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A TROPHIC MODEL FOR KUOSHENG BAY IN NORTHERN TAIWAN

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Key words: food web, ECOPATH, network analysis, thermal discharge.

ABSTRACT

Using the Ecopath with Ecosim software system, a mass-balanced trophic model of Kuosheng Bay, where the Second Nuclear Power Plant is sited on the coast, was constructed. This model comprised 17 compartments, ranging from a trophic level of 1.00 for primary producers and detritus to 3.97 for piscivorous fish. The geometric mean of the trophic transfer efficiencies was 6.5%. The lower efficiencies were attributable to high flows to detritus, suggesting that the food web was more dependent on detritus than on primary producers to generate total system throughput. The total system throughput, system production, and system biomass were comparable to other reported coastal ecosystems, indicating Kuosheng Bay behaved like a typical coastal ecosystem. The total primary production to total respiratory ratio of 1.06 indicates that Kuosheng Bay is an autotrophic system. The low gross efficiency suggests the low fishing pressure in the bay, which implies that the fishery loss resulted from the power plant through impingement and entrainment was insignificant.

INTRODUCTION

Power plants use energy to heat water to create steam, that turns turbines and need large volumes of water to condense the steam after use. They are often sited on coasts because of the availability of a large supply of cooling water. However, the greatest environmental impacts of operation of coastal power plants are the intake and discharge of large volumes of cooling water (McLusky and Elliott, 2004). A large power plant may require 30-50 m^3 s^{-1}, the equivalent of a medium sized river. In taking in this volume, large and small organisms might be sucked into the plant, termed impingement. Fishes and large invertebrates greater than 1 cm^2 would be retained on the initial rotating screens inside the power plant. Hence power plants have been described as stationary trawlers. In Taiwan, Chuang *et al*. (1993) found that the amount of impinged organisms was higher in summer and lower in winter, which might be relevant to fish migration and typhoon occurrence. Nevertheless, Shao *et al*. (1989) argued that a fishery loss in a coastal power plant per year through impingement was small, the equivalent of catch-out only from a few boats for a year.

Larval forms of fishes and invertebrates smaller than 1 cm^2 would pass through the rotating screens and thus flow into the main cooling system of the plant, termed entrainment. In a power plant in Mount Hope Bay, Clark and Brownell (1973) estimated that 7,000,000-16,000,000 individuals of herring juveniles might suffer death through entrainment in a summer. Hall (1977) estimated that about 75% of the total fish eggs and juveniles in coastal waters might suffer injury. In Taiwan, Shao *et al*. (1989) estimated a fishery loss of 10,000 kg for a coastal power plant per year through entrainment, which was much greater than the loss through impingement.

Cooling water is usually treated with chlorine to discourage the settlement of fouling organisms in the heat-exchange system. The introduction of halogenated antifouling agents coupled with high levels of organic matter in the water and the heat produced in the system leads to the production and liberation of chlorine residuals and organohalogens themselves polluting materials when discharge from the plant into receiving waters (Brook and Baker, 1972; Choi *et al*. 2002).

Cooling water is discharged at a higher temperature than that of the receiving waters, which might also lead to population and community changes (Kokaji, 1995). In Biscayne Bay, Florida, Zeiman (1970) found that the increased water temperature would result in decreases in seagrass production and diversity and abundance of zooplankton. Thorhaug *et al*. (1973) further identified that an increase of 2~3°C than the ambient

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would lead to an increase in faunal biomass. However, an increase of 3-4°C than the ambient would lead to a decrease in seagrass biomass. An increase of more than 5°C would lead to disappearance of seagrasses. In tropical/subtropical waters, not only is the added heat dissipated more slowly than in cold seas, but the sea temperature is already near the thermal death point for many organisms.

Hall *et al*. (1978) indicated that thermal discharges might result in changes in primary and secondary productivity, species composition, biomass, and nutrient dynamics in coastal waters. However, ecosystem-scale impacts of power plants on the adjacent coastal waters are still not understood. Trophic models have been successfully used to understand how tropical coastal ecosystems are structured and function (Lin *et al*., 2001). In this study, a matter-balanced trophic model was constructed to characterize the structure and functioning of Kuosheng Bay in northern Taiwan, where the Second Nuclear Power Plant is sited on the coast. The purposes are: (1) to present a model of the trophic interactions within a subtropical bay; (2) to determine the trophic functioning in the bay; (3) to describe quantitatively the characteristics of the bay as a whole in response to operation of a coastal nuclear power plant.

