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メタデータ	言語: eng 出版者: 公開日: 2010-02-16 キーワード (Ja): キーワード (En): 作成者: ラドル, ケネス, 鄧, 漢増, 梁, 国昭 メールアドレス: 所属:
URL	https://doi.org/10.15021/00004381

Energy Exchanges and the Energy Efficiency of Household Ponds in the Dike-Pond System of the Zhujiang Delta, China

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INTRODUCTION

In the Zhujiang Delta of South China an integrated system of intensive agriculture and polycultural aquaculture has evolved during the past two millenia. In the central delta, south of the city of Guangzhou, and centering on Shunde and adjacent counties, this system now covers an estimated 800 km² and supports some 1.2 million persons. The system is composed of three essential components: fish ponds, mulberry dikes and sugar cane dikes. The individual components of the dike-pond system are tightly linked together by energy and materials cycles: plant and animal wastes feed the fish and fertilize the pond; organically rich mud is dug from the pond bottom and spread three times a year as a fertilizer over the dikes; and throughout the year run-off from the dikes gradually returns the mud to the pond bottom, where its nutrients are restored. Apart from natural processes of dissipation, energy and materials are removed from the system only in such economically useful forms as the fish, silkworm cocoons, sugar cane, vegetables and pigs sent to market [RUDDLE *et al.* 1983; RUDDLE *et al.* n.d.].

The fundamental concept underlying highly intensive, integrated aquaculture-agriculture farming systems is that many outputs of sub-systems become inputs for other sub-systems. Thus in the dike-pond system of the Zhujiang Delta not only are the media for the growth of fish and crops provided but so too is the environment in which their food and fertilizer requirements are produced. This results in higher yields for all commodities produced and a wider range of products than could otherwise be obtained. It also results in lower costs for inputs, which, in the absence of such integration would have to be imported from outside the system.

Gradually, however, this traditional tight recycling within the dike-pond system is being supplemented by an import of energy and materials from outside sources. This is particularly evident in the pond component, where chemical

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prophylactics are replacing those traditionally used, and factory-produced concentrated fish feeds are supplanting sugar refinery waste.

In previous articles the evolution and structure [RUDDLE *et al.* 1983], labor supply and demand [RUDDLE 1985a] and household economics [RUDDLE 1985b] of the dike-pond system of the Zhujiang Delta have been examined. This article offers a preliminary analysis of energy exchange as one of the ecological bases for system integration. Analysis of the energetics also permits evaluation of the efficiency with which individual households utilize the material resources available to them. Such an evaluation is of major importance in understanding the rationality of household decision-making under the independent management introduced by the "household responsibility system" of farming.

To understand how those fundamental processes operate in the dike-pond system of the Zhujiang Delta field experiments were conducted on energy exchange and materials flow. In terms of these processes the dike-pond system is inherently extremely complex, thus for experimental purposes a simplified model was employed. In this model the system was divided into the fish pond and mulberry dike sub-systems, linked by the silkworm sub-system.¹⁾ The inputs and outputs of each sub-system were the focus of the field research.

METHODOLOGY

Biological and physical research concentrated on the quantitative analysis of energy exchange, for which the following parameters were measured from April, 1981 until September, 1983, using standard field techniques:

- (1) Solar radiation, net radiation on the dike and over the pond, reflex radiation and photosynthetically active radiation (PAR) on the dike and beneath the pond surface;
- (2) Air temperature gradients, humidity and wind speed over the dike and pond, pond water temperature at selected levels, dike soil temperature and moisture content at selected levels, and the dike soil heat flux;
- (3) Evaporation from the pond surface, precipitation, interception of rainfall by the mulberry canopy and mulberry stem flow;
- (4) Pond water levels; and
- (5) Primary productivity of the pond, fish production, productivity of mulberry, mulberry detritus fall, and silkworm productivity.

Samples of soil, pond water, pond mud, mulberry parts and silkworm excrement were analysed and their nitrogen and carbon contents measured.

For solar radiation an MS-42 pyranometer (EKO Instruments, Japan) was used to measure global radiation, a LI-190SB quantum sensor (LI-COR, USA)

1) Other types of dikes, such as those planted to sugar cane or vegetables, lack the linking silkworm component.

was used to measure the PAR, and a LI-193SB (LI-COR) underwater spherical quantum sensor was mounted 30 cm below the pond surface to measure underwater PAR. Output of the MS-42 was integrated using an MP-060 integrator (EKO Instruments) and those of the LI-190SB and LI-193SB with two LI-550B integrators (LI-COR), for a period of one hour.

Analysis of the biological and physical characteristics of the system required that a semi-permanent field laboratory be established and that sophisticated instruments be placed on dikes and ponds for three years. Given the nature of dike-pond operations together with a lack of space, inadequacy of electricity supply, relatively poor access and other physical difficulties, it was impractical to build a laboratory in a "typical" village. Further, since the social organization of resource use was undergoing major changes during the time of research there was a risk that particular ponds and dikes could not be monitored continuously for a three-year period.

A permanent two-storey building equipped with a laboratory, instrument recording room, dormitories and living facilities was therefore constructed adjacent to the ponds and dikes to be monitored, in the grounds of the Agricultural Experiment Station of Leliu Commune, Shunde County. This decision had no negative impact on research results since the production dikes and ponds monitored for the project were typical of the area, being used by the Station personnel both for their own sustenance and as a baseline against which to compare experimental results.

Household data are based on interviews conducted with 7 percent of those comprising the First Production Team of the Nanshui Brigade of Leliu Commune, Shunde County. In a previous article dike-pond capitalization and management was analyzed, as was the rate of economic return on labor and emerging differences among households as a consequence of the rural reforms recently implemented in China [RUDDLE 1985b]. As in that article so in this analysis of household energy efficiency emphasis is placed on the fish pond, since this element constitutes the ecological core of the entire dike-pond system. To facilitate comparison with the earlier economic analysis, the parameters of the four household ponds used here are the same as used previously [RUDDLE 1985b].

