



Aquaculture

As some of the aquaculture research at New Alchemy becomes ever more intricate and recondite, at least to a layperson (like me), it is well to keep in mind that its underlying rationale is quite simple and easily grasped—beyond the obvious fact that we like fish. What we are attempting to do in a hungry world is to develop ways of producing protein that are both economical and ecological. The first of the articles that follow illustrates this point most clearly. In growing and testing alternative fish foods, Bill McLarney and Jeff Parkin are trying both to reduce the costs of raising fish and to discover food sources for fish, such as earthworms, that produce adequate growth yet could not as readily be fed directly to people, as could soybeans or grains for example.

The articles on closed-system aquaculture, describing our research with solar-algae ponds, may seem more obscure, but the goals and ethics of the research are the same as those that prompt Bill's and Jeff's work. For readers who find themselves struggling with some of it, Donella Meadows, the brilliant systems analyst, best known for the "Limits to Growth" study, has written:

You already appreciate the innovative design of the NAI programs and the valuable scientific and practical lessons that are being learned. What I'd like to point out is the unique and useful process they have evolved for direct interaction between a simulation model of their aquaculture systems and management of those systems.

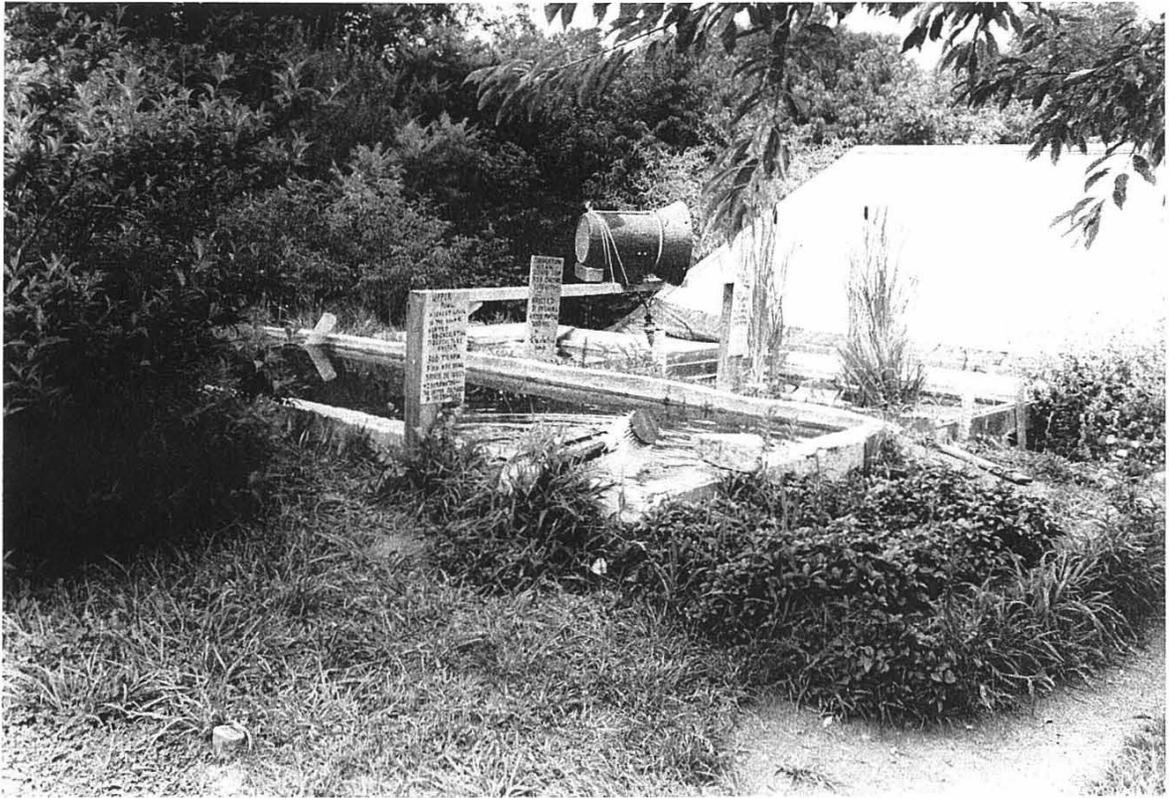
As you probably know, I teach modeling and policy design, and I've been involved with or an advisor to projects using computer simulation in many fields and for many purposes. I often lecture to my students about the ideal process of give-and-take between the model builder and the model user. But I have never seen that ideal achieved—except at New Alchemy. There John Wolfe has managed to keep his models transparent, directed to the actual problems of the group, and flexible to the changing knowledge and concerns of the group. He has transmitted a growing understanding of feedback structure and system dynamics to the others at NAI, while they were transmitting to him their knowledge, ideas, and hunches about aquaculture systems. The staff has been open to this new method of integrating their insights, con-

structively critical as the model evolved, and alert to discrepancies or consistencies between model predictions and real events. The result is a model that is an effective communication tool with which chemists, zoologists, and engineers can point out the connections among light penetration, ammonia concentration, and fish growth. New experiments can be designed and tested both in the model and in the solar ponds. And there is a tighter link between theory and practice than I have ever seen elsewhere; a fast cycling between the deductive and inductive phases of the scientific method. It really warms the heart of an old modeling proponent like me to see just once this powerful tool used with just the right mixture of skepticism and enthusiasm and with frequent checks back and forth between the model and the real world.

I'd also suggest that they document fully the experiments, not only the model, but also the process by which they have integrated the two. And I would hope that this description would be published in the scientific literature, to reach the vast audience that unfortunately has not caught on to New Alchemy's excellent self-produced publications.

Those of us who find ourselves a bit out of our depth in some of the details that Ron Zweig, David Engstrom, and John Wolfe write about and who lack Donella Meadows' expertise to analyze it, perhaps will be pleased to learn that much of the conclusion is hopeful, in the sense of providing food within the given paradigm and using computer simulation to test and improve ecological design.

N.J.T.