MATERIALS AND METHODS

1. Study area

Kuosheng Bay is a semi-enclosed shallow water system in northern Taiwan (25°13'N; 121°40'E) and covers about 8.0 km^2 of surface area (Fig. 1). The average depth is about 15 m. Water temperatures range from about 25°C in summer to about 15°C in winter. Salinities remain high, with slightly lower values in summer (about 32 psu) and higher values in winter (about 35 psu).

2. Modeling approach

The modeling approach is the ECOPATH with ECOSIM V.5.1 software system of Christensen *et al*. (2004). A mass-balanced system of biomass budget equations which, for each group *i*, can be expressed as:

Production by *i* - all predation on *i* - non-predation losses of *i* - export of *i* - accumulation of *i* = 0, or

$$Pi - BiM2i - Pi\,(1 - EEi) - EXi - ACi = 0, \qquad (1)$$

where Pi = the production of (i); Bi = the biomass of (i); $M2i$ = the predation mortality of (i); EEi = the ecotrophic efficiency of (i), i.e., the part of production that is either passed up the trophic level or exported; $1 - EEi$ = "other mortality"; EXi = the export of (i); and ACi = the accumulation of (i) during the study period.

Thus, the production of each group is the amount of biomass available to the system. Most of it will be used by predation ($Bi \bullet M2i$), but a certain amount might be lost through other mortality [$Pi\ (1 - EEi)$] or by export to other systems (EXi), i.e., through sedimentation or through fishery activities.

A predator group is connected to its prey groups by its consumption (QB_j). Thus, equation (1) can be re-expressed as:

$$Bi \times PBi \times EEi - \Sigma jBj \times QBj \times DCji - EXi - ACi = 0, \qquad (2)$$

where PB_i = the production/biomass ratio; QB_j = the consumption/biomass ratio of the predator j; and DC_{ji} = the fraction of the prey (i) in the average diet of predator j.

Consumption of a predator group is then connected to its production:

Consumption = production + respiration + unused, can be re-expressed as:

$$\Sigma jBj \times QBj = Pj + Rj + UNj, \qquad (3)$$

where Pj = the total production rate of predator j; and UNj = the unused consumption of the predator j (20%).

All parameters used to construct the model do not have to be entered since ECOPATH links the production of each group with the consumption of all other groups, and uses the linkages to estimate missing parameters. DC and EX must always be entered, while entry is optional for any of the other four parameters (B, P/B, Q/B, and EE). For further details and algorithms of the ECOPATH model structure see Christensen *et al*. (2004). The pathway flows of the trophic model were further analyzed using the network analysis (Ulanowicz, 1998).

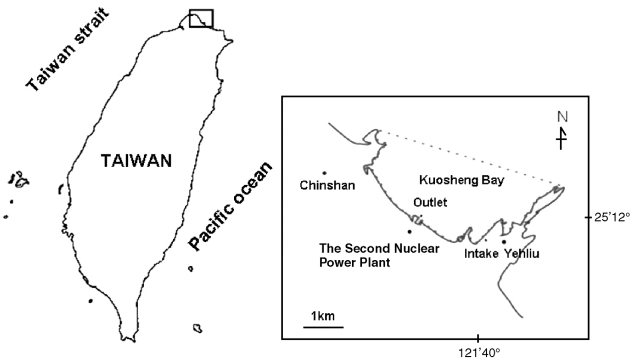

Fig. 1. The study area of Kuosheng Bay.

3. Model compartments

Major species of similar sizes and diets in Kuosheng Bay were grouped within the same compartment according to Feng (2001) and Hwang *et al*. (2001). Bacterial biomass was included in the compartment of detritus as recommended by Christensen *et al*. (2004), because bacterial flow may totally overshadow other flows in the system. A 17-compartment model for the bay was developed (Fig. 2) consisting of the following groups: 1. phytoplankton, 2. epilithic periphyton, 3. herbivorous zooplankton, 4. carnivorous zooplankton, 5. infauna, 6. barnacles, 7. gastropods, 8. bivalves, 9. shrimp, 10. crabs, 11. holothuroids, 12. herbivorous fish, 13. zooplanktivorous fish, 14. benthic-feeding fish, 15. piscivorous fish, 16. detritivorous fish, and 17. detritus. Biomass was in g wet weight (WW) m^{-2} and production and other flow were in g wet weight (WW) m^{-2} yr^{-1}.