Annual excrement and urine production rates used to calculate household pond annual loading rates and therefore energy transfers were, for humans, 0-7 yrs, 175 kg; 8-15 yrs, 350 kg; 16+ yrs, 700 kg. The average annual production of excrement and urine per pig was taken as 2.7 t [Unpub. data, Biogas Research Unit, Xinbu Brigade, Leliu Commune].

EMPIRICAL MEASUREMENT OF ENERGY SUPPLY TO THE SYSTEM

Energy passes through the complex food-web of the dike-pond system and undergoes a series of exchanges as it flows among the sub-systems. It forms a

complex flow which is exported in various forms and via various pathways of the system. Some energy exports, such as those stored in silkworm cocoons or in the fish, are of economic value. Others, like losses in the form of radiation, have no economic worth.

As with all ecological systems, solar radiation is the energy source that drives the dike-pond system. This energy enters the system via three pathways:

- (1) Absorption by the dike crops, which convert solar energy into chemical energy during photosynthesis;
- (2) Absorption by phytoplankton in the pond, and conversion to chemical energy via photosynthesis; and
- (3) Direct inputs into the pond of chemical energy stored in plant materials and waste products, used, respectively, as fish feed and pond fertilizer.

The annual global radiation in Leliu Commune is 4.85×10^3 MJ/m².²⁾ The maximum monthly global radiation occurs in August and the minimum in February. The annual PAR is 2.31×10^3 MJ/m², or about 48 percent of the global radiation.³⁾ The annual PAR cycle is almost the same as that of the global radiation (Fig. 1).

(1) ENERGY ABSORPTION BY DIKE CROPS

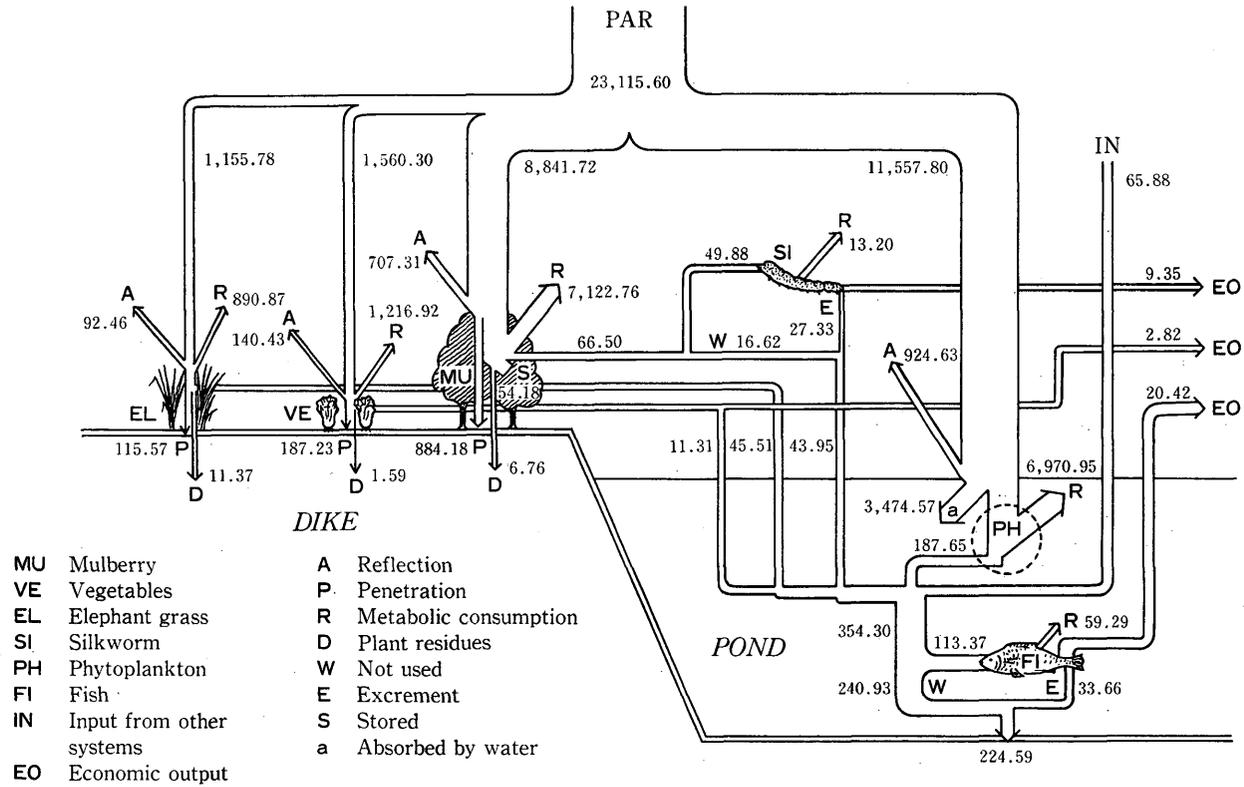
The annual solar radiation reaching the crop canopy is about 48.5×10^6 MJ/ha, of which the PAR accounts for 48 percent (*i.e.*, 23.1×10^6 MJ/ha). During the growing period the PAR intercepted and absorbed by the mulberry canopy is 16.2×10^6 MJ/ha, or about 70 percent of the annual PAR. Thus when mulberry dikes yield leaves at a rate of 30 t/ha/yr, the energy stored in the actual net photosynthesis products is 283.2×10^3 MJ/ha/yr, or 1.75 percent of the PAR absorbed by the canopy during its growth period.

Other crops cultivated are more efficient utiliziers of PAR. On sugar cane dikes yielding at 90 t/ha/yr the radiation converted into chemical energy stored in the actual net products is 628.14×10^3 MJ/ha, or 2.7 percent of PAR; and on dikes yielding Elephant grass at a rate of 187.5 t/ha/yr, the energy stored is about 948×10^3 MJ/ha, or 4.1 percent of PAR.⁴⁾

2) MJ=Million Joules.

3) Of the three main regions into which solar radiation is usually divided, the visible spectrum, from 400–700 nm, plays a fundamental role in photosynthesis. It is therefore designated as Photosynthetically Active Radiation (PAR).