Ron Zweig

Alternatives to Commercial Feeds in the Diets of Cultured Fish

William O. McLarney and Jeffrey Parkin

One of the major impediments to the further development of aquaculture in North America is the cost of conventional fish feeds. A partial solution to the problem is to grow fish less dependent on high-quality animal protein than the channel catfish (*Ictalurus punctatus*) and rainbow trout (*Salmo gairdneri*) that dominate commercial aquaculture on this continent. At New Alchemy this approach is best exemplified by the cultivation of blue tilapia (*Sarotherodon aureus*) in algal "soups" where these filter feeders derive much of their nourishment from the phytoplankton (algae) that surround them. However, if satisfactory yields are to be obtained, we find it necessary to supplement the diets of even these fish with animal protein.

We also must acknowledge that for many potential fish culturists tilapia are not the best fish. In some places they are illegal. In the deep South,

where they might survive the winter in the wild, we discourage their use for ecological reasons. In some places it may be impractical to provide water warm enough for tilapia culture. And some people simply prefer other types of fish.

Yet in attempting to identify North American counterparts of the tilapia, one comes up against a quirk of evolutionary fate. With very few exceptions (notably the buffalofishes, *Ictiobus* spp.), the North American filter feeding fishes are small or otherwise unsuited for cultivation as food animals. Some of our native panfishes, for example the bullheads and sunfishes, have less-exacting dietary requirements than channel cats or trout, but they are carnivores nonetheless. In fact, it is our experience that the term *herbivore*, as applied to fish, lacks precision. Most "herbivorous" fish, including tilapia, are opportunistic feeders, and benefit from

Table 1. APPROXIMATE COSTS ASSOCIATED WITH A 4 FT × 3 FT × 8 IN. EARTHWORM BED.^a

Initial stock (at maximum density)	30 lbs @ \$4/lb = \$120
Concrete block bed	35
50 lbs lime (powdered limestone) ^b	2
50 strips of litmus paper ^b	4
2 cubic ft peat moss (bedding additive)	3

^aThis cost can be reduced by half for each 3 months you allow the initial stock of worms to reproduce and grow under optimum conditions without harvesting. In fact, this is recommended not only for financial reasons but also to gain some working experience prior to relying on the worms.

^bThese quantities are sufficient for a minimum of 1 year.

inclusion of a certain amount of animal protein in their diets.

Faced with these facts, many beginning fish culturists give up searching for an alternative to commercial processed feeds. Others simply give up. There is no gainsaying the effectiveness of processed feeds in most situations. They offer a balanced diet and, when used properly, usually result in good growth, particularly of the species for which they are formulated. Of equal importance in their popularity is the convenience factor. It is just plain handy to feed a dry, packaged product that can be stored until needed, weighed precisely, and used without fuss or mess.

Over half of the production budget of a commercial catfish farmer goes for feed, and this is the rule throughout American aquaculture. The principal ingredients of commercial feeds include fish meal derived from marine fisheries, grains, and synthetic vitamins. In view of the costs of obtaining these materials (including the petroleum-related costs of fishing, agriculture, and vitamin manufacture) plus the costs of processing, packaging, and shipping, the price of fish feed is sure to rise.

Ecological reasoning also suggests the need for an alternative. The conversion of inexpensive fish into fish meal in order to make a feed for expensive fish may be economically justifiable in certain situations, but it is not going to result in cheap food or solve any human nutritional problems. In fact, as Israeli aquaculturist Gerald Schroeder points out, conventional North American aquaculture, using fish-meal-based feeds, results in a net loss of fish. Although alternative sources of animal protein might now prove impractical on a large scale, earthworms and flying nocturnal insects are already available to the small-scale fish producer.

Earthworms

The earthworm is the archetypical fish bait. Though its status as a favored food of freshwater fish is firmly entrenched in folklore, to our amazement we have not been able to find one paper in the scientific literature dealing with earthworms as a

component of cultured fish diets, despite the ease with which they can be cultured. (Some of their other attractive features for the small-scale, diversified food grower as well as details of earthworm culture are discussed in the fifth *Journal*.¹ Common sense and access to a good resource book² should enable any interested person to raise earthworms successfully.

In brief, earthworm culture entails providing housing, routine feeding and watering, and maintaining an approximately neutral pH and suitable temperatures in the "bedding" where the worms live. Most cultured earthworms exhibit greatest vitality at 16°–27° C, or 60°–80° F. Inexpensive housing may be provided by scrounging an old sink, bathtub, or refrigerator liner, or by constructing a plywood or concrete block container. Feeding should be done every two to four days (depending upon the type of feed) with household garbage, paper products, animal manures—almost anything that is biodegradable. It is said that the average American family of four generates enough biodegradable "wastes" to feed a 4 ft × 3 ft × 8 in. earthworm bed generously. Maintaining a pH near neutral is easier than it may sound; buffering is accomplished simply by dusting the feed with lime at feeding time. Table 1 summarizes the costs associated with starting up a 4 ft × 3 ft × 8 in. bed.

We have assumed one of the more expensive types of housing; this cost can be substantially reduced by using one of the options mentioned in the preceding paragraph. No costs are assigned to feed, bedding, or water; most readers will be able to supply the first two free and will be ridding themselves of a potential nuisance in the process.

No monetary value has been assigned to labor, but during a two-week period with five feedings (including watering and buffering the pH) and one pH sample, a generous estimate of the time invested in our system was 1½ hours, or six minutes

¹Jeffrey Parkin. Some other friends of the earth. *Journal of the New Alchemists*. 5: 69–72.

²Gaddie and Douglas. *Earthworms for Ecology and Profit*. Vol. I. Bookworm Pub. Co. 254 pp.

a day. To this should be added the labor of setting up a bed, which will vary quite widely according to the type of housing and bedding selected.

While harvesting earthworms will never be as convenient as pulling a handful of pelleted feed out of a bag, it is greatly facilitated by restricting food distribution to certain areas of the bed (e.g., along either side), which serves to concentrate the worms.