All parameters used to construct the model were assembled as much as possible from previous research data in Kuosheng Bay (Table 1). These research data were collected in spring, summer, autumn, and winter during 1998-2001 to take account of seasonal changes with the exception of phytoplankton and periphyton data, which were determined in 2003. Data of P/B and Q/B for zooplankton and invertebrates are scarce in Taiwan, and estimates were obtained by searching directly in relevant literature (Chang, 1992; Cheng *et al*. 1991; Opitz, 1996). Estimates of Q/B for fishes were computed with an empirical model in Fishbase (Forese and Pauly, 2004) for the dominant species of each group. Data on P/B for fishes were also obtained by searching directly in Fishbase (Forese and Pauly, 2004).

The catches of fishes were obtained directly from the local fishery bureau. The amount of impinged fishes in the nuclear power plant was obtained directly from Hwang *et al*. (2000). Data on amount of entrained fishes in the power plant are lacking. Shao *et al*. (1989) estimated that the amount of entrained fishes was at least 1.5 times greater than the impinged fishes. Therefore, the amount of entrained fishes was then assumed 1.5 times greater the amount of impinged fishes. Factors used for conversion between chloro-

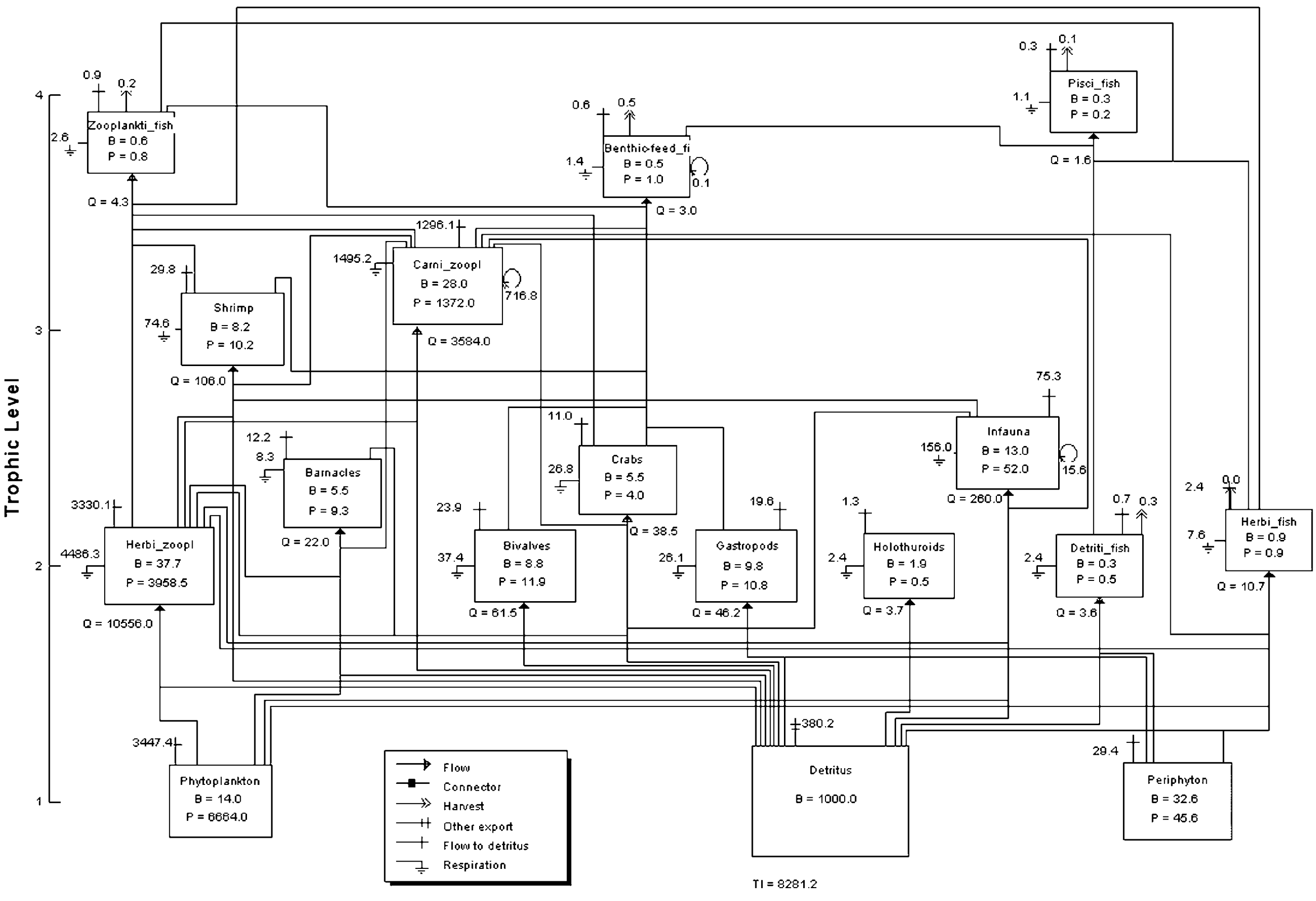

Fig. 2. Trophic model of Kuosheng Bay. Biomass is in g WW m^{-2}. Production and other flows are in g WW m^{-2} yr^{-1}.

Table 1. The compartments and input parameters for the construction of the Kuosheng Bay model

Group name	Biomass (g WW m^{-2})	P/B (yr^{-1})	Q/B (yr^{-1})	Fishery (g WW m^{-2} yr^{-1})	Impingement + Entrainment (g WW m^{-2} yr^{-1})	Literature source
1. Phytoplankton	14.0	476	–	–	–	Lin *et al*. (2002)
2. Periphyton	32.6	1.40	–	–	–	Lin *et al*. (2002)
3. Herbivorous Zooplankton	37.7	105	280	–	–	Hwang *et al*. (2001); Chang (1992); Cheng *et al*. (1991)
4. Carnivorous zooplankton	28.0	49.0	128	–	–	Hwang *et al*. (2001); Chang (1992); Cheng *et al*. (1991)
