et al.* (2003) used only *Ulva* to predict bioremediation waste. Seaweed was modeled as being harvested multiple times over the period in order to maintain stocking densities. Its yield was then exported to abalone culture, while bivalve oysters and clams fed on fine PON. Fine PON was modeled as 3% of the total (Buschmann *et al*., 2009). The maximum amount of N harvested was assumed to be equivalent to the N content measured in seaweed biomass. Schuenhoff *et al.* (2003) data were simulated for 28- and 51-d culture periods.

Sensitivity Analysis

We conducted sensitivity analyses by varying each component by 10% in either direction over 12 mo. Data from Neori *et al.* (2000) were used and all calculations were based on a formulation by Everett *et al.* (2007). The equation of sensitivity analysis are show also in Table 2. Where V (1.1 p) is the value of variable p increased by 10%, V (0.9 p) is the value of variable p decreased by 10%, and V (p) is the value in an unchanged state. If any calculated value was close to 1, we considered sensitivity to be proportional to the original parameter while values close to 2 were considered proportional to p^2.

Results

Performance of IMTA Components

Simulation results reported by Neori *et al.* (2000) indicated that their abalone component produced DIN 104 g N/yr while field data revealed 150 g N/yr. Seaweed was continuously harvested to maintain a desirable stocking density in the pond system. Approximately 20% of the yield was exported to the abalone component, accounting for 325 g N/yr (i.e., 37 kg fresh weight, or FW; 8.1 to 9.5 g N kg/FW). The amount of abalone harvested was estimated by the model as 113 g/yr versus 154 g/yr based on field data. Figure 2 shows the fluctuations in annual seaweed production when co-cultured with an abalone component.

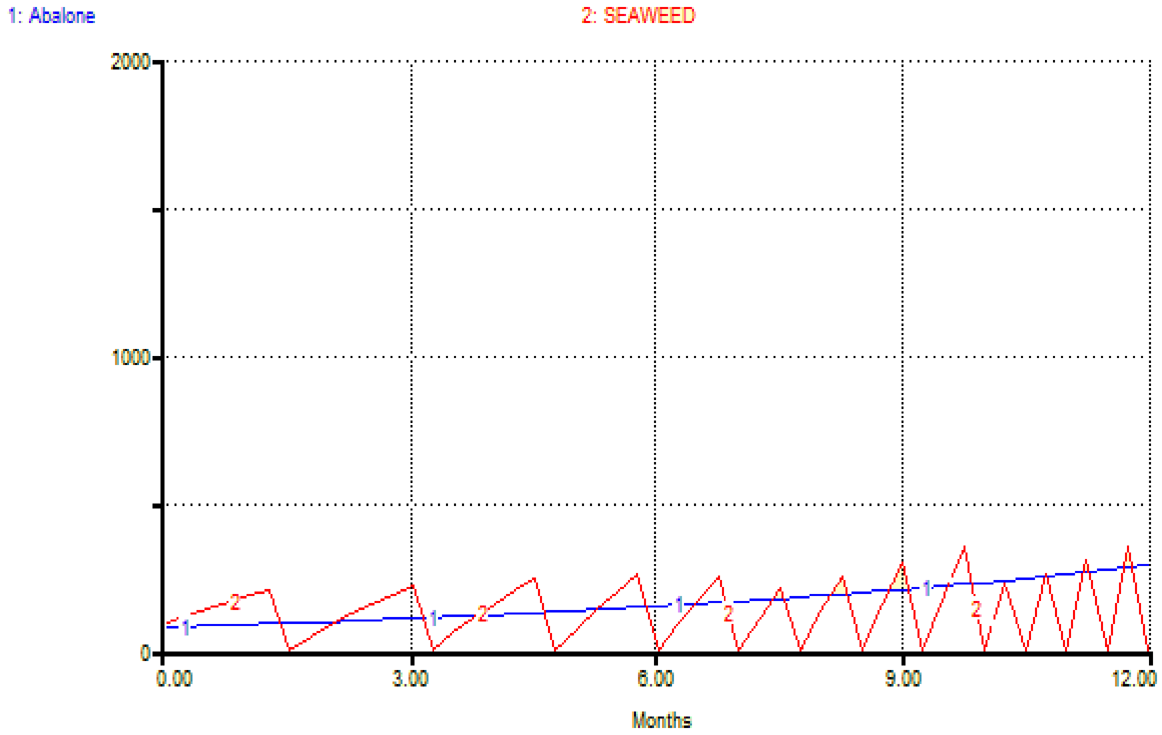

Figure 2. Simulation of seaweed biomass (grams of N) exported to abalone culture (Neori *et al.*, 2000).