This practice also reduces the amount of bedding harvested with the worms. In weighing worms used as fish feed, some allowance must be made for the percentage bedding, which will remain relatively constant as long as the composition of the bedding and the method of feeding are not radically altered. So, after one or two samples, one can weigh the worms as they come out of the bed.

Unlike most artificial and many natural fish feeds, earthworms sink in water. A floating feed is essential in cage culture and desirable in most forms of fish culture, as it permits the culturist to observe feeding and prevents loss of feed in bottom sediments. We get around the problem with worms by using a special feeder, which consists of no more than a piece of perforated styrofoam on which the worms are spread. As worms instinctively flee the light, they pass down through the holes into the water and are eaten one by one. In addition to floating the worms, this system tends to equalize the distribution of worms among the fish. It also cleans the worms, since much of the bedding drops off as they slither down through the holes.

Bedding-free worms may be obtained simply by rinsing with water, but some allowance must be made for water clinging to the worms when they are weighed. A method that we prefer involves spreading the earthworms and bedding thinly over a sheet of burlap or other loosely woven material located under a light source and waiting 10–15

minutes. Seeking to avoid the light, the worms will crawl through the burlap and in the process be stripped of any bedding.

Flying Insects

There are many other organisms that may be cultured as fish food, but an alternative strategy is the capture of creatures that occur naturally in abundance. Among the most apparent sources are nocturnal flying insects, which may be captured with an ultraviolet light trap. Two types of traps are commercially available. The first, originally developed for pest control, employs an electrified grid that, with a flash of light and a crackle, electrocutes insects that light on it. On a "busy" night, the racket is considerable. A second, quieter type was developed specifically as a source of fish food. An impeller fan sucks in the attracted insects and blows them down through a duct into a collector bag or directly onto the water. (See Figure 1.)

We have used both types of bug traps, but prefer the fan type because it is quieter and safer. We are also not sure what "frying" does to the nutritional value of insects. Of the available impeller fan feeders we can recommend the Will-o-the-Wisp, made by Hedlunds of Medford, Wisconsin. We have operated several of these feeders for up to three years, with no maintenance beyond replacement of a bulb. As of spring 1980, the Will-o-the-Wisp sells for \$140. It draws one kilowatt hour of electricity per 12 hours of operation, which at our present rate costs less than three cents a night.

The "bug season" on Cape Cod extends roughly from June through September. Even during this period nightly yields can vary dramatically, from literally nothing on a windy, wet evening to as much as 115 grams (g), or 1/4 lb, on a warm, calm, dry night. Over the past seasons the average nightly yield of our feeders, equipped with collecting bags,

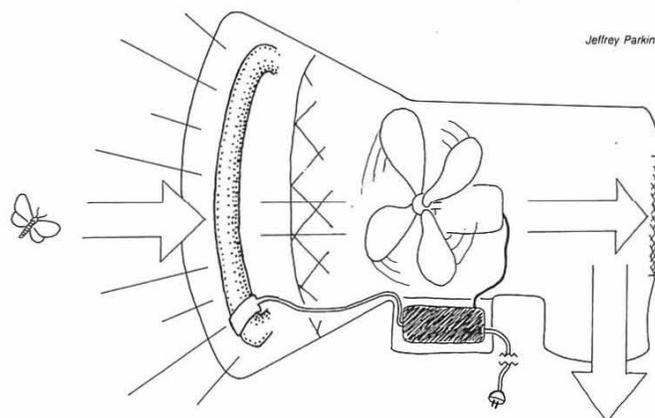


Figure 1. Cross-sectional view of Hedlund-like bug light.

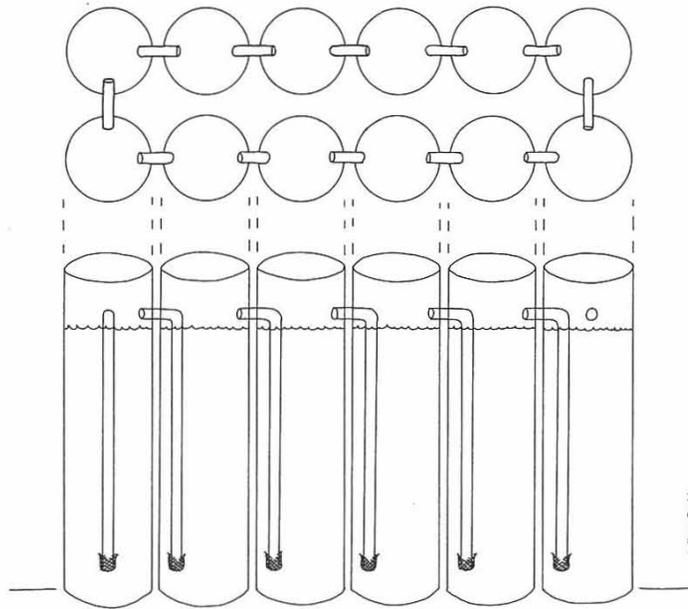


Figure 2. Recirculating aquaculture system. Tanks interconnected with airlift tubes.

has been 16.2 g. It is our impression that, when feasible, the lights should be operated without bags, and catches will improve. Certainly better results will be obtained directly over water; not only is the field of the light less obstructed than in most terrestrial locations, but one can take advantage of insects emerging from the aquatic larval stage.

The kinds of insects captured do not vary nearly as much as their quantity. Apart from a very occasional lacewing, we do not get known beneficial insects as long as the lights are turned off at dawn. The bulk of our catches is composed of midges and moths; over water other types might predominate.

The Fish

The fish species used in this study were the mainstays of New Alchemy aquaculture, the blue tilapia and the yellow bullhead (*Ictalurus natalis*). Blue tilapia, an African cichlid, is the principal fish in New Alchemy's solar-algae pond research, and is described elsewhere in this as well as past *Journals*. Its natural adult diet consists mainly of plant proteins. When young, however, it tends to be a more opportunistic feeder. The yellow bullhead, a native North American catfish, is similarly predominant in our cage culture research. It is a bottom-feeding carnivore whose natural diet consists of small invertebrates. The hardiness of both these species makes them ideal experimental animals.

