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MULTIPLE USE SYSTEMS FOR AQUACULTURE

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Abstract.— Two recirculating aquaculture systems were constructed using a sequence of five tanks each. Each system contained two plant species, duckweed (*Lemna minor*) and chinese water chestnut (*Eleocharis dulcis*); two fish species, channel catfish (*Ictalurus punctatus*) and tilapia (*Tilapia aurea*); and a freshwater prawn (*Macrobrachium rosenbergii*). Duckweed production during the 132-day experiment reached as high as 87.2 tons/hectare/year (t/ha/yr). Water chestnut production was not successful in the restricted light situation of the lab, but in an outdoor test planting, corn production was 37.2 t/ha/yr. Four feeding trials were attempted using the following percent of fish body weight: 2.5% commercial feed; 5% wet duckweed; 15% wet duckweed; and 15% wet duckweed with 1% commercial feed. Feed to flesh conversion ratios averaged 1.97:1 for the three control tanks and 1.44:1 overall for the treatment tank. The fish-fed duckweed and commercial feed grew as well or better than those fed commercial food alone.

Malnutrition is a serious problem, especially in the developing nations (Mayer 1976). In the United States, annual food production continues to increase despite large losses of prime farmland each year (Jorling 1978). According to Chapman (1969), the biggest problem is not one of food availability, but the lack of protein. Fish and related foods are being developed as alternate protein supplies that can be produced at reasonable prices. There is a great potential for aquaculture in the Great Basin area that includes the multiple use systems, one of which is described in this article.

Approximately 6.4 kg (14 lbs) of fish per capita are consumed annually in the U.S. (USDA 1980). In 1979, over half of this was imported (Holden 1978) at a cost of over $3 billion, according to USDA statistics. Fish is an excellent protein source that is low in fatty acids and under optimal conditions can be produced at costs competitive with other animal products (Ray 1981).

Successful culture of warm water fish requires a constant supply of warm water of approximately 27 C (Caulton 1978, USDA 1973). Most warm water aquaculture in this country is in the south and southeast because of near subtropical weather and abundant surface waters (Flemming 1978, Landreneau 1981, USDA 1973). However, other regions have potential for warm water aquaculture systems if alternate energy sources for heating the water—such as waste heat from coal-fired electrical generation, geothermal water, and solar concentrators—could be used. This could increase the nation's production of fish products and would place the fish closer to the market, thus cutting transportation costs.

The objective of this study was to develop a multiple-use approach to warm water aquaculture involving two species of warm water fish, channel catfish (*Ictalurus punctatus*), and tilapia (*Tilapia aurea*); two species of aquatic plant, duckweed (*Lemna minor*) and chinese water chestnut (*Eleocharis dulcis*); and a freshwater prawn (*Macrobracium rosenbergii*). These species were chosen because of their reported compatibility, high productivity, and marketability (Dunseth 1977, Suffern 1980). The goals for the project were to monitor productivity, water quality, and test feeding of duckweed to catfish and tilapia. A brief description of each of the plant and animal species follows.

Channel catfish was well known as a food fish in the United States. They tolerate a wide range of dissolved oxygen and temperature levels, grow well on artificial feeds, and tolerate crowded conditions associated with intensive culture. Diseases such as *Ichthyopthirius* ("Ich") can cause severe problems if

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preventative measures are not taken. Due to propagation techniques, large numbers of fingerlings can be produced. Flesh quality and good public image are responsible for their marketability (USDA 1973). Channel catfish are bottom-feeding omnivores that can reach marketable size of 454 g (1 lb) in 8 to 10 months at 27 C (Brown 1977). One farm in Buhl, Idaho, produces up to 4.5 t/ha/yr (2 t/a/yr) at a 2:1 feed conversion ratio (Ray 1981). Other farms have reached feed conversion ratios as low as 1.3 to 1.5:1 (Brown 1977).

Tilapia are virtually unknown to the United States consumer. In the Far East, Africa, and the Middle East they have been cultured for thousands of years. Tilapia are intolerant to temperatures below 9–15 C (Suffern 1980). They feed low on the food web, eating mostly aquatic macrophytes (Caulton 1978). They also feed on waste products of other aquatic and terrestrial animals (Infanger 1976, Melarney and Todd 1977, Moav et al. 1977, Rumsey et al. 1981). Except for temperature tolerance, tilapia is a hardy species. They have been known to withstand oxygen levels as low as 1 mg/l and salinity as high as 72,000 mg/l (Balarin 1979). At 100 g tilapia become reproductively active with resultant decreased weight gain. To avoid this, hybrid crosses and hormone treatments that result in mostly male offspring have been developed (Shelfon et al. 1978). High-density stocking seems to disrupt social behavior that can slow or stop reproduction (Suffern 1980). Marketable size of 200 to 900 g (0.5 to 2 lbs) can be reached in 12 to 18 months (Lauenstein 1978). Experiments at Oak Ridge, Tennessee, have shown an estimated 56 t/ha/yr can be produced in aerated sewage. Feed conversion for tilapia has been reported at 1.3 to 1.5:1 (Collis and Smitherman 1978, Lauenstein 1978). Test marketing shows this fish has excellent taste and a demand for its meat can be developed (Dunseth 1977).