4) The energy utilization efficiency of sugar cane and Elephant grass is higher than that of mulberry, since they are C-4 plants, whereas mulberry is a C-3 plant. The former has a much lower CO₂ compensation point and much lower light saturation than the latter, hence it has a much higher productivity. C-4 plants apparently lack photorespiration when photosynthesising under optimum conditions, thus they have very high rates of CO₂ assimilation compared with most C-3 plants [ETHERINGTON 1982]. The maximum recorded annual yield is 85 t/ha dry matter from Elephant grass in El Salvador and Puerto Rico, where the efficiencies of solar energy utilization were 5.4 and 4.9 percent, respectively [COOPER 1975]. In our case from the Zhujiang Delta the dry matter yield of Elephant grass is about 43 t/ha (*i.e.*, in the middle rank).



After Deng *et al.* [n. d.] and Ruddle *et al.* [n. d.]

Figure 1. Energy Flow in the (Mulberry) Dike-Pond System (10^8 MJ/ha/yr)

(2) ENERGY ABSORPTION BY PHYTOPLANKTON

Phytoplankton is the main producer in the pond, and therefore plays a fundamental role in fish cultivation. It comprises the food for Silver carp, and sustains the zooplankton consumed by other fish, such as the Bighead carp.

The average albedo of the pond is about 8 percent. Thus the annual PAR penetrating the water surface is 21.3×10^6 MJ/ha, of which approximately 67 percent is absorbed by phytoplankton. The net primary production of phytoplankton is about 22.4 t dry matter/ha/yr, in which the energy stored is 375.3×10^3 MJ/ha. The efficiency of PAR utilization is approximately 1.6 percent.

Owing to an abundance of plankton and suspended matter water transparency is only 30–40 cm, therefore the incident irradiance is attenuated rapidly and 30 cm below the water surface PAR is only 0.25×10^3 MJ/m², or 11 percent of that received at the surface. As a result primary productivity is low, because photosynthesis by phytoplankton is restricted to the first 50 cm of the water column.

(3) CHEMICAL ENERGY INPUTS TO THE POND

The silkworm sub-system provides the energy linkage between the mulberry and pond sub-systems. It absorbs energy stored in harvested mulberry leaves, and, since most outputs of silkworm rearing enter the fish pond as a mixture of mulberry leaf waste and silkworm excrement (*cansha*), transmits the energy to the pond. In general, some 75 percent of the mulberry leaves supplied is consumed by the silkworms. Together with silkworm excrement the remaining 25 percent of unconsumed leaf debris is dumped into the pond. When 30 t/ha/yr of mulberry leaves is fed to silkworms 16.2 t of *cansha* is produced, in which the energy stored is 97.65×10^3 MJ, or 66 percent of that supplied to the silkworms.

The fish pond is the most complex component of the entire dike-pond system, since it has the most ramified structure and complex food-web. This is mirrored in a complex pattern of energy flow.

Energy enters the pond along four principal pathways: —

- (1) Via solar energy converted and stored by phytoplankton;
- (2) Via energy stored in the *cansha*;
- (3) Via energy stored in crops used as fish feed; and
- (4) Via energy contained in other feedstuffs and manures.

Total energy input in the control pond is 333.3×10^3 MJ/ha/yr, 106.3×10^3 (31.9 percent) of which is stored in concentrated feeds, 21.3×10^3 (6.4 percent) in pig manure, 99.3×10^3 (29.8 percent) in *cansha* and 106.3×10^3 (31.9 percent) in the green fish feeds. Energy stored in the annual net primary production is another main energy source for fish. The total energy input to the fish is therefore 708.6×10^3 MJ/ha/yr. Of this, 375.6×10^3 (53 percent) is derived from phytoplankton, 106.2×10^3 (15 percent) from green feeds, 99.2×10^3 (14 percent) from *cansha*, 21.3×10^3 (3 percent) from pig manure, and

106.2×10^3 (15 percent) from concentrated feeds.

The energy intake by the fish accounts for only 32 percent of the total energy input to the pond. Some 72 percent of this intake energy is absorbed, and the remainder output with fish excrement and in the process of respiration. The energy stored in an annual total fish yield of 7.5 t/ha is 40.83×10^3 MJ/ha, only about 5.8 percent of the total input.

MODELLING ENERGY FLOW

Based on those observed rates of energy exchange in the control pond a simplified system of energy exchange in the dike-pond system can be modelled. In this model two energy inputs exist, solar energy and that contained in the various feeds which input to the pond energy from other sub-systems. There are two main energy outputs; the aggregate economic output of products and natural losses.

A two-way energy exchange system exists between the dike and the pond. Energy enters the pond via materials grown on the dikes and then fed to the fish, and, in the case of the mulberry dike, via silkworm excrement. This is then returned to the dike in the form of pond mud. However, the energy contained in the mud cannot be utilized directly by the crops.

In this model a 1 ha mulberry dike-pond system is assumed in which 50 percent of the area is dike and 50 percent pond. Of the former, 0.45 ha is planted to mulberry and 10 percent, or 0.05 ha, under Elephant grass. During the winter rest period vegetables are interplanted with the mulberry. The following crop yields are assumed: mulberry leaves 30 t/ha, silkworm cocoons 2.1 t/ha, Elephant grass 225 t/ha and vegetables 3.75 t/ha. It is further assumed that 80 percent of the vegetive matter harvested is used as fish feed and 20 percent consumed by humans. Approximately 16 t of waste is produced per ha of mulberry. It is assumed that all is put into the pond. Finally, the net primary production of phytoplankton is taken as 22 t/ha (dry weight). Thus from these sources the total energy supplied to the pond to produce fish is 288.42×10^3 MJ.

Based on the energy conversion rate of fish (*vide supra*), an additional 65.88×10^3 MJ of energy must be added to the pond in order to harvest 3.75 t of fish from 0.5 ha of ponds. This can be done by adding externally-produced concentrated feeds, and pig excrement from within the system.