The Experimental Set-Up

The seven feeding trials described in this article were carried out in a recirculating system composed of twelve 60-gallon cylindrical tanks interconnected with airlift tubes (see Figure 2).

By recirculating the water we attempted to equalize any effects of water quality on growth. The siphon intakes were covered with nylon screens to eliminate the exchange of fish and/or food between tubes. Water flowed through the system at an average of 1.9 liters/minute (0.5 gallons/minute). As there was no purification system, 25% of the water was siphoned off from the bottom of each tube every month and replaced with tap water. Light was provided 14 hours/day by two overhead fluorescent fixtures. The bottom 18 inches of the tubes was wrapped with black plastic to give the bullheads a refuge with some semblance of "cover."

Diets Tested

The experimental diets were made up of three components in varying percentages: mixed nocturnal flying insects, as captured by a Will-o-the-Wisp bug light fish feeder; cultured earthworms (*Eisenia foetida*); and the commercial feed Purina Trout Chow® (henceforth referred to as PTC). The purpose was to determine what portion, if any, of a standard PTC diet could be replaced by either of the two fresh feeds without loss of growth,

and if a small fresh dietary supplement added to a normal PTC feeding regime could result in increased growth. Because of the size of our fish and the pellet size of feed available, we ground the PTC and used that portion retained by a 1.0 millimeter (mm) sieve. The earthworms also had to be chopped, into 2–4 mm lengths, to make them acceptable to the fish and to ensure even distribution of this feed among the individual fish. Insects were weighed and fed fresh, as captured, except that some of the largest moths were removed.

All feeding was done while the lights were on. At least four hours separated feeding of one component of a mixed diet from another, so that neither feed was wasted as a result of preference by the fish for one or another.

In each of the trials, one of four diets was fed to three tanks of fish. In the tilapia trials there were eight individual fish per tank, fin clipped so that they could be individually weighed. Twenty

unmarked bullheads were kept in each tank and weighed as a group. After weighing, all fish were returned to their tanks, except following Trial 6, when all the bullheads were randomly redistributed among the tanks. No group of three tanks received the same diet in two consecutive trials.

Results: Tilapia

Two replicate trials were conducted with tilapia. Water temperatures over Trials 1 and 2 ranged from 21.9°–23.3° C (71.5°–74.0° F), and 23.0°–24.4° C (73.5°–76.0° F), respectively.

Diurnal fluctuations in temperature never exceeded 0.3° C (1.0° F). Table 2 and Figure 3 summarize the results of these two trials.

Although the results obtained with diet B in Trial 1 are inconsistent with the rest of the data, Trials 1 and 2 suggest that with increased replacement of PTC by earthworms, the growth rate of

Table 2. FEEDING TRIALS 1 AND 2 WITH TILAPIA.

Trial No.	Diets			Mean Initial Wt. (g/fish)	Mean Gain (g/fish)	% Gain ^b	F ^c	Significance ^c
	% ^a PTC	% ^a Worms	% ^a Bugs					
1	A	3.0	0	3.9	1.5	38.6	6.2	<97.5%
	B	3.0	0.5	4.6	1.2	26.3		
	C	2.5	0.5	4.1	1.5	36.6		
	D	1.5	1.5	4.5	1.1	23.7		
2	A	3.0	0	5.6	2.0	35.2	15.8	<99.5%
	B	3.0	0.5	5.4	1.8	34.2		
	C	2.5	0.5	5.8	1.7	29.2		
	D	1.5	1.5	5.6	1.2	21.9		

^aPercent of total fishes' body weight fed daily (applies throughout tables).

^bBased upon total weights, not the listed means (applies throughout tables).

^cThe two columns at the right in Tables 2–5 are the results of a statistical test called *analysis of variance*. This numerical manipulation basically takes into account variations (in growth rates) between the fish in individual tanks relative to variations between fish in tanks grouped by different diets; this is reflected in the F values. In so doing, one can get some measure of the probability that the overall observed results occurred as an outcome of the experiment and not by chance. The percentages in the Significance columns depict this probability. By statistical convention (and a conservative lot they are), any degree of significance less than 90% is considered chancy and of no statistical value.

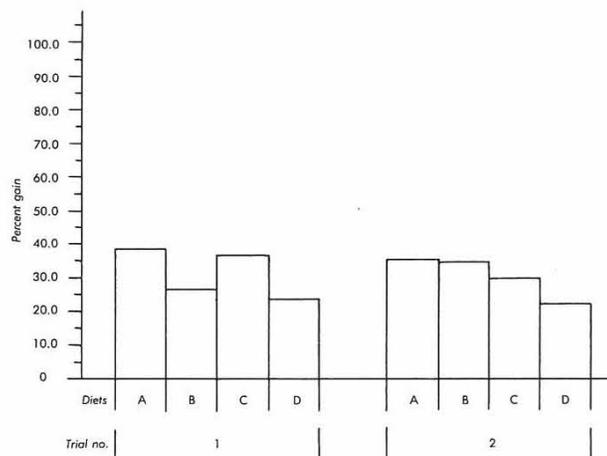


Figure 3. Results of tilapia feeding trials, nos. 1 and 2.

Table 3. FEEDING TRIALS 3 AND 4 WITH YELLOW BULLHEADS.

Trial No.	Diet			Mean Initial Wt. (g/fish)	Mean Gain (g/fish)	% Gain	F	Significance
	% PTC	% Worms	% Bugs					
3	E	3.0	0	0.76	0.42	54.7	1.9	>90.0%
	F	3.0	0.5	0.79	0.51	64.3		
	G	2.5	0.5	0.80	0.47	58.4		
	H	1.5	1.5	0.76	0.40	52.5		
4	E	3.0	0	1.2	0.40	34.4	11.3	<99.5%
	F	3.0	0.5	1.2	0.61	52.1		
	G	2.5	0.5	1.3	0.54	41.8		
	H	1.5	1.5	1.3	0.44	34.8		

tilapia was reduced. Nor did the addition of a small percentage of worms to a 3% PTC diet improve the growth rate.