The DIN waste produced by abalone flowed into the fish component and the amount of feed for that component was set in the model according to field calculations. For example, if the growth rate per day was 0.67% (Neori *et al.*, 2000; or 0.70% from the model estimate), then a fish initially weighing 12 kg would produce 30 kg/m^2 biomass (modelled). By contrast, that yield would be only 28 kg/m^2 if the field data were used for predicting the final harvest. Our simulation also showed that the DIN and feces in fish effluent contained 1,944 g N and 413 g N, respectively, per annum, compared with 1,879 g N and 392 g N, based on field data. Although seaweed culture could directly take up DIN from fish culture, water flow still limited that capacity. For both *Ulva* and *Gracilaria*, 195 kg were harvested (model) versus 134 kg (field). The model simulation also indicated that seaweed could remove up to 88% of the total DIN from fish effluent through harvest. Therefore, the total amount of organic waste from fish and abalone feces, plus uneaten pellets, increased in our IMTA model. When sea cucumber was incorporated, the level of total organic compounds was reduced by 48%, and the model calculated an absorption capacity of 70%.

Modeling based on data from Shpigel *et al.* (1993) presented a simulated scenario that utilized oysters and clams as filter feeders. The variable ‘fed input’ directly influenced N contents throughout the entire system, with input values of 1,226 kg N/yr and an estimated harvest of 201 kg N via fish (16% as yield N). By contrast, the field data indicated 185 kg N/yr from the harvest, even though potential production was estimated to be 318 kg N/yr (26% as yield nitrogen). Fish effluent produced 558 kg N as DIN and 118 kg N/yr as particulate organic compounds, while the amount from uneaten feed pellets was 245 kg N/yr. By filtering fine organic particulates, the bivalves processed 32 kg N/yr and produced 44 kg N/yr as DIN, which then continued from fish and bivalves through to the seaweed component. Seaweed took up 68% of the DIN by converting it into 410 kg N as harvested biomass. This compared with a harvest of 273 kg N estimated from the field data. Figure 3 shows that, during 2 mo of culturing, the amount of N taken up by seaweed could surpass the level of DIN in a system. The addition of a sea cucumber component improved the capacity for total PON absorption by 44%, such that the extra biomass could take up 174 kg N/yr. The complexities of an IMTA system based on the research of Shpigel *et al.* (1993), is depicted in Figure 4.

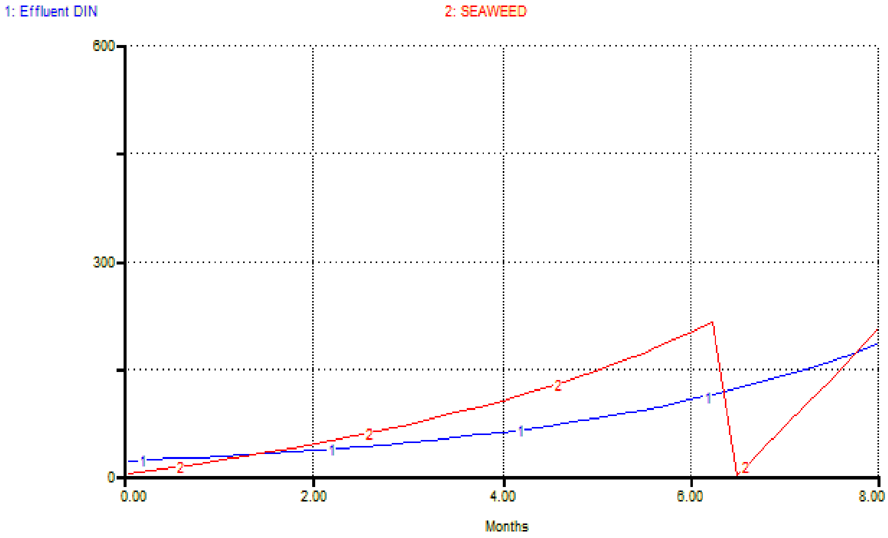

Figure 3. Simulation model showing that concentrations of dissolved nitrogen (kg N) are surpassed by levels taken up by seaweed (Shpigel *et al.*, 1993)