Duckweed occurs in still or slightly moving waters. Flourishing growth is frequently found in stagnant small ponds or ditches rich in organic matter (Hillman 1961). Duckweed reproduces vegetatively by rapid clonal growth. Under proper conditions, weight can double every 2 to 4 days (Harvey and Fox 1973, Rusoff et al. 1980). Duckweed growth is 2 to 20 times faster than the fastest growing terrestrial plants. Their fronds do not form a complex structure but instead break into colonies. There is a total absence of woody tissue (Hillman and Culley 1978).

Production of duckweed has been reported to reach levels of 20 t/ha/yr (1488 lbs/a/mo) dry weight in some experiments (Said et al. 1979) and as high as 33.6 t/ha/yr (2500 lbs/a/mo) in others (Culley and Epps 1973). In comparison, alfalfa production for 1979 in the United States averaged 7.13 t/ha/yr (3.18 t/a/yr) dry weight (USDA 1980). Crude protein content of alfalfa is around 16% (Hillman and Culley 1978)—duckweed ranges between 20% and 40% (Culley and Epps 1973, Rusoff et al. 1980). In one test duckweed produced more than twice as much protein/ha as the best alfalfa pasture and 10 times as much as soybeans (Walsh and Palmer 1979).

According to Rusoff, Blackeney, and Culley (1980), duckweed protein has potential as a food supplement for animals and they project it could be used as a dietary supplement for man. They found the essential amino acid content of duckweed protein met FAO standards except for methionine. Hillman and Culley (1978) reported that dairy cows will accept up to 75% of the total dry weight of their feed as duckweed with no ill effects.

The chinese water chestnut is a sedge, family Cyperaceae. It grows to a height of five feet and reproduces through rhizomes and corms. Corms are widely used in Chinese cooking. Corms 25–30 mm in diameter are most useful for sale while smaller, and larger corms are used for propagation or animal feed (Squires 1979). Tops can be used as an animal's food supplement. In ponds at Clemson University, chinese water chestnut corms are produced at a rate of 4,664 kg/ha/yr (2.08 t/a/yr) (McCord and Loyacano 1978). These ponds had lower levels of NO_3 and NH_4-Nitrogen than those without water chestnuts. Effectiveness of nutrient removal by aquatic plants is affirmed by Boyd (1970).

Disadvantages to water chestnut and duckweed production are cost of harvest and removal of water from plant tissue. Duckweed contains as much as 95% water (Rusoff et al.

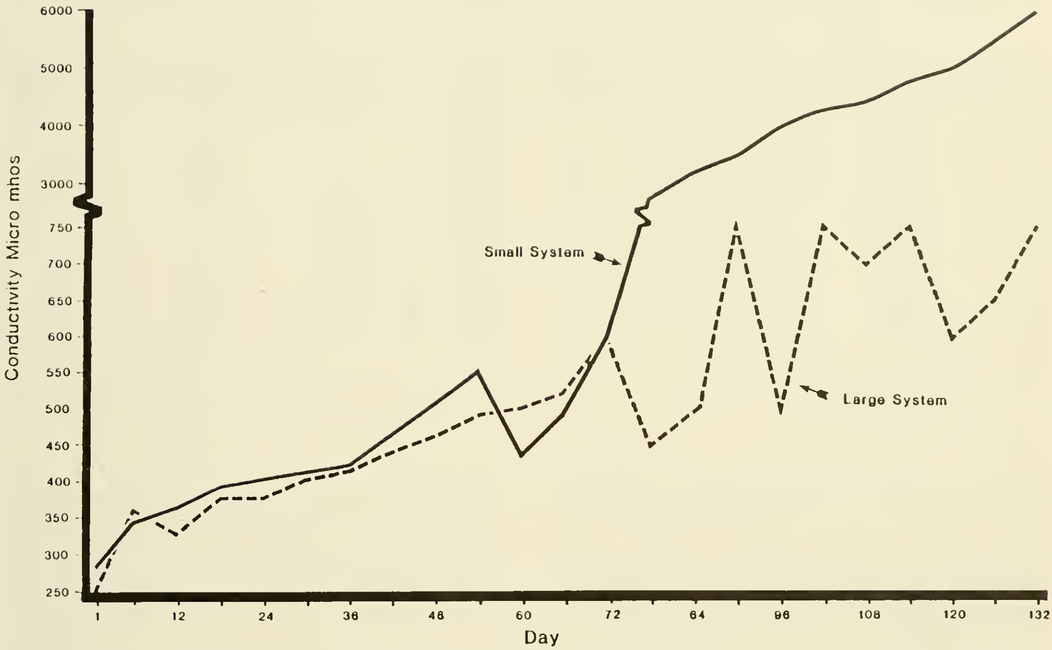


Fig. 1. System design, capacity, and directions of water flow.