In a previous experiment at New Alchemy in which worms were fed to blue tilapia, similar amounts of earthworms were effective in increasing growth over that obtained with a base diet of roasted soy meal and rolled oats fed at the rate of percent of body weight per day.³ Although the fish in this earlier experiment, unlike those in the current trials, were maintained in an algal "soup," their base diet contained no animal protein.

Results: Bullheads

Trials 3 through 7 were conducted with yellow bullheads and yielded more encouraging results than the tilapia trials. Trials 3 and 4 formed a pair of replicates, as did Trials 5 and 6. Trial 7 was not replicated.

During Trials 3 and 4 water temperatures ranged from 22.2°–23.3° C (72.0°–74.0° F) and 21.7°–25.6° C (71.0°–78.0° F) respectively. Diurnal fluctuations in temperature did not exceed 0.3° C (1.0° F). The experimental diets used in these trials were the same as those used with tilapia in Trials 1 and 2.

The fact that the growth rates are greater in Trial 3 than in Trial 4 can be attributed to better water quality in Trial 3, to the early effect of increased feed rations (these fish had been kept at subsistence levels prior to Trial 3), and to the slightly smaller size of the test fish in Trial 3.

Table 3 and Figure 4 summarize the data from these two trials.

Unlike tilapia, yellow bullheads do appear to derive significant nutritional benefits from earthworms either as a supplement to a normal PTC diet, or as a substitute for PTC at least up to 50%. Since in both Trials 3 and 4 the growth rate for diets E (PTC with no supplement) and H (half PTC and

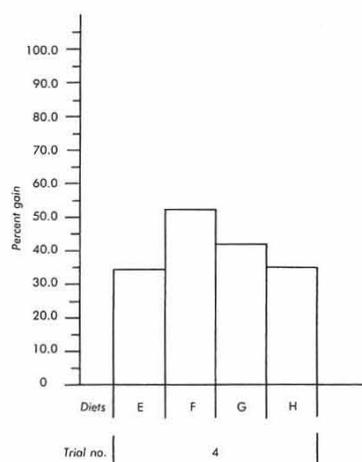


Figure 4. Results of yellow bullhead feeding trial no. 4. (Trial 3 not shown as the significance was less than 90%.)

half worms) were nearly identical, while supplementation with worms or substitution with a lower proportion of worms produced improved growth, it is possible that 50% represents the highest proportion of worms that can be substituted for PTC without adversely affecting growth. Higher proportions, or perhaps an all-earthworm diet, will be tested in future trials.

It is instructive to look at the feed conversion⁴ in Trial 4. Commercial aquaculturists, using dry feeds, consider anything less than 2.0 respectable and aim to hit close to 1.0. In Trial 4, both diets E and H resulted in feed conversions of approximately 1.0. The small additions of earthworms in diets F and G produced conversions of 0.81 and 0.87 re-

⁴Feed conversion is the ratio of the amount of feed fed to the gain in weight of the animal. Theoretically, it is impossible to achieve a conversion less than 1.0, since that would indicate that output (growth) exceeded input (feed). However, when one is using an essentially dry feed, such as most commercial feeds, and measuring wet weight of fish, such figures are possible since the weight of fish includes the water in fish tissue. In almost all outdoor situations there is also some input of "natural" feed, which causes the conversion ratio of the feed supplied by the aquaculturist to appear lower than it really is. Input of "natural" feeds is virtually nil in indoor experiments.

³William O. McLarney and Jeffrey Parkin. Cage culture. *Journal of the New Alchemists*. 6: 83–88.

Table 4. FEEDING TRIALS 5 AND 6 WITH YELLOW BULLHEADS.

Trial No.	Diet			Mean Initial Wt. (g/fish)	Mean Gain (g/fish)	% Gain	F	Significance	
	% PTC	% Worms	% Bugs						
5	I	3.0	0	1.7	0.67	39.0	504.2	<99.5%	
	J	3.0	0	1.5	1.6	100.8			
	K	2.0	0	1.0	1.6	84.7			
	L	2.0	1.0	0	1.8	0.89			49.8
6	I	3.0	0	3.0	1.1	34.7	15.0	<99.5%	
	J	3.0	0	2.7	1.7	64.1			
	K	2.0	0	1.0	2.9	1.5			50.4
	L	2.0	1.0	0	2.9	1.2			42.1

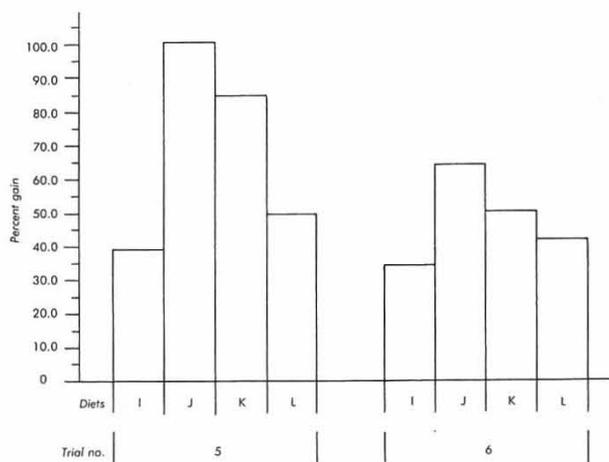


Figure 5. Results of yellow bullhead feeding trials, nos. 5 and 6.

spectively (based on dry weight of worms). It is evident that the effect of the earthworms cannot be accounted for in terms of their protein content alone. The addition of worms was, through some mechanism, improving the efficiency with which the fish were utilizing their feed. A similar synergistic effect was observed in feeding Chironomid midge larvae to tilapia.⁵

Replicate feeding Trials 5 and 6, incorporating flying insects as well as earthworms, were conducted with the same group of yellow bullheads. The water temperature ranges were 23.3°–25.6° C (74.0°–78.0° F) over Trial 5, and 21.1°–24.4° C (70.0°–76.0° F) over Trial 6. Diurnal temperature fluctuations did not exceed 0.5° C (2.0° F). Table 4 and Figure 5 summarize the information from these two trials.