5. Infauna	13.0	4.00	20.0	–	–	Hwang *et al*. (2001); Opitz (1996)
6. Barnacles	5.48	1.70	4.02	–	–	Hung *et al*. (1998); Opitz (1996)
7. Gastropods	9.82	1.10	4.70	–	–	Hung *et al*. (1998); Opitz (1996)
8. Bivalves	8.79	1.35	7.00	–	–	Hung *et al*. (1998); Opitz (1996)
9. Shrimp	8.15	1.25	13.0	–	–	Hung *et al*. (1998); Opitz (1996)
10. Crabs	5.50	0.73	7.00	–	–	Hung *et al*. (1998); Opitz (1996)
11. Holothuroids	1.85	0.29	2.00	–	–	Hung *et al*. (1998); Opitz (1996)
12. Herbivorous fish	0.89	1.06	12.0	0.01	0.00660	Feng (2001); Forese and Pauly (2004)
13. Zooplanktivorous fish	0.64	1.29	6.75	0.24	0.00011	Feng (2001); Forese and Pauly (2004)
14. Benthic-feeding fish	0.52	1.97	5.84	0.52	0.00033	Feng (2001); Forese and Pauly (2004)
15. Piscivorous fish	0.26	0.62	6.00	0.15	0	Feng (2001); Forese and Pauly (2004)
16. Detritivorous fish	0.28	1.67	13.0	0.30	0	Feng (2001); Forese and Pauly (2004)
17. Detritus	1000	–	–	–	–	Hwang *et al*. (2001)

phyll *a*, carbon, displacement volume, dry weight, and wet weight were based on the table summarized by Opitz (1996).

Detritus comprises the organic materials in the water column and on sediments. Water from the bay was filtered through an acid-cleaned, dried, and pre-weighed Nucleopore membrane filter to determine the detrital biomass after firing in a 400°C muffle furnace. Sediments were collected by Eckman Birge Grab (15 cm × 15 cm) and dried in an oven at 60°C. The dried sediments were then ground to powder for analyses of organic materials. Detritus on sediments was limited to the top 5 cm of sediments, which is generally available for uptake by epifauna and fish.

Data on the diet of zooplankton and invertebrates were obtained by searching directly in the literature (Cheng *et al*. 2001; Opitz, 1996). Diet compositions of fishes were determined by stomach content analyses of the dominant species (Feng, 2001), and were recorded in percent of volume of major prey groups (Table 2). The program routine of ECOPATH assumes the food matrix remains stable, which would not occur over the long term but which may be reasonable for the short term.