1980). Koegel, Livermore, and Bruhn (1975) found that harvesting rooted aquatic plants costs \$60–\$94 per acre, which is higher than expected for duckweed, which could be skimmed off the surface (Culley and Epps 1973). Plants can be dried by various methods, including sun drying and oven drying (Lawson et al. 1974).

Macrobrachium rosenbergii is the most popular freshwater prawn under cultivation in the United States. It must be maintained in warm water because its intolerance to cold temperatures is similar to that of tilapia (Stickney 1979). Shang and Fujimura (1977) studied the economics of establishing a *M. rosenbergii* operation in Hawaii, evaluating ponds ranging in size from 0.4 to 40 hectares. These authors determined that at a price of \$6.60/kg (based on reasonable wholesale prices in Hawaii), a farm for freshwater prawns would become profitable if it were at least 4 hectares in area. *Macrobrachium* species require water of low salinity during spawning and larval development but may spend the remainder of their lives in fresh water (Bardach et al. 1975).

MATERIALS AND METHODS

Two recirculating systems, with no outflow, involving a sequence of five tanks each were constructed (Fig. 1). The large system had approximately twice the capacity of the small system. The experiment covered 132 days. Two tanks per system contained tilapia and channel catfish. Another two tanks per system contained duckweed. Into one duckweed tank per system were placed 25 freshwater prawn, each 1 cm long. Into the other two duckweed tanks were placed two tilapia each (6.3 g combined weight in the large system, 9.3 g in the small system). The fifth tank in each system contained the biological filter composed of crushed oyster shell and *Nitrosomonas* and *Nitrobacter* nitrifying bacteria (Stickney 1979). The filter tanks contained 10 six-inch clay pots in the large system and 5 in the small system, with three water chestnut corms planted in each pot.

The water in each system was circulated from the filter tank into the first duckweed tank, then into the first fish tank, next into a second duckweed tank, then a second fish

TABLE 1. Large system lower tank (weights, feed, conversions). Day 1 = 25 February 1981.

	Fish weights (g)								
	Catfish		Tilapia			Feed (g)		Conversion
Day	Wt.	% gain	Wt.	% gain	Total	Duckweed	Commercial	(feed/flesh)
1	58.4		182.6		241.0			
14	104.3	79	265.8	46	370.1		78.0	0.60
30	145.0	39	400.8	51	545.8		148.8	0.85
45	213.2	47	619.2	54	832.4		257.1	0.90
60	186.7	0	590.4	0	777.1	691.5	0	0
75	178.8	0	608.5	3	787.3	1631.0°	0	0
91	124.0	0	695.5	14	819.5	1576.0°	105.4	8.17
100	155.9	26	761.5	9	917.4	1106.1°	73.8	1.88
117	230.5	48	930.0	22	1160.5	2201.6°	147.2	1.51
132	293.5	27	1202.0	30	1495.5	54.0°	273.2	0.83

Total gain = 1254.5 g
Total feed—duckweed = 726.0 g dry wt
—commercial = 1083.5 g
Overall conversion = 1.44
°Duckweed from an outside source

tank, and back into the filter (Fig. 1). Well water was used in the large system for the entire experiment but in the small system only for the first 77 days. On day 77 well water was changed over to waste water effluent from a coal-fired power generation plant.

Catfish and tilapia received a pelleted commercial catfish food fed at 2.5% of their body weight per day. The rate was adjusted on 15-day intervals according to the growth of the fish. In the large system, beginning on day 45 of the experiment, duckweed was substituted for the commercial food in one fish tank. Duckweed was fed to the fish at the rate of 5% of the fish's weight per day for two weeks, then 15% for the next two weeks, and finally 15% duckweed supplemented by 1% dry weight commercial food for the remainder of the experiment. Fish and prawns in the duckweed tanks fed on existing plants and waste materials that flowed through the system. Duckweed was harvested as necessary to promote maximum growth and prevent clogging of screens. The wet weight of duckweed harvested was recorded. Standard florescent lamps provided light for all plant growth except for wide spectrum florescent lamps over the water chestnuts in the large system. The lamps were set on 16-hour on and 8-hour off time periods.