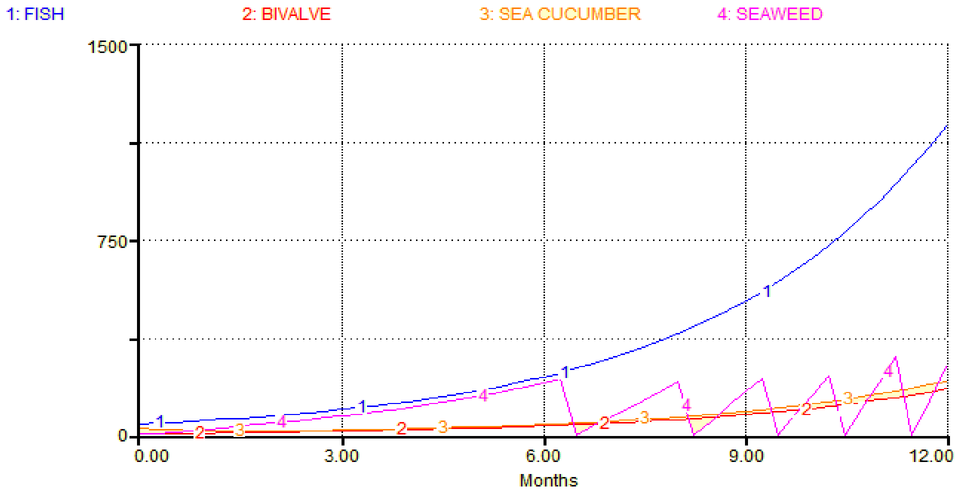

Figure 4. Simulation of annual nitrogen flux (kg N) when integrating fish, bivalve, seaweed and sea cucumber, based on data from Shpigel *et al.* (1993).

On the semi-commercial scale, as first described by Schuenhoff *et al.* (2003), our model evaluated data obtained through intensive sampling over 51 d and 28 d of culture. For both periods, the estimated annual fish harvest was 53.0 kg and 28.2 kg, respectively, values that were quite similar to field measurements of 52.0 kg and 27.0 kg, respectively. However, differences were found in effluent DIN, with model values of 3,535 g N and 1,881 g N for 51 and 28 d, respectively, versus 4,760 g N and 3,670 g N, respectively, from the field. Likewise, predictions for PON from fish feces were 752 g N (51 d) and 400 g N (28 d) from the model compared with 1,261 g N (51 d) and 881 g N (28 d) from the field. For seaweed, the gains were 138.3 kg (1,245 g N) at 51 d and 41.4 kg (373 g N) at 28 d for the model and 171.3 kg (1,542 g N/m^2) at 51 d and 75.3 kg (678 g N/m^2) at 28 d for the field. The simulation model of nitrogen contents in biomass from fish and seaweed during 28 d of culture is presented in Figure 5.

Finally, the loss of DIN from the entire system, due to flow and unassimilated forms of N, was modeled at 1,488 g N (51 d) and 753 g N (28 d) versus field measurements of 3,154 g N (51 d) and 2,853 g N (28 d). Table 3 shows how our model values compared with results from previous pilot studies that utilized all components incorporated into an IMTA system based on nitrogen contents.