There are a few published studies dealing with the use of ultraviolet bug lights in fish culture,⁶ but to our knowledge these two feeding trials are

the first in which measured amounts of insects captured by this means were fed to fish and compared with other feeds. It may surprise some readers that bullheads, which are not surface feeders in nature, would feed on flying insects, which float. However, in these trials and in other situations at New Alchemy, captive yellow bullheads learned to accept this food the first time it was presented.

As is obvious from Table 4 and Figure 5, Trials 5 and 6 resulted in significant and parallel trends. The control diet plus a supplement of captured insects (diet J) yielded by far the greatest growth. The partial substitution of insects for the control diet resulted in the next highest growth (diet K). When earthworms were substituted in the same proportion as the insects, resultant growth was less, but it was still significantly greater than for the control diet. The control diet (I) of PTC again produced the lowest growth, albeit good in its own right. There was once more an overall reduction in the growth rates (percent gains) between these first and second replicate trials. Greater initial size at the start of Trial 6 and a 0.8° C (3° F) temperature drop may have contributed to this.

⁵William O. McLarny, Joseph S. Levine, and Marcus M. Sherman. Midge culture. *Journal of the New Alchemists*. 3:80-84.

⁶Heidinger, 1971; Newton and Merkowski, 1976.

Table 5. FEEDING TRIAL 7 WITH YELLOW BULLHEADS.

Trial No.	Diet			Mean Initial Wt. (g/fish)	Mean Gain (g/fish)	% Gain	F	Significance
	% PTC	% Worms	% Bugs					
7	M	4.0	0	4.0	1.9	47.4	13.8	<99.5%
	N ^a	4.0	0.5	4.1	2.2	54.8		
	O	3.0	0.5	3.8	2.0	51.3		
	P	3.0	1.0	3.6	1.9	53.0		

^aThe three tanks receiving this diet ranked first, second, and twelfth (last) overall. The tank that ranked twelfth (35.4% weight gain) appeared to be an anomaly and we have thus omitted it from the data presented here.

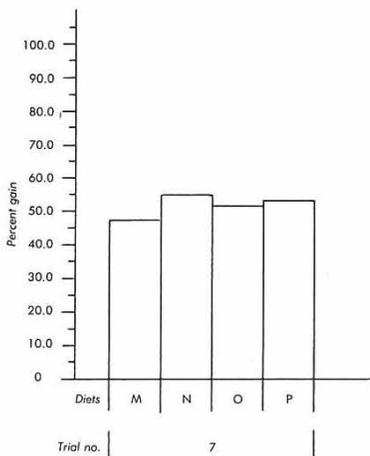


Figure 6. Results of yellow bullhead feeding trial no. 7.

Once again feed conversion was affected by supplementation or substitution of a portion of the PTC diet with fresh feeds. The conversion for diet I (all PTC) was 1.0; for the earthworm-substituted diet (L) it was 0.86, and the insect supplemented or substituted diets (J and K) produced conversions of 0.75 and 0.71 respectively.

Further trials with flying insects were not possible because of the end of our "bug season," but one more earthworm trial (Trial 7) was carried out. The purpose of this trial was to investigate the feasibility of further increasing the basic PTC ration to 4.0% of total body weight daily, with or without supplementation, and to compare such diets with supplemented diets based on the normal feeding rate of 3.0%. Table 5 and Figure 6 summarize the results of this trial.

The results indicate that even at higher rates of feeding, supplementation with worms increased the growth rate of yellow bullheads, and that diets O and P (3.0% PTC supplemented with 0.5% and 1.0% worms, respectively) were superior to a 4% daily feeding of PTC alone. Conversions for diets M through P were, respectively, 1.0, 0.98, 0.82, and 0.90, once again indicating that incorporation of earthworms in the diet increased the efficiency of utilization of other food.

Discussion

The ultimate goal of this sort of research is to enable aquaculturists to replace some or all of the costly and ecologically inappropriate fish-meal-based feeds with cheaper and more appropriate sources of protein. The studies reported here also suggest that the rate of growth and efficiency of feed utilization by fish receiving a full portion of a fish-meal-based commercial diet could be increased by supplementation with fresh feeds. This effect could be especially significant in the North, where getting a head start on the growing season can make the difference between a crop of "harvestable" or "sub-harvestable" fish in the fall.

Our work suggests that both earthworms and mixed flying insects could be used as substitutes or supplements for fish meal. Determining the economic feasibility of the two feeds and comparing them to other feeds in that respect is difficult. As consideration of Trials 1 and 2 reported here and the earlier work with blue tilapia and earthworms⁷ shows, the appropriateness of a fresh feed supplement cannot be discussed apart from consideration of the base diet. Nor will the conclusions reached necessarily be the same for different species, size groups, or geographic regions. The most that can be done here is to discuss the economics of our operation.

Earthworms are the more complicated of the two feed sources to consider in economic terms. Although in our trials they were less valuable than insects as a supplement or substitute for commercial feed, they potentially confer three additional economic benefits. The first is the efficient disposal of biodegradable wastes, which leads directly to the second, provision of a superior potting soil and/or soil amendment. These benefits may be particularly significant in urban settings where space is limiting or in a highly diversified subsistence agriculture situation.

⁷William O. McLarney and Jeffrey Parkin. Cage culture. *Journal of the New Alchemists*. 6: 83-88.