Oxygen, temperature, pH, conductivity, and nitrite levels were measured daily. Temperature and conductivity were measured with a standard conductivity meter. Oxygen and pH were measured with an Altex Selec-Ion 5000 ion analyzer with Orion Research

TABLE 2. Large system upper tank (weights, feed, conversions) Day 1 = 25 February 1981.

	Fish weights (g)						
	Catfish		Tilapia				Conversion
Day	Wt.	% gain	Wt.	% gain	Total	Feed (g)	(feed/flesh)
1	48.3		193.9		242.2		
14	75.2	56	272.6	41	347.8	79.3	.75
30	119.4	59	377.5	39	496.9	139.2	.93
45	157.8	32	541.9	44	699.7	223.2	1.10
60	200.7	27	725.0	34	925.7	262.5	1.16
75	261.0	31	937.0	29	1198.0	324.8	1.19
91	280.8	8	976.7	4	1257.5	420.0	7.06
100	319.2	14	1063.4	9	1382.6	282.6	2.26
117	347.2	9	1127.5	6	1474.7	553.6	6.01
132	431.0	24	1308.0	16	1739.0	479.7	1.81

Total gain = 1496.8 g
Total feed = 2764.9 g (commercial)
Overall conversion = 1.85

TABLE 3. Small system upper tank (weights, feed, conversions) Day 1 = 25 February 1981.

	Fish weights (g)						
	Catfish		Tilapia				Conversion
Day	Wt.	% gain	Wt.	% gain	Total	Feed (g)	(feed/flesh)
1	28.2		123.4		151.6		
14	42.6	50	183.8	49	226.4	49.4	0.66
30	45.0	7	251.7	37	296.7	91.2	1.30
45	62.7	38	354.1	41	416.8	133.2	1.11
60	93.5	50	446.8	26	540.3	156.0	1.26
75	10.5	0	237.0	0	247.5	165.5	0*
91	16.5	60	333.7	41	350.2	93.0	0.91
100	20.0	25	348.1	5	368.1	79.2	4.42
117	39.0	95	459.0	32	498.0	147.2	1.13
132	42.0	10	546.0	23	606.0	162.5	1.50

Total gain = 454.4 g
Total feed = 1077.2 g (commercial)
Overall conversion = 2.37 (due to high mortality from day 60–75)
*Mortality due to low D.O. and feeding stress

probes. Nitrite light transmittance levels were measured with a Bausch and Lomb Spectronic 20 using sulfanilamide and dihydrochloride solutions and standard test procedures (Spotte 1970).

RESULTS

For the first 45 days of the experiment, fish in all tanks were fed commercial feed. The fingerling catfish showed gains of up to 79% of body weight each 15-day period during the first 45 days. The tilapia showed similar gains during the same initial period. As a result, the feed to flesh conversion ratio for both ranged from 0.60:1 to 1.30:1 (Tables 1 to 4). The rapid growth spurt is expected from fingerlings. All fish showed general declines in percent growth every 15 days through the rest of the experiment (increased conversion ratio). Major declines in growth rates in the control tanks after day 45 were the result of mortality from low dissolved oxygen levels. In the treatment tank, the fish fed only duckweed at the 5% level lost weight (Table 1) between days 45 to 60. When fed duckweed at 15% from day 60 to 75, the catfish continued to lose weight but tilapia increased in weight slightly. The 15% level of duckweed was supplemented with 1% commercial food from day 76 through the rest of the experiment. Under this regime the tilapia began to increase in weight more rapidly, but the catfish, due to mortality of some of the fish, lost weight between days 75 and 91, probably due to overnight low oxygen stress. Both tilapia and catfish in the treatment tank from day 91 responded to the

TABLE 4. Small system lower tank (weights, feed, conversions) Day 1 = 25 February 1981.

	Fish weights (g)						
	Catfish		Tilapia				Conversion
Day	Wt.	% gain	Wt.	% gain	Total	Feed (g)	(feed/flesh)
1	28.5		96.0		124.5		
14	30.0	7	140.5	46	170.5	40.3	0.88
30	43.1	43	180.0	29	223.1	60.8	1.16
45	61.0	42	275.5	53	336.5	100.8	0.89
60	94.0	54	378.5	36	472.5	126.0	0.93
75	118.0	26	474.5	26	592.5	165.2	1.38
91	94.3	0	506.2	7	600.5	217.0	0*
100	119.7	27	536.5	6	656.2	135.0	2.42
117	170.5	43	603.0	13	773.5	262.4	2.24
132	203.0	19	717.0	20	920.0	250.9	1.71

Total gain = 795.5 g
Total feed = 1358.4 g (commercial)
Overall conversion = 1.71
*Mortality due to low D.O. from day 75–91.

combined diet and equaled or exceeded the weight gains in the three control tanks. The overall conversion ratios for the four fish tanks were 1.44:1 in the treatment tank and 1.71 to 2.37:1 in the three control tanks.