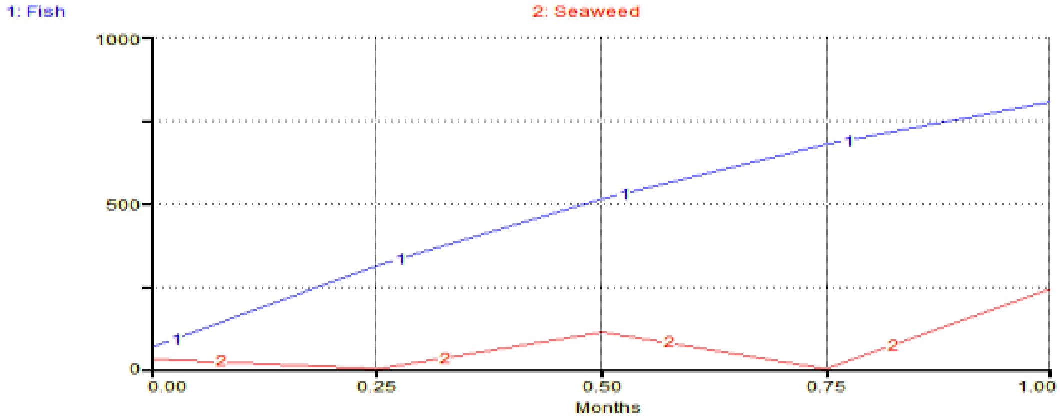

Figure 5. Simulated levels of nitrogen flux (grams of N) when fish are co-cultured with seaweed for 28 d, based on data from Schuenhoff *et al.* (2003).

Table 3. Comparisons of estimated values between our model and those previously published, incorporating the nitrogen budget.

Variable component	**Neori *et al.* (2000) in *grams N***	**Model in *grams N***	**Shpigel *et al.* (1993) in kg *N***	**Model in *kg N***	**Schuenhoff *et al.* (2003) in g *N* (A)***	**Model in *g* (A)***	**Schuenhoff *et al.* (2003) in g *N* (B)****	**Model in *g N* (B)****
ABALONE								
1. Seaweed input	410	325	N/A	N/A	N/A	N/A	N/A	N/A
2. Abalone harvest	154	113	N/A	N/A	N/A	N/A	N/A	N/A
3. Abalone DIN output	150	104	N/A	N/A	N/A	N/A	N/A	N/A
4. Abalone feces	107	73	N/A	N/A	N/A	N/A	N/A	N/A
(Deficit/Surplus)	***(1)***	***35***						
FISH								
1. Fed input	3918	3918	1226	1226	7416	7416	5184	5184
2. Harvest	768	829	185	201	1809.75	1512	1097	804
3. DIN output	1879	1944	122	558	4760	3535	3670	1881
4. Uneaten feed	*N/A*	805	*662*	245	*N/A*	1483	*N/A*	1037
5. Feces	392	413	122	118	1261	752	881	400
Abalone DIN input	150	104	N/A	N/A	N/A	N/A	N/A	N/A
(Deficit/Surplus)	***1069***	***31***	***135***	***104***	***(414)***	***134***	***(464)***	***1062***
BIVALVE (OYSTER AND CLAM)								
1. Bivalve feed input	N/A	N/A	784	196	N/A	N/A	N/A	N/A
2. Bivalve harvest	N/A	N/A	177	32	N/A	N/A	N/A	N/A
3. Bivalve DIN output	N/A	N/A	306	44	N/A	N/A	N/A	N/A
4. Bivalve feces	N/A	N/A	78	28	N/A	N/A	N/A	N/A
(Deficit/Surplus)			***223***	***92***				
SEAWEED								
1. DIN input	1879	1944	306	602	2305	3535	950	1881
2. Seaweed harvest	762	1,387	275	410	1542	1245	678	373
3. Seaweed discarded	67	0	0	0	0	0	0	0
4. DIN output	394	391	30.7	120	0	707	0	376
5. Seaweed export to abalone	339	325	0	0	0	0	0	0
6. Seaweed import	53	0	0	0	0	0	0	0
(Deficit/Surplus)	**264**	***(159)***	***0.3***	***72***	***763***	***1583***	***272***	***1132***
SEA CUCUMBER								
1.Total organic compound	*N/A*	1,291	*N/A*	392	*N/A*	N/A	*N/A*	N/A
2. Sea cucumber organic absorption	*N/A*	908	*N/A*	274	*N/A*	N/A	*N/A*	N/A
3. Sea cucumber harvest	*N/A*	624	*N/A*	174	*N/A*	N/A	*N/A*	N/A
4. Sea cucumber feces	*N/A*	147	*N/A*	41	*N/A*	N/A	*N/A*	N/A
(Deficit/Surplus)		***520***		***177***				
System dimension	3.3 m^3	3.3 m^3	750 m^3 **(C)*****	750 m^3	40 m^3 **(D)*******	40 m^3	40 m^3	40 m^3