The total energy input of 354.3×10^3 MJ required to attain a fish production of 7.5 t/ha/yr is composed of 187.8×10^3 (53.0 percent) from phytoplankton, 43.9×10^3 (12.4 percent) from *cansha*, 56.7×10^3 (16.0 percent) from green feed, 10.9×10^3 (3.1 percent) from pig excrement, and 54.9×10^3 (15.5 percent) from concentrated feeds (Fig. 1). These modelled estimates align closely with those derived from the field analyses (Table 1).

Table 1. Summary of Observed and Modelled Energy Inputs to the Control Pond

Input	Observed		Modelled	
	$\times 10^3$	%	$\times 10^3$	%
Phytoplankton	375.6	53.0	187.8	53.0
Green feeds	106.2	15.0	56.7	16.0
Silkworm waste	99.2	14.0	43.9	12.4
Pig excrement	21.3	3.0	10.9	3.1
Concentrates	106.2	15.0	54.9	15.5

In this system there are 5 principal energy paths:

- (1) PAR \rightarrow Mulberry leaves \rightarrow Silkworms (\rightarrow Cocoons)
 ↓
 (cansha) \rightarrow Fish
- (2) PAR \rightarrow Vegetables
 ↓
 \rightarrow Fish;
- (3) PAR \rightarrow Elephant grass \rightarrow Fish;
- (4) PAR \rightarrow Phytoplankton \rightarrow Fish; and
- (5) Additional fish feed \rightarrow Fish.

The first path flows through all three sub-systems, the second and third through both dike and pond, and the remaining two through only the pond. Both producers and consumers are involved in the first four paths, whereas there are only consumers in the fifth.

The total energy input for this system amounts to $23,181.48 \times 10^3$ MJ/ha/yr, most of which is solar radiation. Energy contained in additional fish feeds

Table 2. Monthly and Annual Solar Radiation at Leliu⁽¹⁾ (MJ/m²)

	JAN.	FEB.	MAR.	APR.	MAY	JUN.	
Q	378.14	224.87	300.67	347.99	430.07	492.04	
PAR	169.63	103.45	139.90	166.70	211.51	239.58	
PAR _w	14.66	11.73	26.38	17.17	22.61	22.19	
	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.	ANNUAL
Q	537.69	579.56	469.43	411.64	306.53	367.67	4846.30
PAR	266.38	287.73	229.52	194.76	141.57	160.83	2311.56
PAR _w	27.64	28.48	23.03	16.33	17.59	16.75	244.56

Table Notes:

(1) Average of 1981 and 1982.

MJ=Million Joules.

Q=Global Radiation.

PAR=Photosynthetically Active Radiation.

PAR_w=PAR measured in pond water at 30 cm depth.

Table 3. Energy Budget of Primary Production in the (Mulberry) Dike-Pond System (10^3 /MJ/ha/yr)

Input		Output
PAR INPUT		
Fish pond	13, 557. 80	
Mulberry	8, 841. 72	
Vegetables	1, 560. 30	
Elephant Grass	1, 560. 30	
NET PRIMARY PRODUCTION		
Phytoplankton		184. 65
Mulberry		127. 44
Vegetables		15. 72
Elephant Grass		56. 88
ENERGY LOSS		
Radiation		6, 526. 41
Heat		16, 204. 5
TOTALS	23, 115. 60	23, 115. 60

derived from other sub-systems accounts for only 0.28 percent of the total.

The annual total PAR is $23,115.60 \times 10^3$ MJ/ha, 50 percent of which reaches the pond surface, 38.25 percent the top of the mulberry canopy, and 6.75 percent and 5.0 percent the vegetable and Elephant grass canopies, respectively (Table 2). As a result of reflectance from the pond water surface and from crop canopies, of penetration through the canopies, and of absorption by both the pond water and the particles suspended within it, the PAR absorbed by the main producers on the dike and in the pond (*i.e.*, mulberry, vegetables, Elephant grass and phytoplankton) amounts to $16,589.20 \times 10^3$ MJ/ha.

Owing to biological and environmental limiting factors, as well as to the physiological requirements of the producers, nearly 98 percent of the PAR is dissipated as heat. Energy converted in the photosynthesis process and fixed in the net primary products is 387.69×10^3 MJ/ha. Of this, 48.4 percent is produced by phytoplankton, 32.87 percent by mulberry, 4.06 percent by vegetables and 14.67 percent by Elephant grass (Table 3). The efficiency of solar energy (PAR) utilization is therefore only 1.86 percent.

Of that net primary energy production, 0.73 percent is output for direct human use, 80.2 percent is supplied to the main consumers within the system, 13.98 percent is stored in the living parts of the mulberry, and 5.09 percent enters the soil via detritus fall and stubble.

When silkworm and fish, the two main consumers of the system, are combined the total energy input for secondary production amounts to 376.85×10^3 MJ/ha, of which 17.65 percent is supplied to silkworms and 82.35 percent

Table 4. Energy Budget of Secondary Production in the (Mulberry) Dike-Pond System (10^8 MJ/ha/yr)

Input		Output	Stored
INTAKE ENERGY			
Mulberry Leaves	66.50		
Fish Feed and Manures	310.35		
ECONOMIC ENERGY			
Silkworm Cocoons		9.35	
Fish		20.42	
LOST ENERGY			
Metabolism		72.49	
Decomposition		132.90	
STORED ENERGY			
Pond Mud			141.69
TOTALS	376.85	235.16	141.69

to fish. Most is derived from within the system itself (*i.e.*, from net primary production), but 17.5 percent is input from outside (Table 4).

Energy contained in silkworm waste is not included within the energy supply, since it flows only between the consumers. The total energy stored in the second-

Table 5. Total Energy Budget of the Mulberry Dike-Pond System (10^8 MJ/ha/yr)

Input		Output	Stored
ENERGY INPUT			
PAR	23,115.60		
Feeds and Manures	65.88		
ECONOMIC ENERGY			
Silkworm Cocoons		9.35	
Fish		20.42	
Vegetables		2.82	
LOST ENERGY			
Radiation		6,526.41	
Metabolism		16,273.99	
Decomposition		132.90	
STORED ENERGY			
Mulberry root and stem			54.18
Detritus Fall			19.72
Pond mud			141.69
TOTALS	23,181.48	22,965.89	215.59

dary economic products equals 29.77×10^3 MJ/ha, of which 31.4 percent is from cocoons and 68.6 percent from fish (Table 4). Thus the total secondary economic energy utilization efficiency is 7.9 percent, a much higher figure than for primary production.