Ron Zweig

There is also the possibility of managing earthworms as a cash crop. (Earthworm casts or fecal matter are also incorporated into some of the best and most expensive commercial potting mixes.) Under optimal conditions, earthworm populations double every three to four months. In the case of the worm bed described earlier, this translates into 30 lb of worms every three to four months, or at least 90 lb of worms per year. With some luck in retailing, the costs listed in Table 1 could be covered within the first year, with worms to spare for the fish. From then on, the cost of worms would be minimal. Making back the costs solely through feeding the worms to fish and cutting back on commercial feed would require a long time.

At the present time, earthworm culture solely as a fish feed probably cannot be economically justified. (Much less can one justify the purchase of worms, at the current price of \$4/lb, wet weight, compared to commercial fish feeds at 30 cents/lb, dry weight.) However, if worms are treated as a cash crop and/or if one quantifies the value of

biodegradable waste disposal and agricultural use of the resulting product, worm culture can often be justified. As the price of commercial fish feeds increases, the economic incentive to grow earthworms as a fish feed seems destined to increase, and eventually earthworm culture for that purpose alone may be justifiable.

The economics of "bug light" fish feeders are comparatively straightforward. Amortizing the total materials cost (\$140 for a Will-o-the-Wisp plus \$36 for two replacement bulbs) over a 10-year period yields an annual cost of \$17.60. Added to this is a season's worth of electricity, amounting to about \$3.40 at current rates, netting a total cost of \$21 for a year. Our total catch averaged over the past two seasons was 1,820 g (4.01 lb) per season. Taking into account that these bugs are 75% water, the corresponding dry weight is 455 g (1.0 lb).

On that basis it would be difficult to justify economically the use of such a feeder under our conditions. However, Cape Cod is not prime "bug country," and even here we are sure we would do much better if our lights were placed directly over an outdoor fish culture system. More studies of the economic feasibility of bug-light feeders need to be made. The earliest such study indicated that they were economically feasible in rearing bluegills (*Lepomis macrochirus*) in cages in southern Illinois.⁸ However, a later study did not indicate positive results in open pond culture of fingerling channel catfish in Arkansas.⁹

We attempted to find out what an average nightly catch might be in the Midwest or South, where hot, sultry summer nights are the rule, but the only other data we could obtain came from Vermont. Barry Pierce of Goddard College reports approximately twice our average nightly catch, though their bug season is a month shorter. Contributing to their catches are the bug light's focus on the college's compost pile and a one-week mayfly "bloom" (during which they get well in excess of 100 g, wet weight, per night).

The studies reported here, and earlier feeding trials at New Alchemy, represent only a tiny fraction of the possibilities that could be explored. We feel that the most important aspect of our work is to affirm that, at least for the small-scale grower, there are options to total dependence on fish-meal-based commercial feeds.

⁸Heidinger, 1971.

⁹Newton and Merkowsky, 1976.



Defining and Defying Limits to Solar-Algae Pond Fish Culture

David Engstrom, John Wolfe, and Ron Zweig

After several years of careful experiments monitoring fish growth in solar-algae ponds, it began to seem as though we were coming up against a ceiling. We could grow fish rapidly for short periods of time, or slowly for long periods of time, but we could not achieve efficient fish growth past a surprisingly consistent limit of food introduced into the pond. Beyond this point, water-chemistry conditions made it too difficult to grow even the hardy tilapia very efficiently or rapidly. To regain good growth, we would have had to drain the pond, refill it with fresh water, reintroduce the fish.

The first section of this article delineates this limit to fish growth with our standard solar-algae pond methods. The second section describes a component we have added recently to some of our solar-algae ponds that circumvents the old limit.

This addition is a settling tank next to a series of connected solar-algae ponds. This modification doubles the amount of food we can introduce, and likewise the amount of fish growth we can expect.

Part 1: Growth Efficiencies Under Good Water Quality for All Experiments to Date

A summary of the feeding rates and growth relationships from selected solar-algae ponds from the summers of 1978 and 1979 illustrates our best tilapia fish growth (Table 1). In these experimental periods, during which water quality remained good, one gram of dry trout chow pellets led to approximately one gram of wet weight fish growth. Since the trout chow contains 8% nitrogen (by weight) and wet weight fish contains 4% nitrogen, the data indicates that the tilapia growth incor-

Table 1. FEEDING AND GROWTH DATA FOR SELECTED PONDS WITH GOOD WATER QUALITY.^{1,2}

Ponds(s)	Year	NSF Report No. Experiment No.	Length of Good Water Quality (Weeks)	Total Food Fed (G)	Total Nitrogen Fed (G)	Feeding Rate, (G food/Day)	Growth Rate, (G/Day)	Growth Rate, (lb/Yr)	Total Growth, (G)	Nitrogen Assimilation Efficiency (%)	Unassimilated Food (G)		
H	1978	3,2	3	2,210	172	105	75	60	1,575	44	1,238		
L	1979	4,1	5	2,485	194	71	71	57	2,485	49	1,267		
L	1978	3,2	6	2,562	200	61	68	50	2,856	48	1,485		
J	1978	3,2	8	5,147 ^a	196	92	44	35	2,464	49	2,514		
GHIJ	1979	4,3c	8	2,520	197	45	45	35	2,520	53	1,184		
K	1979	4,1	9	2,900	226	46	43	35	2,709	47	1,537		
Selected averages											198	2,435	48

^aRabbit feed (all others are trout chow).

porated roughly half of the nitrogen in the fish feed. Nitrogen is an interesting element to track because it is roughly proportional to protein content in feeds and fish biomass (though beware: different proteins contain different proportions of nitrogen, and different plants and animals contain different mixes of proteins) and because unassimilated nitrogen can be transformed into ammonia and nitrite, both toxic to fish. In all cases, a nitrogen input limit was reached, bringing an end to good water quality and rapid fish growth. We could stock a pond with between 20 and 400 fish, with an average size of 10–300 g per fish, at a density of 1–6 kilograms (kg) total per pond, and with good water quality could expect the same assimilation efficiency and growth. Once the limit of the pond to absorb the unassimilated feed was reached, growth declined. The trout feed data show the limit to be about 2½ kg of feed containing about 200 grams of nitrogen.