*51 d culture
**28 d culture

***750 m^3 fish pond with184 m^3 bivalve pond, 315 m^3 seaweed pond
**** 40 m^3 fish pond with seaweed yield shown in m^2

Nitrogen Budget

In estimating nitrogen fluxes within an IMTA system, our model calculated both deficit and surplus N, presenting a nitrogen budget for each component. As the most abundant N distributor, fish accounted for annual surpluses of 31 g N to 104 kg N. For the abalone component, 35 g N/yr was modeled as the excess while the bivalve component showed a surplus of 92 kg N/yr. In contrast, a deficit of 159 g N/yr was predicted for the seaweed component, while sea cucumbers were associated with surpluses of 520 g N to 177 kg N/yr. Under short-term culture, the largest surplus was found with the simulated seaweed component, i.e., 1,132 g N at 28 d and 1,583 g N at 51 d. Details of nitrogen budgeting associated with each component are shown in Table 3.

Production Capacity

This simulation model was used to determine the market value of each component, based on productivity. We also evaluated the capacity to reduce nitrogen levels as an ecosystem service provided by extractive components. For example, the nutrient trading credit (NTC) was defined as having an average value of 0.35% nitrogen for seaweed, which meant that the NTC for this component ranged from 10.00 to 30.00 USD/kg. The values of organic extractive components, such as seaweed were estimated based on Chopin (2011) and shellfish were estimated, based work by Rose *et al*. (2014) at value 150.00 USD per pound of N removal.

Abalones are the most commercially valuable gastropods, with worldwide market prices of USD 43.00 to 100.00/kg FW (www.bbc.business.com). Our model-simulated production over 12 mo was 113 g N and approximately 7 kg FW, with a value of USD 301.00 to 700.00. Fish culture resulted in production capacity of up to 30 kg. Based on a commercial value of approximately 7.40 USD/kg for *Sparus aurata* (www.Fish.com), this meant that 3.3 m^3 of pond culture for fish could yield USD 222.00/yr.

As an extractive organism, seaweed is more beneficial because of both its economic and ecosystem values, based on market price and NTCs, respectively. Our model found that the total seaweed harvest per annum was approximately 190 kg, accounting for 1,712 g N. Therefore, economic values were USD 13,871.90 (USD 73.01 x 190 kg; biofuel price) for *Ulva* (Nikolaisen *et al*., 2011) or USD 95.00 (USD 0.50 x 190 kg; common market price) if we used *Gracilaria* (WWF Indonesia, 2014). Furthermore, the NTC for these seaweeds ranged from USD 17.00 to USD 51.00 (1,712 g N x USD 10.00-30.00; Chopin, 2011).

Another extractive organic remover, the sea cucumber, can be quantified by NTC, although its worth has not yet been determined. Its value would be approximately USD 1.50 to 58.00/kg according to prices on current international trade markets.

Sensitivity Analysis

Our model simulation showed that the most sensitive components were seaweed and sea cucumber (Table 4). A change of 10% in their variable rates of growth influenced their productivity by 2.1-fold (seaweed) and 2.2-fold (sea cucumber). By comparison, those fold-changes were 1.0 to 1.16 for abalone and 0.78 to 1.77 for the fish component. This new model was relatively insensitive to most variables. In fact, only three parameters had sensitive values >1.5: uneaten feed, seaweed harvest, and sea cucumber harvest.

Table 4. Sensitivity analysis of component variables in IMTA system.