The two tilapia in the lower duckweed tank of the large system grew from 6.2 g to 77.0 g in 75 days. This was more gain per day than the fish in any of the fish tanks. Though not fed, they were free to feed upon existing plants and waste entering their tank. No duckweed was harvested from this tank because the fish kept its biomass low. The fish placed into the small system's lower duckweed tank had similar growth, increasing from 9.3 g to 42 g in 34 days. Their presence was a factor in that tank's lower duckweed production during days 1 through 45 (Table 5).

Table 5. Duckweed production (Day 1 = 25 Feb. 1981).

	Amount harvested (g)		
Date	Large system upper tank	Small system upper tank	Small system lower tank*
2 April	458.2	317.1	250.8
20	698.9	–	–
22	–	266.0	139.7
12 May	275.0	319.5	–
20	126.0	–	–
21	–	–	203.0
23	–	170.0	–
27	327.0	–	–
30	–	192.0	–
2 June	–	142.0	–
4	286.0	–	–
8	129.0	–	–
13	–	140.0	–
14	–	–	138.0
15	135.0	–	–
16	135.0	–	–
17	135.0	–	–
19	135.0	–	–
20	135.0	–	–
21	–	70.0	70.0
23	44.0	–	–
24	–	–	54.0
25	102.0	–	–
26	45.0	–	–
27	57.0	–	–
29	45.0	–	–
30	110.0	–	–
1 July	63.0	–	–
2	40.0	–	–
6	65.0	–	–
Totals (g)	3546.1	1616.6	975.7
t/ha/hr	82.3	87.2	52.4
(t/a/yr)	36.7	38.9	23.4

*Fish were included in this tank.

Due to small size (1 cm) the 25 freshwater prawns placed in each system were not weighed or measured until day 75. The prawns were left to feed on plants, algae, and waste products of the system. By day 75, they averaged 3 cm in length, but numbers had dropped from 25 per tank to approximately 15, probably due to oxygen-stress-induced mortality and cannibalism. By day 132, 10 remained per tank with an average length of approximately 5 cm.

On day 1 the duckweed tanks were each innoculated with 10 g of duckweed in the small system and 20 g each in the large system. The presence of fish precluded duckweed harvest from the large system's lower tank. Duckweed production was between 52.4 and 87.2 t/ha/yr (23.4 to 38.9 t/a/yr) for the three remaining tanks containing duckweed (Table 5). The lower figure (52.4 t/ha/yr) was a result of tilapia foraging in the small system's lower tank. Low dissolved oxygen levels were attributed to high respiration rates of plants and biological filter organisms (Fig. 2).

Chinese water chestnuts did not grow well in the lab because of light limitations. Standard florescent lamps over the large filter were replaced with wide spectrum florescent lamps at day 75, but there was only a slight improvement in growth noticed. Plants continued to live but reached a maximum height of only 0.6 m, and no corms were produced by these plants. At the Hegerhorst system in Benjamin, Utah, water chestnuts from the same stock planted in an outdoor pond reached a height of over 1.5 m. Production was 237 t/ha/yr (106 t/a/yr) total biomass and 37.2 t/ha/yr (16.6 t/a/yr) corm production.

With the exception of oxygen and nitrite, water quality parameters remained within acceptable limits for the test plants and animals. At times, oxygen concentrations dropped and stressed the catfish, tilapia, and prawns (Fig. 2). Figure 3 shows that between days 9 and 35 the nitrite (NO_2) levels were high in both systems. Nitrifying bacteria had not become established in sufficient numbers to handle the heavy organic load from fish feed and wastes. As bacteria numbers increased, the nitrite levels dropped into acceptable ranges in both systems. The pH