4. Modification strategy of input values

The first step in verifying the realism of the model was to check whether the EE was less than 1.0 for all groups, since it is not possible for any group to use more biomass than it produces. The second step was to check if the GE (the gross food conversion efficiency, i.e., the ratio between production and consumption) was in the range of 0.1 to 0.3, as the consumption of most groups is about 3-10 times higher than their production. The final step was to compare the output values to independent field measurements and relevant literature data from other coastal waters.

RESULTS

1. Model validation

The estimated EE values of all compartments (Table 3) were less than 1.0. The EE of detritus is defined as the ratio between what flows out of the detritus and what flows into the detritus. The estimated EE value of detritus was less than 1, which indicates that more was entering the detritus group than was exiting. The estimated net efficiencies (the net food conversion efficiency, i.e., the ratio between production and assimilated food) of all compartments were greater than the GE values. Most GE values except that of barnacles were in the range of 0.1-0.3 and were comparable to values reported in the literature for macroinvertebrates (Mann, 1982), zooplankton (Conover, 1974), and fish

Table 2. Diet composition in percentage of volume of prey groups assembled from the literature for the construction of the Kuosheng Bay model

Prey/predator	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Phytoplankton	0.30		0.15	0.23						0.53				
2. Periphyton					0.30					0.17				0.15
3. Herbivorous zooplankton		0.75	0.11	0.15			0.15	0.04		0.09	0.30			
4. Carnivorous zooplankton		0.20	0.13	0.08			0.31	0.12		0.01	0.65	0.01		
5. Infauna			0.06				0.12	0.01						
6. Barnacles								0.04						
7. Gastropods												0.13		
8. Bivalves												0.10		
9. Shrimp											0.02	0.49		
10. Crabs											0.02	0.20		
11. Holothuroids														
12. Herbivorous fish											0.01		0.37	
13. Zooplanktivorous fish												0.03	0.30	
14. Benthic-feeding fish												0.04	0.23	
15. Piscivorous fish														
16. Detritivorous fish													0.10	
17. Detritus	0.70	0.05	0.55	0.54	0.70	1.00	0.42	0.79	1.00	0.20				0.85

Table 3. Calculated parameters for the Kuosheng Bay model

Group name	EE	GE	Respiration (g WW m^{-2} yr^{-1})	Flow to detritus (g WW m^{-2} yr^{-1})	Predation mortality (g WW m^{-2} yr^{-1})	Net efficiency	Trophic level	Omnivory index
1. Phytoplankton	0.48	–	0.00	3447	229	–	1.00	0.00
2. Periphyton	0.36	–	0.00	29.4	0.62	–	1.00	0.00
3. Herbivorous Zooplankton	0.69	0.38	4486	3330	72.7	0.47	2.00	0.00
4. Carnivorous zooplankton	0.58	0.38	1495	1296	28.3	0.48	3.19	0.30
5. Infauna	0.55	0.20	156	75.3	2.21	0.25	2.48	0.63
6. Barnacles	0.17	0.42	8.31	12.2	0.28	0.53	2.31	0.41
7. Gastropods	0.04	0.23	26.1	19.6	0.04	0.29	2.00	0.00
8. Bivalves	0.03	0.19	37.4	23.8	0.04	0.24	2.00	0.00
9. Shrimp	0.16	0.10	74.6	29.8	0.19	0.12	3.01	0.89
10. Crabs	0.17	0.10	26.8	11.0	0.13	0.13	2.37	0.57
11. Holothuroids	0.00	0.15	2.42	1.28	0.00	0.18	2.00	0.00
12. Herbivorous fish	0.68	0.09	7.60	2.44	0.70	0.11	2.11	0.50
13. Zooplanktivorous fish	0.97	0.19	2.63	0.89	0.87	0.24	3.80	0.30
14. Benthic-feeding fish	0.98	0.34	1.41	0.63	0.81	0.42	3.70	0.24
15. Piscivorous fish	0.93	0.10	1.09	0.32	0.00	0.13	3.97	0.53
16. Detritivorous fish	0.98	0.13	2.44	0.74	0.56	0.16	2.00	0.00
17. Detritus	0.96	–	0.00	0.00	–	–	1.00	0.59

(Caddy and Sharp, 1986). The outputs of the Kuosheng Bay model verified its realism.