Variable*	Normal value	Effect +10%	Effect –10%	Unit	Sensitivity analysis
Abalone					
Abalone harvest	113	125	101	g N/yr	1.06
Abalone DIN released	104	115	92	g N/yr	1.15
Abalone PON released	73	81	64	g N/yr	1.16
Fish					
Fish harvest	829	800	670	g N/yr	0.78
Fish DIN released	1944	1884	1567	g N/yr	0.82
Fish feces released	413	400	333	g N/yr	0.81
Uneaten feed	805	973	687	g N/yr	1.78
Seaweed & Sea cucumber					
Seaweed harvest	1712	1920	1200	g N/yr	2.10
Sea cucumber harvest	624	698	423	g N/yr	2.20

*Based on data from Neori *et al*., 2000

Discussion

This new model can potentially estimate the flux in nitrogen removal by each incorporated organism depending upon its capacity to take up and assimilate that nutrient into its biomass, without regard for the influence of anthropogenic activities. Our goal with this model was to demonstrate that implementing an IMTA can reduce the occurrence of negative environmental impacts and add economic and ecosystem benefits at harvest time. Although such simulation models often optimize production capacity. Because it is focused on crop productivity and nutrient removal, N contents vary according to the time period used for development and assessment prior to harvest.

The utility of this model for estimating DIN levels in effluent and fish feces at the time of harvest is similar to that associated with predictions based on field data. However, our model results differ from those described from the model of Schuenhoff *et al.* (2003) in terms of effluent and particulate organics (i.e., feces), here revealing a rate of 47% for effluent DIN versus 64% reported by Schuenhoff *et al.* (2003). The rate of DIN excretion found here is similar to that shown in studies by Islam (2005) and Bouwman *et al.* (2013), in which values ranged from 30% to 54% for general finfish. Castine *et al.* (2013) calculated a similar rate, 48%, for trout fish. In contrast, Neori and Krom (1991) determined a rate of 66% for the finfish *S. aurata* while Folke and Kautsky (1989) reported 62% DIN removed by *Salmo salar*. Another contrast in assimilation rates was found for particulate organic feces, i.e., 17% predicted by the model of Schuenhoff *et al.* (2003) versus 10% from our model and those of Gowen and Bradbury (1987), as well as Wang *et al.* (2012) and Bouwman *et al.* (2013) for salmon and general finfish, respectively. These differences in excretion rates are not only species specific but also vary according to feeding strategies, e.g., frequency, size of fish, and their ontogeny (Bolliet *et al.*, 2001; Islam, 2005). Moreover, stocking density and physical force are other factors that affect rates of metabolism (Wu, 1995).

The incorporation of a filtration pond in the model by Schuenhoff *et al.* (2003), but not in our model, also influenced those values. Such ponds can reduce the level of DIN by 50 to 70% before it passes to a seaweed biofilter. Therefore, applying certain harvesting quotas to manage seaweed stocking densities can help decrease the amount of nitrogen within a culture system. Figure 2 illustrates the correlation between seaweed N biomass and DIN flow, increasing during stages of active growth but decreasing at harvest time. As a main input of N, the amount of feed can be altered to increase the stability of sinking rates and optimize fish sizes (Wu, 1995). Likewise, the quality of a nutritional diet N on feed can be changed from feeding with trash fish to supplying artificial feeds (Xu *et al.*, 2007). In general, advances in feed nutrition technology have had an important role in determining nutrient contents within the environment of an aquaculture system.

This model showed that seaweed could take up 20 to 88% of the available DIN. During short periods of culture, those rates can range from 20 to 35% (Schuenhoff *et al.*, 2003) while longer terms mean that 68 to 88% of the excess DIN can be taken up within the system. These contrasts might be explained by variations in light levels and photoperiods that are related to seasonal changes as well as to the capacity of nutrient reserves (Harrison and Hurd, 2001; Broch and Slagstad, 2012). Uptake rates might also be affected by shorter culture periods or decisions to harvest fish at a developmental stage where DIN excretion is maximized. Therefore, adjustments must be made when co-culturing seaweed and fish.