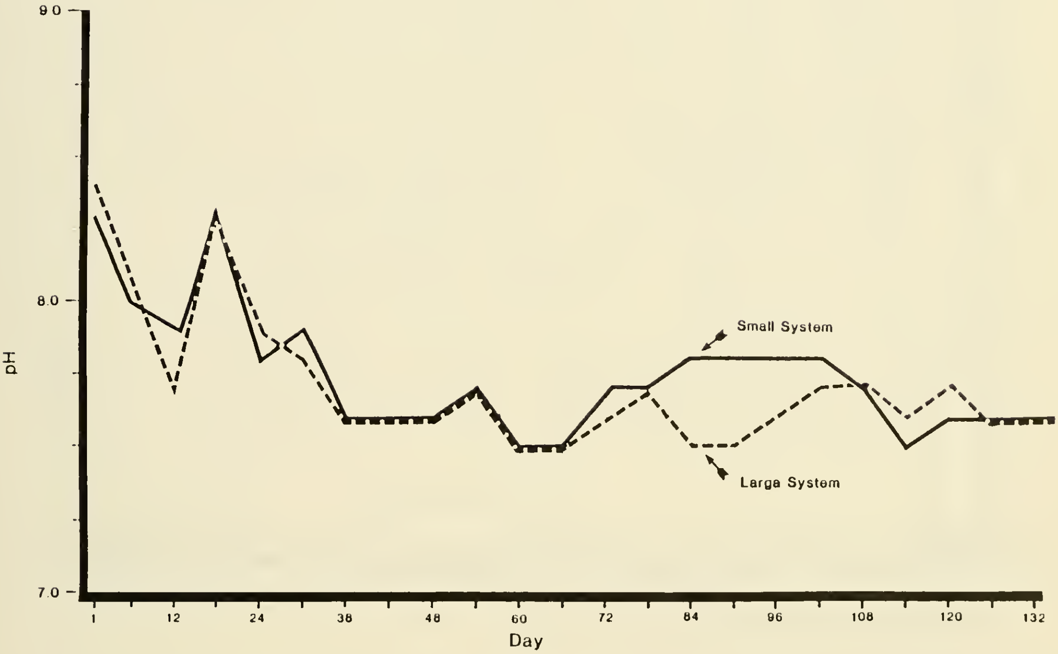


Fig. 2. Oxygen concentration in large and small systems expressed as milligrams per liter (ppm) during 132-day research period (data points every 6th day).

remained fairly constant between 7.5 and 8.0 through the entire experiment (Fig. 4). Conductivity started low but steadily increased because of evaporation through the 132nd day (Fig. 5). Means and ranges of water quality parameters are shown in Table 6.

The increase in conductivity on day 77 in the small system was due to the change from well water to evaporation pond water from a coal-fired generation station. There were no significant variations in production that could be attributed to the new water. Tilapia spawned during this time in the lower tank. The fry were placed in the lower duckweed tank of the large system and after 79 days averaged 5.3 g and 60.5 mm each, feeding only upon plants, algae, and waste products.

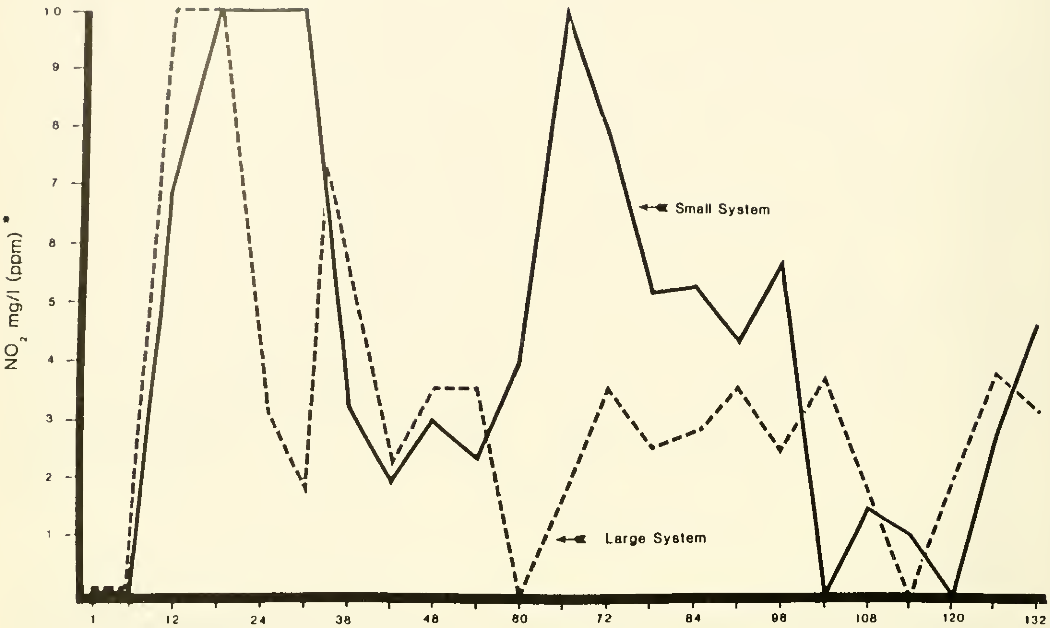
Discussion

Catfish, though observed to occasionally feed on duckweed, are bottom feeders and did not adjust to feeding on floating duckweed. Catfish readily consumed tilapia fecal

TABLE 6. Water quality summary.

	Large system		Small system	
Parameter	Mean	Range	Mean	Range
Temperature (C)	26.8	23.0–31.0	27.2	25.0–30.0
pH	7.7	7.4–8.5	7.7	7.2–8.4
Conductivity (umho's)	535	250–800	510/4930*	440–600/2900/6000*
Oxygen (mg/l)	3.95	1.62–7.2	5.14	1.26–7.80

*Higher conductivity levels are the result of the change from well water to evaporation pond water.