The energy contained in silkworm waste is not dissipated because it is re-used by the fish. Unconsumed fish feed and fish excrement reach the pond bottom and combine with the sediments. There, through a series of biochemical and chemical processes, part of the energy contained in the sediments is released with various gases, and the remainder stored in the mud, which is then periodically returned to the dikes as fertilizer. This feedback accounts for 37.6 percent of the total secondary energy input. But it cannot be utilized by plants directly. The energy dissipated as heat during the metabolic processes of the consumers accounts for 54.5 percent.

Thus of the total energy input to the dike-pond system 28.15 percent is lost as radiation together with 70.78 as heat and with gases, and 0.93 percent is retained in the living parts of the crops, dike soil and pond mud. Only 0.14 percent is output in the form of economically useful products (Table 5). The economic energy output is 32.58×10^3 MJ/ha/yr, of which fish accounts for 62.66 percent, cocoons for 28.68 percent and vegetables for 8.66 percent.

THE ENERGY EFFICIENCY OF HOUSEHOLD PONDS

The efficiency with which pond inputs and phytoplankton are converted to fish in ponds contracted by individual households can be compared in energy terms (Table 6). For this purpose the research station pond in which field observations of energy exchanges were made is used as a control that represents standard pond management practises employed in the region under the former collectivist system of resource management. Variations from this standard level manifested by the ponds of the individual households, which are now free

Table 6. Energy Conversions in Fish Ponds for the Four Households and the Control Pond

	A		B		C		D Total A+B+C	E Output	Conversion Rate			
	Excrements		Green Feeds		Concentrates				10 ³ MJ/ha	10 ³ MJ/ha	D:E	A:E
	10 ³ MJ/ha	A/D %	10 ³ MJ/ha	B/D %	10 ³ MJ/ha	C/D %						
HH 1	340.23	38.6	535.95	60.9	4.29	0.5	880.47	41.22	21.4:1	8.3:1	13.0:1	0.1:1
HH 2	366.25	48.2	253.35	33.3	140.41	18.5	760.01	41.22	18.4:1	8.9:1	6.2:1	3.4:1
HH 3	562.47	68.1	102.10	12.4	160.60	19.5	825.17	38.39	21.5:1	14.7:1	2.7:1	4.2:1
HH 4	185.34	61.7	114.83	38.3	—	—	300.17	28.86	10.4:1	6.4:1	4.0:1	—
CP	120.66	36.2	106.32	31.9	106.32	31.9	333.30	40.83	8.2:1	3.0:1	2.6:1	2.6:1

Note: HH=Household; CP=Control Pond.

Table 7. Supply of Inputs to Household Fish Ponds

Input	Extrapolated Application Rate (t/ha/yr)	Actual Application Rates						Recommended Rates	
		Produced by Household			Supplied Externally			t/ha/yr	Actual
		(t)	(\$)	(%)	(t)	(\$)	(%)		
HOUSEHOLD 1									
A: EXCREMENTS									
Pig	151.50	42.00	127.92	84.0	8.00	24.36	16.0	} 65.0	21.4
Human	10.60	1.84	24.24	52.5	1.66	21.94	47.5		
B: GREEN FEEDS									
Elephant grass	7.58	2.50	50.76	100.0	0.00	0.00	0.0	} 52.5	17.3
Kitchen and field waste	13.60	2.25	0.76	50.0	2.25	0.76	50.0		
Sugar cane waste	60.60	0.00	0.00	0.0	20.00	253.80	100.0		
C: CONCENTRATES									
Concentrates	0.27	0.00	0.00	0.0	0.09	13.70	100.0	6.3	2.1
HOUSEHOLD 2									
A: EXCREMENTS									
Pig	113.60	22.50	101.52	100.0	0.00	0.00	0.0	} 51.6	10.2
Human	25.60	5.07	66.98	100.0	0.00	0.00	0.0		
Silkworm	8.30	1.66	42.26	100.0	0.00	0.00	0.0		
B: GREEN FEEDS									
Elephant grass	12.60	2.50	50.76	100.0	0.00	0.00	0.0	12.6	2.4
Sugar cane waste	25.20	0.00	0.00	0.0	5.00	50.76	100.0	4.2	0.8
C: CONCENTRATES									
Concentrates	8.83	0.00	0.00	0.0	1.75	507.61	100.0	6.7	1.3

		HOUSEHOLD 3								
A: EXCREMENTS										
Pig	229.50	22.72	45.68	100.0	0.00	0.00	0.0	}	59.6	5.9
Human	30.10	2.98	39.26	100.0	0.00	0.00	0.0			
B: GREEN FEEDS										
Elephant grass	25.25	2.50	50.76	100.0	0.00	0.00	0.0		25.2	2.4
C: CONCENTRATES										
Concentrates	10.10	0.00	0.00	0.0	1.00	152.28	100.0		6.7	0.6
		HOUSEHOLD 4								
A: EXCREMENTS										
Pig	34.09	4.50	13.71	100.0	0.00	0.00	0.0	}	45.6	6.0
Human	34.84	4.60	61.04	100.0	0.00	0.00	0.0			
B: GREEN FEEDS										
Elephant grass	28.40	3.75	76.14	100.0	0.00	0.00	0.0		28.4	3.7
C: CONCENTRATES										
Concentrates	0.0	0.0	0.0	0.0	0.00	0.00	0.0		6.8	0.9

to select rates and types of inputs [RUDDLE 1985 a and b], are thus a reflection of the individual household's perception of the relative value of different pond inputs in fish production, or of the inputs available to the household or that can be afforded by it.