To exploit the high rates of nutrient uptake by seaweed, planners should select genera such as *Ulva*, which can remove nearly 80% of the excess N and under some conditions, up to 100% of the ammonium (Cohen and Neori, 1991; Troell *et al.*, 1999; Macchiavello and Bulboa, 2014). *Gracilaria* is another suitable candidate because of its high economic value (Yang *et al.*, 2015) as well as its ability to remove at least 80% of the ammonium (Chopin *et al.*, 2001) and up to 95% during the springtime (Buschmann *et al.*, 1996). Because of their different morphological features, *Ulva* is often used for water treatments, e.g., recirculating-flow systems, while *Gracilaria* is valuable for mass production. Nonetheless, our model was able to predict values similar to those estimated by Neori *et al.* (2000) for potential seaweed harvests.

The last component of this simulated IMTA system incorporated sea cucumber as a deposit feeder to PON. One benefit of our model was that uneaten feed could be considered part of PON while that system also modeled feces, a variable that could affect the availability of total PON. Decreasing the amounts of PON depends upon the rates of feeding and ingestion by deposit species (Slater and Carton, 2007). As a slow-growing organism that also ingests food slowly, sea cucumber can survive for several months without additional food, and individuals require more than one year reaching market size. Nevertheless, *Cucumaria frondosa* has been suggested as a suitable extractive organism for an IMTA system (Nelson *et al*., 2012) because it can potentially remove 44 to 48% of total PON when harvested. Therefore, co-culturing sea cucumber can play as significant a role as seaweed in an integrated system.

We used model simulations to determine the nutrient budget in an IMTA system because failing to estimate nutrient levels when developing a management plan can have unintended negative consequences for coastal or marine environments. Our model enabled us to predict nutrient imbalances for each component by examining stocking densities or by focusing on physical factors, such as water flow or speed of currents, but retention times and size dimensions of a culture site also affected nutrient in the system (Sara *et al*., 2012; Chopin *et al*., 2012; Rose *et al*., 2014).

Modeling can be applied to detect nutrient surpluses or deficits in a system. Our model discounted any negative impacts such as through eutrophication. Surplus organic nutrients can be controlled by incorporating suspended organisms or sea cucumbers in the bottom layers. Therefore, when devising an IMTA system, one must analyze nutrient outputs and fluxes in order to mitigate possible imbalances.

Productivity can be modeled for all system components. However, the challenge when estimating capacity is to assess cultivation costs as easily as possible. Recognizing economic benefits and providing economic incentives can make the expansion of management plans more profitable. For example, *Ulva*, when used as a biofuel, has a higher market value than *Gracilaria*. Therefore, wisely selecting the most appropriate organism(s) for co-cultivation can also lead to greater environmental improvements (Navarete-Mier *et al*., 2010; Chopin *et al*., 2012).

Strong emphasis has been placed on the co-culture of abalone with seaweed, while integration culture of seaweed in an aquaculture system has been suggested for worldwide applications (Chung *et al.*, 2002, 2011; Neori *et al*., 2007; Ridler *et al*., 2007; Chopin, 2001, 2012). Additional feeding strategies can be a suitable option if model simulations detect a decline in production. By introducing additional food such as commercial feed, biomass yields can be increased although profitability can be diminished as a consequence. However, when one examines the overall capital budget, using only waste from one organism component can increase farm revenues (Ridler *et al*., 2007) and minimize environmental damages (Chopin, 2011).

Finally, reducing nutrient concentrations through the use of biofilter organisms, such as seaweed, bivalves, and sea cucumber, is a critical part of a bioremediation system. Therefore, we believe our land-based aquaculture model can be productive because it includes such a biofilter system. Furthermore, our sensitivity analyses demonstrated that the STELLA model is adequate for predicting reasonable outcomes when comparing between model and field data.

Conclusion

This model estimated the N-removal capacity for each component in a land-based system of aquaculture that considered the role of nutrient waste control. Our results serve as an appropriate strategic guideline for IMTA implementation that can increase management and predictive capacities and improve the social acceptability of such systems.

Acknowledgements

This work has been supported by a grant from the National Research Foundation of Korea (NRF-2013R1A1A2009359) to IKC and from the Ministry of Education (BK21 plus Grant 21A20131500003). The authors are grateful to Prof. T.S. Lee for his kind guidance in model development.

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