1.0 on this scale equals 1.0 ppm or greater
Any measurement less than 0.1 ppm NO_2 was recorded as 0

Fig. 3. Nitrite concentration in large and small systems expressed as milligrams per liter (ppm) during 132-day research period (data points every 6th day).

strands, which were green in color from consumed duckweed. Growth of catfish indicates an available food value in tilapia wastes. Prawns grew quite readily in the system feeding only on in-system plants plus wastes from the fish. Low dissolved oxygen levels and cannibalism reduced their numbers, indicating a need for aeration and cover if prawns are to be a productive component of this system.

Tilapia will accept duckweed as food. When duckweed was first offered, neither catfish nor tilapia readily fed on the plant. After a few days tilapia readily consumed the duckweed. The delay in accepting duckweed may have been the result of preconditioning to commercial food. Best growth occurred when duckweed was supplemented with commercial feed, suggesting that duckweed may be lacking (Rusoff et al. 1980) in some nutrients needed for proper fish growth. Further research is needed on feeding plants to tilapia.

Duckweed grew well under the standard florescent lights. It supplied a source of food and also improved water quality by removing nitrogen and adding oxygen during the light phase. Plant respiration during the dark phase did decrease oxygen levels and stress the animals. For this reason air was added via an air stone in each tank. Duckweed production may be enhanced with sunlight. Chinese water chestnuts did not grow well in the laboratory under artificial lights, but the chestnuts grown outside at the Hegerhorst farms reached maturity and produced corms, suggesting that light was a limiting factor in the lab. In future experiments this must be taken into consideration.

The main problems encountered with water quality were low oxygen levels and high nitrite levels. Oxygen, through aeration, was added to counteract biochemical oxygen demand (BOD) and plant respiration. It was also needed by the filter organisms for conversion of ammonia to nitrate. During the