2. Trophic structure

Trophic levels were estimated by the program from the weighted average of prey trophic levels and varied from 1.00 for primary producers and detritus to 3.97 for piscivorous fish in Kuosheng Bay (Fig. 2). The detritus pool was a food source of many compartments in the bay. The most prominent biological group in terms of biomass and energy flow in the bay was herbivorous zooplankton. It comprised 23% of the system's total biomass (excluding detritus) and consumed 72%

of the available primary production and detritus. An omnivory index of zero indicates that herbivorous zooplankton feed on a single trophic level of 1.00 (Table 3). The large omnivory indices of shrimp, infauna, crabs, infauna, and piscivorous fish (> 0.50) indicate the variance of trophic levels of their prey. Therefore, their flows don't concentrate on a single trophic level.

3. Pathway flows

The trophic aggregation routine in ECOPATH aggregated the 17 groups from Kuosheng Bay in a simple Lindeman food chain with 5 integer trophic levels (Fig. 3). Primary producers (trophic level I) comprised phytoplankton, periphyton, and detritus. On trophic level V, flows were ascribed only to benthic-feeding and piscivorous fish. The relative contribution of phytoplankton to the system primary production was about 99%. About 37% of the system matter flow originated from primary producers and the other 63% was from detritus, indicating that Kuosheng Bay was more dependent on the detritus pool than primary producers to generate total system throughput. This is because that only half of primary production of phytoplankton and periphyton was directly predated, and the other half was not immediately used by upper trophic levels and thus flowed into the detrital pool.

The transfer efficiency of matter is the ratio between the sum of exports and flow that is predated by the next level, and throughput on the trophic level. Trophic level II achieved a transfer efficiency of 25% for the combined flows from primary production and detritus. Transfer efficiencies declined sharply for trophic level III to IV, dropping to 2.7-4.1%, and then increased back to 8.8% for trophic level V. The geometric mean of the transfer efficiencies was 6.5%.

4. Ecosystem attributes

Ecosystem studies conducted in tropical/subtropical coastal waters are few. Total system throughput (the sum of consumption, exports, respiratory flows, and flows into detritus) of Kuosheng Bay was 29,692 g WW m^{-2} yr^{-1}, which was much lower than that of the tropical lagoon Chiku Lagoon in Taiwan, but was higher than that of Tongoy Bay, a subtropical coastal system in Chile (Table 4). The sum of all production, the total net

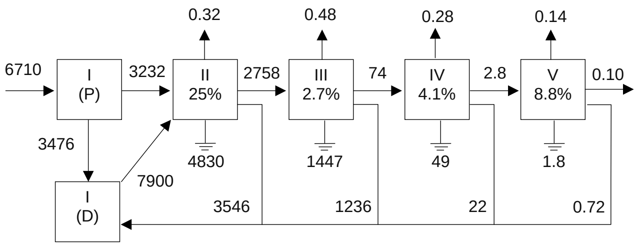

Fig. 3. Flow network of organic matter and trophic efficiencies (%) of the Kuosheng Bay model. The flow (g WW m^{-2} yr^{-1}) web is aggregated into a concatenated chain of transfers through five integer trophic levels. Flows from primary producers (P) and from detritus (D) and flows out of the tops of boxes represent export, and flows out of the bottoms represent respiration.

Table 4. Comparisons of ecosystem attributes among Kuosheng Bay, Chiku Lagoon and Tongoy Bay

	Kuosheng Bay (this study)	Tongoy Bay (Wolff, 1994)	Chiku Lagoon (Lin *et al.*, 1999)	Units
Sum of all consumption	14701	7669	70966	g WW m^{-2} yr^{-1}
Sum of all export	1.23	3103	4775	g WW m^{-2} yr^{-1}
Sum of all respiratory flow	6328	4021	45815	g WW m^{-2} yr^{-1}
Sum of all flow into detritus	8281	6040	39983	g WW m^{-2} yr^{-1}
Total system throughput	29692	20835	157653	g WW m^{-2} yr^{-1}
Sum of all production	12143	9689	61729	g WW m^{-2} yr^{-1}
Fishery's mean trophic level	3.32	3.63	3.40	
Total catches	1.23	63	890	g WW m^{-2} yr^{-1}
Gross efficiency (catch/NPP)	0.02%	1.8%	1.8%	
Total net primary production (NPP)	6710	7125	50600	g WW m^{-2} yr^{-1}
Total primary production/total respiration	1.06	1.77	1.10	
Net system production	381	3103	4775	g WW m^{-2} yr^{-1}
Total primary production/total biomass	40	30	24	
Total biomass/Total throughput	0.006	0.011	0.013	
Total biomass (excluding detritus)	167	263	2096	g WW m^{-2}
Finn's cycling index (FCI)	32	10.1	10.8	
Average path length (APL)	4.4	4.9	2.9	