In this analysis the same four households (HHs1-4) examined in previous articles [RUDDLE 1985 a and b] are again used. Each household pond is of a different size (0.33, 0.198, 0.099 and 0.132 ha for HHs 1-4, respectively), thus all measurements of inputs and outputs have been extrapolated to t/ha.

For this analysis pond inputs have been simplified [*cf.* RUDDLE 1985b] (Table 7) and household pond energy efficiency is measured by the equation: Fish Yield (FY)=Phytoplankton (P)+Excrements (E)+Green Feed (GF)+Concentrated Feed (CF), in which the energy values are: $P=9.4 \times 10^3$ MJ/t, $E=2.1 \times 10^3$ MJ/t, $GF=6.0 \times 10^3$ MJ/t, $CF=15.9 \times 10^3$ MJ/t. For simplification "excrements" includes human, pig and silkworm waste (*cansha*); "green feeds" includes Elephant grass, kitchen and field waste, and sugar cane waste.

The ponds of all four households are less efficient energy converters than is the control pond. In the latter a total of 333.3×10^3 MJ/ha/yr of a balanced mixture of inputs (36.2 percent excrements, 31.9 percent green feeds and 31.9 percent concentrated feed) yielded 40.83×10^3 MJ/ha of fish. This represents an energy conversion ratio of 8.2 : 1.

The best household pond energy conversion ratio was attained by that of HH 4, at 10.4 : 1, which compares well with the control pond figure. With a total energy input of 300.17×10^3 MJ/ha/yr, this pond yielded 28.86×10^3 MJ/ha of fish. It is noteworthy that this is the most traditionally managed of the four ponds examined, in that the inputs are excrements and green feeds only. No concentrated feed is applied.

In contrast all three remaining ponds achieved poor energy conversion ratios, at 18.4, 21.4 and 21.5 for HHs 1-3, respectively. Whereas in the control pond 1 t/ha of fish can be produced with a total energy input of 44.4×10^3 MJ/ha, and in that of HH 4 56.6×10^3 MJ/ha are needed, the three remaining ponds perform poorly. In the ponds of HHs 1-3, 116.3, 100.4 and $117.0 (\times 10^3$ MJ/ha) are required, respectively, to produce 1 t/ha of fish.

Thus a considerable amount of the energy input to the householders' ponds is not required for fish production. In addition to being wasted, this unnecessarily excessive input of material may, by raising BOD levels, inhibit fish production by reducing levels of dissolved oxygen.

In the ponds of all four households in excess of 80 percent of the energy input is derived from the traditionally used excrements and green feeds. However, the relative percentages of these components vary among households from 38.6 to 68.1 percent for excrements and from 12.4 to 60.9 percent for green feeds. On the other hand, reflecting its recent availability, expense, and

general lack of familiarity to local farmers, is the relatively little use still made of concentrated feeds. None is used by HH4, it constitutes only 0.5 percent of the energy input to the pond of HH1, and slightly under 20 percent in the two others. In no household pond does the rate of concentrate use approach that of the control pond, in which it comprises 31.9 percent of the total energy input.

IMPROVING THE ENERGY EFFICIENCY OF HOUSEHOLD PONDS

In the pond operated by HH1, for example, present input rates create an excess energy loading of 547.1×10^3 MJ/ha over the rate required to produce fish at 1 t/ha in the control pond. By a reduction of that portion of the excrement and green feed loading accounted for by purchased inputs (Table 7), excrement loading could be lowered by 18 percent and green feed loading by 83 percent. This would reduce energy loading of excrement origin to 278.99×10^3 MJ/ha (*i.e.*, by 61.24×10^3 MJ/ha) and that from green feed sources to 91.11×10^3 MJ/ha (*i.e.*, by 444.84×10^3 MJ/ha). This would give a total energy reduction of 506.08×10^3 MJ/ha, for a total input of 374.39×10^3 MJ/ha. This loading is still 41.09×10^3 MJ/ha in excess of that in the control pond.

By this simple remedial action alone a total of 97.1 t/ha (29.2 of excrements and 67.9 of green feeds) of inputs could be eliminated, as could a total cash expenditure of 911 \$(U.S.)/ha (Table 8). However, excrement loading would remain excessive in this pond. This could be further reduced by introducing household supplied excrements to the pond at a rate of 65 t/ha, and selling the remainder (about the same rate) to other users. This would then give an energy loading of excrement origin of approximately 136.5×10^3 MJ/ha.

Were this action to be taken an energy deficit of 101.4×10^3 MJ/ha would

Table 8. Purchase Price of Pond Inputs, Shunde County (Aug., 1983)

Input	Price (\$ [U.S.]/t)
A: EXCREMENTS	
Pig	3.05
Human	13.02
Silkworm	41.00
B: GREEN FEEDS	
Elephant grass	20.30
Sugar cane waste	12.69
Household waste ⁽¹⁾	2.00
C: CONCENTRATES⁽²⁾	152.28 (284.26)

Table Notes;

⁽¹⁾ Category includes kitchen and field vegetable waste.

⁽²⁾ Prices for blended concentrate produced by the factory in Leliu Town. Free market price given in parentheses.

be created. This could be compensated for by the supply of 6.37 t/ha of concentrated feed (which supplies energy at the rate of 15.9×10^3 MJ/ha/t) for a public price of 970 \$ or a "private" price of 1810.73 \$.

Assuming that this additional input of concentrated feed could be obtained at the public price of 152.28 \$/t (Aug., 1983) then the switch in pond energy sources could be made with virtually no difference to the household economy. Further, given the dramatic improvements in pond water quality that would result from this change in inputs, fish yields would increase, thereby providing a greater return on labor and operating capital than is experienced at present.

At 760.01×10^3 MJ/ha, the energy loading of the pond operated by HH 2 exceeds that of the control pond by 426.71×10^3 MJ/ha. Levels of all categories are greater than those of the control pond. Apart from concentrates and the sugar cane waste component of green feeds, all inputs are generated within the family holding.