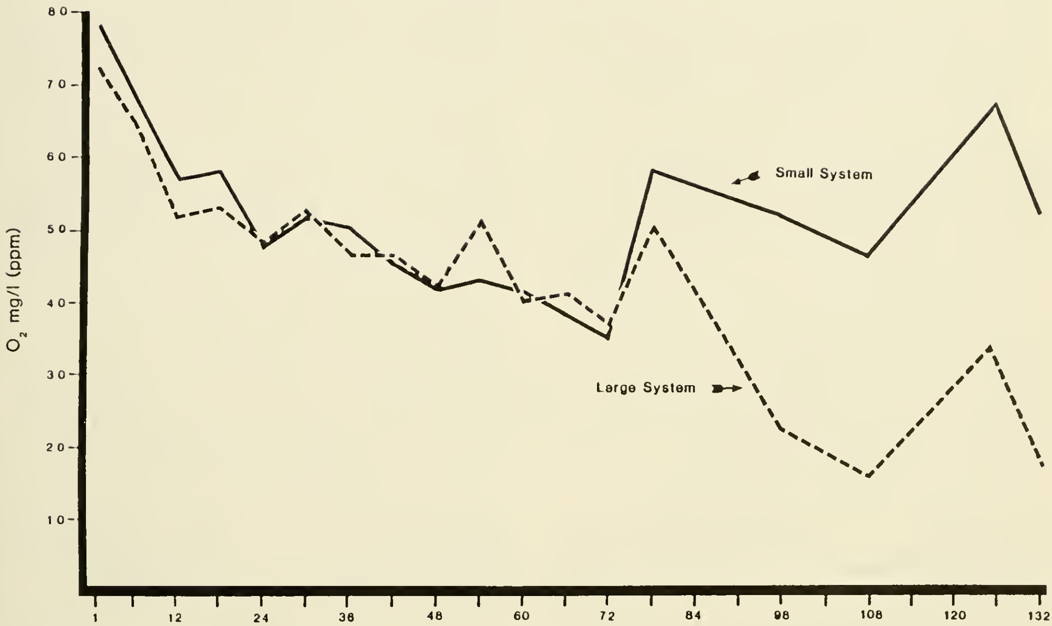


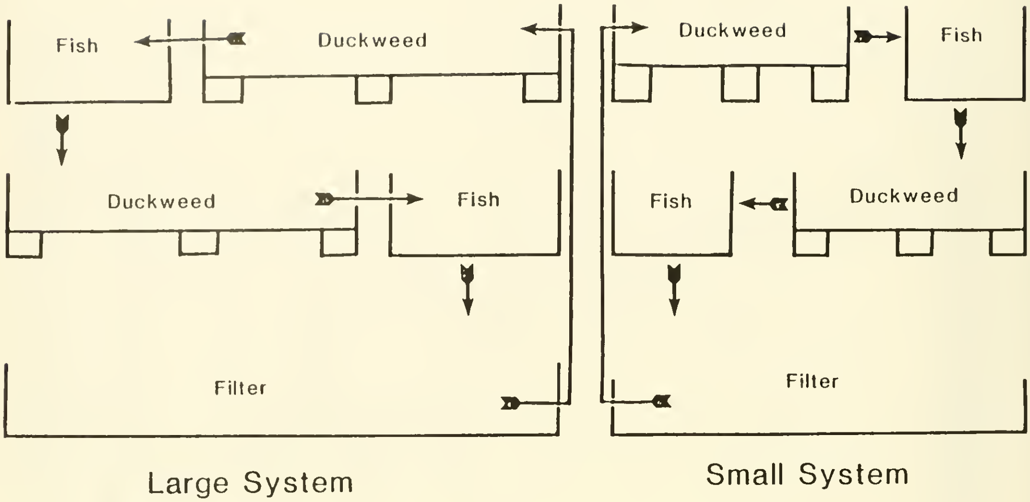
Fig. 4. Water pH in large and small systems during 132-day research period (data points every 6th day).

early stages of the experiment, the nitrogen loading from fish food and wastes caused nitrite levels to exceed 1 mg_ (1 ppm), stressing both tilapia and catfish as evidenced by their "gulping" action at the water surface. After filter organisms became established and oxygen was added, high nitrite levels were no longer a problem.

The closed, recirculating, polyculture system is economically feasible and energy efficient, especially when duckweed, produced using waste nutrients from within the system, is reintroduced as a supplemental food. The USDA Economic and Statistical Service (USDA 1981) reports that feed and fingerlings account for 75% to 80% of production costs in most aquaculture projects. A typical catfish feed contains soybean, corn, and fish meal protein. The costs for these ingredients continue to escalate. Duckweed as a food supplement can help cut project feed costs by maintaining a low commercial feed to fish tissue conversion ratio. Duckweed could be grown in shallow ponds less than 0.5 m deep enriched by waste from livestock or fish systems.

The five plant and animal species used in this study would provide useful and marketable products. Tilapia and catfish have been sold for $1.20 to $2.40/lb dressed weight depending on the geographical area. Freshwater prawns have retailed for as much as $5.00 to $7.00/lb and water chestnut corms for around $1.00 to $2.00/lb. The economic values of this type of polyculture system are obvious—the more that is produced per unit of nutrient and energy input, the better the cost to benefit ratio. Although this system will produce a protein source suitable for human consumption, it can also produce other benefits.

1. The system could provide a secondary use of industrial waste heat and water.
2. Waste heat and water from geothermal projects could be used in this type of system.
3. Alcohol production is a potential use for duckweed or other aquatic plants produced in aquaculture operations. Waste heat, water, and nutrients from alcohol production might also be used in a polyculture system.



Filter tank I.D.	0.69 × 2.39 × 0.31 m	Filter tank I.D.	0.42 × 1.80 × 0.23 m
Fish tanks I.D.	0.64 × 0.69 × 0.38 m	Fish tanks I.D.	0.43 × 0.51 × 0.38 m
Duckweed tank I.D.	0.69 × 1.50 × 0.23 m	Duckweed tank I.D.	0.43 × 1.04 × 0.23 m
Total system capacity	923.6 liters	Total system capacity	546.5 liters
Total surface area, duckweed tank	2.53 m^2	Total surface area, duckweed tank	0.89 m^2
Larger system is 2.4 times larger than the small system			

Fig. 5. Water conductivity in large and small systems during 132-day research period (data points every 6th day).

4. Surface farming operations could use nutrient-enriched water flowing from aquaculture operations.
5. The aquaculture operations are nonconsumptive of water. Loss of water is mostly limited to evaporation.
6. Duckweed could be used as a protein supplement for cattle. Other aquatic plants could prove equal or better for this purpose than duckweed.

This study was conducted in a laboratory situation, and results may not necessarily reflect what would happen on a larger scale. Energy budgets were not addressed in this study and are subjects for future experimentation. The actual value of these benefits are subjects for future research under pilot plant or production conditions. Future designs might include rotating, contact, or trickling filters directly in or over the top of individual raceways. The use of alternate energy sources to heat the water is growing in interest. Solar domes, collectors, and concentrators appear potentially valuable as sources of energy for aquaculture systems, especially in areas where water is available but temperatures are not suitable for warm water aquaculture. Aquaculture can provide a high-protein, low-fat product to consumers and at the same time provide diversity and stability to agriculture and agribusiness in many areas of the nation. Aquaculture can provide landowners a use for resources considered marginal for other uses. It can provide an alternative or complementary source of income.

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