primary production, the total biomass, the total primary production to total biomass ratio, and the total biomass to total throughput ratio were also comparable to ratios reported from Tongoy Bay. These outputs suggest that Kuosheng Bay behaved like a typical coastal system in terms of structure and trophic functioning. The total primary production to total respiratory ratio of 1.06 indicated that Kuosheng Bay is autotrophic, which implies that more organic matter was produced than consumed in the bay. The Finn's cycling index (FCI) indicated 32% of flow in a system that is recycled compared with the total system throughput (Table 4). The Finn's mean path length (MPL) measured the mean number of 4.4 groups that a unit of flux will experience from its entry into the system until it leaves the system.

However, the fishery yield from Kuosheng Bay was low (1.23 g WW m^{-2} yr^{-1}, Table 4). The fishery loss of 0.007 g WW m^{-2} yr^{-1} resulted from the power plant through impingement and entrainment was relatively negligible. The fishery's mean trophic level was high, suggesting that the fishery in the bay concentrated on fishes of higher trophic levels. Benthic-feeding fish alone accounted for about 43% of the total fishery biomass and were the most important fishery species in terms of biomass in the bay, whereas herbivorous fish alone accounted for 85% of the total impinged and entrained fishes. The gross efficiency (fishery catch: net primary production ratio) was only 0.02%, which was much lower than the ratios from Tongoy Bay and Chiku Lagoon, suggesting the fishing pressure in the bay was low.

DISCUSSION

The Kuosheng Bay model shows that the structure of food web in the bay comprised 4 integer tropihc levels, which is typical for the food web of Chiku Lagoon and other coastal ecosystems (Lin *et al*., 1999). Details of the transfer of organic matter from food sources to top predators in a food web can be revealed by network analysis. A comparative approach with other coastal ecosystems using the results from network analysis is helpful to characterize the functioning of the Kuosheng Bay model.

Net primary production of Kuosheng Bay was lower than those reported from estuaries, coastal lagoons, and coral reefs, but was comparable when compared with other bays (Table 5). The highest values occurred at the Great Barrier Reef (Johnson *et al*., 1995) and Chiku Lagoon (Lin *et al*., 2001), which was about 15- and 8-fold that of Kuosheng Bay, respectively. The lowest values occurred at Takapoto Atoll lagoon (Niquil *et al*. 1999), which was about 63% of that of Kuosheng Bay.

In Kuosheng Bay, the transfer efficiencies for trophic levels II were higher than the reported range of 10%-20% in coastal zones (Odum, 1971; Barnes and Hughes, 1988). However, transfer efficiencies for trophic levels III, IV, and V were relatively low, but were comparable to other systems (Table 5). The geo-

Table 5. Comparisons of net primary production (NPP: g WW m^{-2} yr^{-1}), trophic transfer efficiency for each level and the geometric mean (II-V), detritivory to herbivory ratio (D:H), average path length (APL), and Finn cycling index (FCI) among coastal ecosystems