The rate of excrement loading can be reduced to 35 percent of its present level, *i.e.*, from 147.5 t/ha to 51.6 t/ha. This would reduce energy loading from excrements to 128.19×10^3 MJ/ha from the present 366.25×10^3 MJ/ha. Assuming that the less expensive pig excrement were used to satisfy household pond requirements, the sale of 25.6 t of human excrement, 62 t of pig excrement and 8.3 t of *cansha* would yield an extra cash income of 862.7 \$(U.S.). Green feed loading could be reduced by 55 percent by the elimination of almost 21 t/ha of sugar cane waste. This would reduce the energy loading from this source to 114.01×10^3 MJ/ha, and would reduce the cash outlay on green feeds by almost 256 \$ (*i.e.*, from 319.78 \$ to 63.45 \$).

Concentrates are being loaded at a rate of 8.83 t/ha, giving an energy loading about 34×10^3 MJ/ha above that of the control pond. Concentrate input could therefore be reduced by some 24 percent to give an energy loading of 106.72×10^3 MJ/ha. In other words, the rate of concentrate loading can be reduced by 2.11 t/ha to 6.72 t/ha. This would result in a saving on present cash outlays of 321.3 \$, if the concentrates were purchased at the controlled public price, or \$600 if they were bought on the free market.

In that way, and using the same inputs, an energy loading of 348.92×10^3 MJ/ha—still slightly above that of the control pond—can be achieved. This will result in three major benefits for HH 2: —

- (i) Bring in a cash income of 862.7 \$/ha on the sale of excrements hitherto put into the pond;
- (ii) Reduce the actual cash outlay for purchased inputs by 577.3–856 \$/ha, depending on the purchase price of the concentrates; and
- (iii) By reducing BOD loading, enhancing DO levels and improving water transparency (and hence phytoplankton productivity) will increase fish yields, thus producing a greater cash income on fish sales.

The pond operated by HH 3 receives an energy loading 491.87×10^3 MJ/ha

in excess of that of the control pond. This overloading is largely the result of the excessive input of excrements; the pond operated by HH 3 being loaded with 4.66 times more excrement than the control pond. The excrement loading in this pond can be reduced by a rate of 200 t/ha (to 59.6 t/ha). This would reduce the energy loading by 432×10^3 MJ/ha, to 130.47×10^3 MJ/ha.

Were the excrement loading of the pond satisfied from pig excrement produced on the farm unit, all the human excrement of the household could be sold to other users, instead of being input to the household pond. This would produce a cash income of 391.9 \$/ha, and the 169.9 t/ha of surplus pig excrement would yield a further 518.2 \$/ha. Thus an additional cash income at the rate of 910.1 \$/ha could be generated by a reduction of excrement loading.

Fifty percent more concentrated feed than is necessary is also loaded into this pond. Loadings could be reduced to 6.74 t/ha, thereby lowering energy inputs by 53.42×10^3 MJ/ha, to 107.18×10^3 MJ/ha, or almost equal to that of the control pond. This would result in savings on cash outlays of 511.6–955.1 \$/ha, at no loss in fish productivity. Green feeds are input to this pond (just Elephant grass) at a rate marginally below that of the control pond.

Were those modifications to be made to the input rates for this pond, total energy input would fall to 339.75×10^3 MJ/ha, or slightly in excess of that of the control pond. In addition, a cash income of 910.1 \$/ha that is now foregone would be generated by the sale of excess excrements, and 511.6–955.1 \$/ha would be saved on present cash outlays for concentrates. By modifying its pond energy loading thus, this household could reap an additional profit of 1421.7–1865.2 \$/ha, without considering the further profit that would accrue from increased fish yields.

In complete contrast to the ponds operated by the other three households, the inputs made into the pond operated by HH 4 load less energy than do those made to the control pond. This slight deficit, of 33.13×10^3 MJ/ha below the control pond, occurs because no concentrated feeds are used in the pond of HH 4. All inputs (two excrements and Elephant grass) are generated on the farm unit. Excrements are loaded at a rate some 33 percent greater than in the control pond. Excrement loadings could be reduced by one third, and 23 t/ha of human excrement sold at 13.02 \$/t to raise 299.46 \$ for the purchase of almost 2 t of concentrates at the public sale price.

The input of 2 t of concentrated feed would provide 31.8×10^3 MJ/ha to the pond. This would reduce the energy input to 256.83×10^3 MJ/ha, a deficit of 76.47×10^3 MJ/ha, or just over double the existing deficit. This could be made up by the purchase of a further 4.8 t/ha of concentrates, to provide a total of 108.27×10^3 MJ/ha (which aligns closely with the control pond) of energy derived from this source. However, the purchase price of an extra 4.8 t/ha of concentrates would be 730.9 \$/ha at the controlled public price and 1364.4 \$/ha at the free market price.

Thus in the case of the pond operated by HH 4 it is difficult to suggest that the energy sources be better balanced and brought into closer alignment with those of the control pond. Such a modification could only be justified if improvements to water quality caused by the addition of concentrates would raise the fish yield sufficiently to cover the cost of the additional 4.8 t/ha of concentrates.

Since this pond has the most efficient energy conversion rate of all four household ponds examined, and because all inputs made to it are generated from within the farm unit, at only an opportunity cost, it is tempting to recommend that this operation not be tampered with. There is, after all, far less justification for doing so than in the case of the other three households' ponds.

THE IMPACT OF MODIFIED ENERGY INPUTS ON HOUSEHOLD ECONOMIES

An analysis of the impact of modified pond energy inputs on household economies can be made by converting the extrapolated rates of recommended changes to actual rates, by the factor of pond area (*vide supra*).

Thus in HH 1 if the cash expenditures of \$300.8 for the purchase of excrements and green feeds is eliminated, and \$65.3 generated by the sale of excess household supplied excrements, an additional working capital of \$366.1 will become available for the purchase of concentrates. This new purchase would require the outlay of \$320. Were the recommended changes made in the management of this pond a direct benefit would be the addition of \$46.1 to the household income. Total income would increase marginally by 3 percent [*cf.* RUDDLE 1985b]. Although only a marginal increase in income can be predicted from the changes made in energy inputs, income should be further boosted by increased fish yields resulting from improved pond water quality as a consequence of the change in inputs.