Study site	Climate	NPP	II (%)	III (%)	IV (%)	V (%)	Mean (%)	D:H	APL	FCI (%)
Chiku Lagoon (Lin *et al*., 2001)	tropical	50,600	15	7.7	7.8	2.8	12	1.4	3.1	15
Terminos Lagoon (Manickchand-Heileman *et al*., 1998)	tropical	11,754	6.7	6.9	7.4	6.8	7	4.6	10	7
Takapoto Atoll lagoon (Niquil *et al*., 1999)	tropical	4,254	23	12	16	NA	17	0.6	NA	18
Great Barrier Reef (Johnson *et al*., 1995)	tropical	97,163	5.7	17	18	0.5	5.4	1.0	3.5	26
Tiahura Reef[a] (Arias-Gonzalez *et al*., 1997)	tropical	17,650	8.7	9.2	9.0	4.8	7.7	NA	NA	NA
Tongoy Bay (Wolff, 1994)	subtropical	7,125	14	11	14	14	14	0.8	4.9	10
Kuosheng Bay (this study)	subtropical	6,710	25	2.7	4.1	8.8	6.5	2.4	4.4	30
Sundays Beach (Heymans and McLachlan, 1996)	temperate	10,556	24	10	7	11	12	12	2.3	13
Ythan Estuary (Baird and Ulanowicz, 1993)	temperate	12,000	6.4	2.4	3.2	5.6	3.7	10	2.9	25
Swartkops Estuary (Baird and Ulanowicz, 1993)	temperate	12,652	3.5	8.3	0.8	1.1	2.8	1.5	3.9	44
Kromme Estuary (Baird and Ulanowicz, 1993)	temperate	16,046	1.7	7.1	3.2	7.1	3.4	6.7	2.4	26
Ems Estuary (Baird and Ulanowicz, 1993)	temperate	1,409	17	7.0	3.3	NA	7.4	0.5	3.4	30
Chesapeake Bay (Wulff and Ulanowicz, 1989)	temperate	17,436	18	7.2	7.0	1.2	5.7	5.0	3.6	30
Baltic Sea (Wulff and Ulanowicz, 1989)	temperate	8,594	19	20	5.9	14	13	1.5	3.3	23

[a]mean for the fringing reef and the barrier reef. NA: data not available.

metric mean of trophic efficiencies of Kuosheng Bay was similar when compared with other coastal systems. As a matter of fact, almost all trophic efficiencies are lower than the value of 15% proposed by Ryther (1969) for coastal waters with the exception of that of Takapoto Atoll lagoon. Most values from coastal ecosystems were lower than the range (10%-20%) commonly reported in the literature (Odum, 1971).

The lower transfer efficiencies of Kuosheng Bay were attributable to high flows to detritus (Fig. 3). The higher D:H ratios of bays, estuaries, and coastal lagoons when compared with coral reefs (Table 5) suggest that they were relatively more dependent on the detritus pool than on primary producers to generate total system throughput. However, Kuosheng Bay differed from Tongoy Bay and Chiku Lagoon in the extent that detritivory dominated over herbivory, i.e., primary production in Tongoy Bay and Chiku Lagoon was exploited more by consumers than it was in Kuosheng Bay. Niquil *et al*. (1999) found that the D:H ratio in Takapoto Atoll lagoon would decrease by augmenting primary productivity by 10%. In temperate systems, the Swartkops estuary mildly polluted by agriculture and industry (Baird and Ulanowicz, 1993) and the eutrophic Baltic Sea (Wulff and Ulanowicz, 1989) showed much lower D:H ratios than values for other estuaries. Therefore, the greater dependence on herbivory in Chiku Lagoon was likely to be induced by the high rate of nutrient loading (Lin *et al*., 2001). A lower D:H ratio in Tongoy Bay was likely resulted from periodic intrusions of upwelling water and the dominance of planktonic production (Wolff, 1994). Nevertheless, in Kuosheng Bay, the rapid turnover rate of phytoplankton fosters continuous transfer to detritus. Thus the food web of the bay was mainly based on the detritus pool.

The cycling of matter and energy is considered an important process in the functioning of natural ecosystems (Odum, 1969). About 96% cycled flows in Kuosheng Bay were associated with the detritus pool. The FCI of Kuosheng Bay was high when compared with those of other coastal systems (Table 5). Like the Tiahura reef (Arias-Gonzalez *et al*., 1997), coral reefs also have a greater fraction of recycled matter. The APL of 4.4 was also higher than those of other coastal systems. The higher conservation of organic matter suggests that Kuosheng Bay was a relatively mature coastal ecosystem.

In conclusion, despite the intake and discharge of large volumes of cooling water, the Kuosheng Bay model shows that the structure and functioning behaved like a typical coastal ecosystems. The fishery loss caused by the power plant through impingement and entrainment was insignificant. The area affected by the coastal power plant might be limited to the plume of hot water and its immediate surroundings, rather than the entire bay. This was reflected by the contour map of water temperature, which showed the plume of hot water was limited to a 500 m radius around the coastal power plant (Hwang *et al*., 2001).

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