Similarly, in HH 2 if excessive energy loading is reduced cash outlays for purchased inputs could be reduced by \$50.7 for green feeds and to either \$63.6 or to \$118.8 (depending on the purchase price) for concentrates. In addition, \$170.8 could be raised by the sale of excrements produced by the household. This would add \$285-340 to the household income, an increase of some 10 percent [*cf.* RUDDLE 1985b].

In HH3 the sale of surplus excrements generated by the household would yield an additional income of \$90, and a reduction in the amount of concentrates purchased would reduce that expense by \$50.6-94.5. In this way there would be an addition of \$140.6-184.5, or 9-12 percent, to this household's income of \$1519.5 [*cf.* RUDDLE 1985b].

HH4 could generate \$39.5 by the sale of surplus excrements. It would then have to spend \$136.7-255.15 on the purchase of concentrates, *i.e.*, a loss of \$97.2-215.6 on the switch in inputs. In the case of this household were the

proposed modifications made to pond inputs, income would actually decrease by 4–9 percent [*cf.* RUDDLE 1985b], depending on the price at which concentrates could be purchased. If they could be obtained at the lower, public price then the slight reduction in income could easily be compensated by the sale of increased fish yields. At the higher, private price, however, that would not be so certain easily assured.

CONCLUSION

There remain, however, several limitations to the scenario analyzed here. In summary, these are the regular and sufficient supply of concentrated feed to local pond operators from the newly opened factory in Leliu Commune; the adoption of concentrated feeds as a consequence of repeated and successful demonstration effects; a continued market for household produced and surplus excrements that would absorb these surpluses as they continued to increase with the wider adoption of concentrates; the ability to divert sugar cane waste to other productive industrial uses (*e.g.*, pelletized feeds); and the industrial use of *cansha*, among others.

The ripple effects of inducing thousands of pond contracting households to modify energy inputs to the dike-pond system are not without solution at the higher spatial levels. However, persuading the Cantonese peasant to forego the time-honored use of easily and locally available and assured pond inputs, and to replace them with those from a less certain and externally widely dependent source will be far less simple.

ACKNOWLEDGEMENTS

The field research on which this article is based forms part of a much broader study of the human ecology of the dike-pond system of the Zhujiang Delta undertaken from January, 1980 until December, 1983. The entire research project was conducted under the joint financial sponsorship of the United Nations University, Tokyo, and the Chinese Academy of Sciences, through the Guangzhou Institute of Geography. It constituted one component of the project on water-land interactive systems conducted by the former Programme on the Use and Management of Natural Resources of the U. N. University, and co-ordinated by the first author.

For the research on energy exchanges we are particularly indebted to the kindness of Mr. Pan Zhenbiao, Head of the Leliu Commune Agricultural Experiment Station, for permitting us to construct a large, permanent research facility in his station, and to set up instruments and lay electrical cables throughout the station. We are also grateful to those householders of the First Production Team of the Nanshui Brigade who provided detailed data on inputs made to their own ponds.

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中国，珠江デルタの家族経営養魚池における エネルギー循環とエネルギー効率

ラドル・ケネス，鄧 漢 增，梁 国 昭

本論文は華南，珠江デルタにおける養魚システムでのエネルギー利用効率を，個人管理で家事労働によって経営されている養魚池と，実験的にコントロールした養魚池とで比較，検討したものである。すなわち，1981年4月から1983年9月にわたって実験養魚池において実施した太陽エネルギー，光合成 (PAR)，その他のパラメーターの測定にもとづき，養魚システムでのエネルギー循環とそれに関する労力および資本投下についての分析をおこなったものである。

調査のおこなわれた，すべての家族経営の養魚池において，実験養魚池に比較するとエネルギー利用効率において劣る，という結論が導かれた。実験養魚池においては排世物，植物性飼料，濃縮飼料のインプットが年間， 333.3×10^3 MJ/ha で， 40.83×10^3 の漁獲が得られ，

エネルギー転換率は 8.2 : 1 である。最も効率のよい家族経営養魚池においても、1 t/ha の漁獲にたいして、 56.6×10^3 MJ/ha のインプットを必要とし、エネルギー転換率は 10.4 : 1 である。他の養魚池においては、1 t/ha の漁獲のために、おのおの 116.3, 100.4, 117.0 ($\times 10^3$) のインプットがなされている。

この結果にもとづき、家族経営養魚池におけるエネルギー効率の改善勧告を関係当局におこなった。養魚池にたいするエネルギーのインプット率を変えるだけで世帯あたりの現金収入が 4-12% 増加するばかりではなく、そのことにより養魚池内の有機分の減少にともなう水質改善がおこなわれ、漁獲の増加が見こまれるからである。

ABSTRACT

This article examines the use of energy within the dike-pond system of the Zhujiang Delta, South China, and compares the efficiency of a control fish pond with that of a sample of individual, household fish ponds. Based on the measurement of solar radiation, photosynthetically active radiation (PAR) and other relevant parameters over a control dike-pond system, from April, 1981 to September, 1983, the energy budget of the dike-pond system and energy exchanges within it were analyzed. A simplified model of the energy paths within the system was then constructed from those empirical observations. The energy inputs to four typical household ponds were then evaluated against the control pond and the model.

All household ponds examined were less efficient energy converters than the control pond. In the latter a total of 333.3×10^3 MJ/ha/yr of inputs (excrements, green feeds and concentrated feed) yield 40.83×10^3 of fish; *i.e.*, a conversion ratio of 8.2 : 1. In comparison, the best household energy conversion ratio is 10.4 : 1, in which 56.6×10^3 MJ/ha are needed to produce 1 t/ha of fish. In the other ponds analyzed 116.3, 100.4 and 117.0 ($\times 10^3$) are required to produce 1 t/ha of fish.

Recommendations are made for the improvement of the energy conversion efficiency of household ponds. If implemented, this would immediately increase household cash incomes by 4-12 percent, as a result of changed rates of energy inputs. An additional benefit, not measured here, is the increased fish yield from improved pond water quality with a reduced organic loading.