We also experimented with rabbit feed (see Table 1, Pond J, 1978). Rabbit feed contains half as much nitrogen and protein as trout chow, but costs one-third the price. The data suggest that the *nitrogen* input limit is nearly equal to trout chow. However, one must feed twice as much rabbit feed to put in the same amount of nitrogen. Since the fish are satiated by bulk of food (and not the nitrogen content), one cannot feed rabbit chow at twice the rate of trout chow. Even though the ultimate nitrogen input limits are nearly the same, the *rate* of nitrogen input must be lower with rabbit feed, and therefore the growth rates with rabbit feed must also be slower. Additionally, the ultimate nitrogen limit may also be lower for rabbit feed than with trout chow (Pond J had better long-term growth than two other replicate ponds with only beginning and end fish weights). This would be expected, since nitrogen in the feed is not the only contributor to declining water quality. The oxidation of carbonaceous materials also stresses the aquacul-

ture system, lowering oxygen and pH levels and increasing carbon dioxide concentration.

Good water quality did not last long in Pond H in 1978 (three weeks) because the feeding rate quickly exceeded the ability of the ecosystem to absorb the excess nitrogen. At slower feeding rates, bacterial transformation and algal assimilation appeared to maintain acceptable water quality for extended growth periods. The dynamics are very complex, with the algae preventing nitrogen from appearing in soluble form while keeping only a two-to-three-day supply of excess nitrogen in the living algae biomass at one time. The great majority of nitrogen accumulates in floating and sedimented dead algal cells and fish feces, and the release of nitrogen back into solution (as toxic ammonia) depends heavily on bacterial activity.

For all ponds except Pond H (Table 1), breakdown in the ecosystem's ability to absorb unassimilated feed occurred when total nitrogen put into the system had reached about 200 g. At this point fish growth in all ponds was about 2.4 kg regardless of the total growing time.

Certain peculiarities of algal behavior from summer 1978, data now seem more understandable. All three closely monitored ponds exhibited strong declines in algal density from September 9 to 11, coinciding with a loss of water quality for Pond L but not for Pond J (Pond H had already experienced an influx of toxic nitrite two weeks earlier). Here Pond L had reached "critical" total nitrogen while Pond J reached that level two weeks later.

Within the limits of the 10%–20% weekly water replacement strategy practiced with all of these ponds, the recycling of nitrogen and suspended detritus may reach a "critical" level. Accumulated nitrogen load may combine with algae crashes to determine the time when water quality declines sharply. To overcome this over an entire year, one would have to transfer the fish to fresh water each time 200 g of feed nitrogen had entered the pond.

It is important to point out that although fish growth almost always drops off after a nitrogen input of 200 g, a period of recovery sometimes follows in which fish growth resumes at a fairly rapid rate. In 1978, Pond H demonstrated this phenomenon. The recovery is probably due to increased food availability: teeming bacteria populations foster a bloom of edible high-protein protozoans.¹ Nitrogen assimilation efficiencies of recovered ponds, however, never exceeded about 30%.

With the drain and restart strategy, feeding rate and growth time can be chosen, keeping in mind the labor of restarting a pond. One can choose a five-to-nine-week growth period and apportion the 2.5 kg of food (equivalent to 200 g nitrogen) accordingly to achieve the final 2.4 kg of fish. Obviously, shorter growth periods are desired for higher continual fish production.

These growth statistics are based on experiments during summer months. It now seems reasonable to project short-term growth periods over a six-month growing season. The ponds would yield 10 kg of fish growth over this time if restarted every six weeks. Since the fish are capable of growing faster, other methods of water purification to remove nitrogen and stimulate algal activity seem appropriate.

Part 2. Methods of Extending the Period of Good Water Quality

There exist many biologically-sound water purification methods that can propel solar-algae pond fish culture beyond the food input limit described here. Many of these methods can be combined in one solar aquaculture system. Six approaches that we are presently experimenting with are as follows:

1. Enhanced Algal Assimilation of Ammonia, Phosphate, and Carbon Dioxide

Rapid algal assimilation of fish toxins occurs with strong algae growth. The article in this journal, "Modeling Algal Growth and Decline in Solar-Algae Ponds" argues that increasing the settling rate of suspended midwater particulates enhances algal growth and nutrient assimilation.

2. Enhanced Detrital Removal by Incorporating Auxiliary Settling Tank Components

This method removes organic material before it can decompose. Otherwise, the decomposition process will release toxic ammonia and carbon dioxide, and will consume beneficial oxygen. One example of this approach is described in Part 2 of this article.

3. Hydroponic Vegetable Culture (Nitrogen and Phosphorus Removal)

Hydroponic filters attached to solar-algae ponds can simultaneously purify water and produce vegetables. The sole source of nitrogen and phosphorus for the plants is the ammonia, nitrate, and phosphate dissolved in the water column. This design directly incorporates the wastes of one process as a resource for another food-production unit, and may prove critical for high-yield winter greenhouse aquaculture.

4. Nitrifying Bacterial Filter (Transforms Toxic Ammonia and Nitrate to Relatively Benign Nitrate)

Nitrifying bacteria within the solar-algae ponds presently oxidize toxic ammonia into nitrite and finally into benign nitrate. However, the bacterial populations may be severely limited by the amount of stable surface area upon which to form colonies. An attached bacterial filter with the correct flow-through rate may prove useful in avoiding high ammonia and nitrite concentrations by speeding up the nitrification process.²

5. Increased Exchange of Nutrient-Laden Water with Fresh Water

This approach "opens" the essentially closed solar-algae ponds researched to date. If the water is replaced in a slow continuous flow, the shock to the ecosystem of suddenly siphoning off and replacing a major fraction of the water column could be avoided. The removed water should be shunted to agriculture, since it is a fertile irrigant. Rapid water replacement should be avoided during winter operation unless the cold incoming water is pumped through a solar collector.

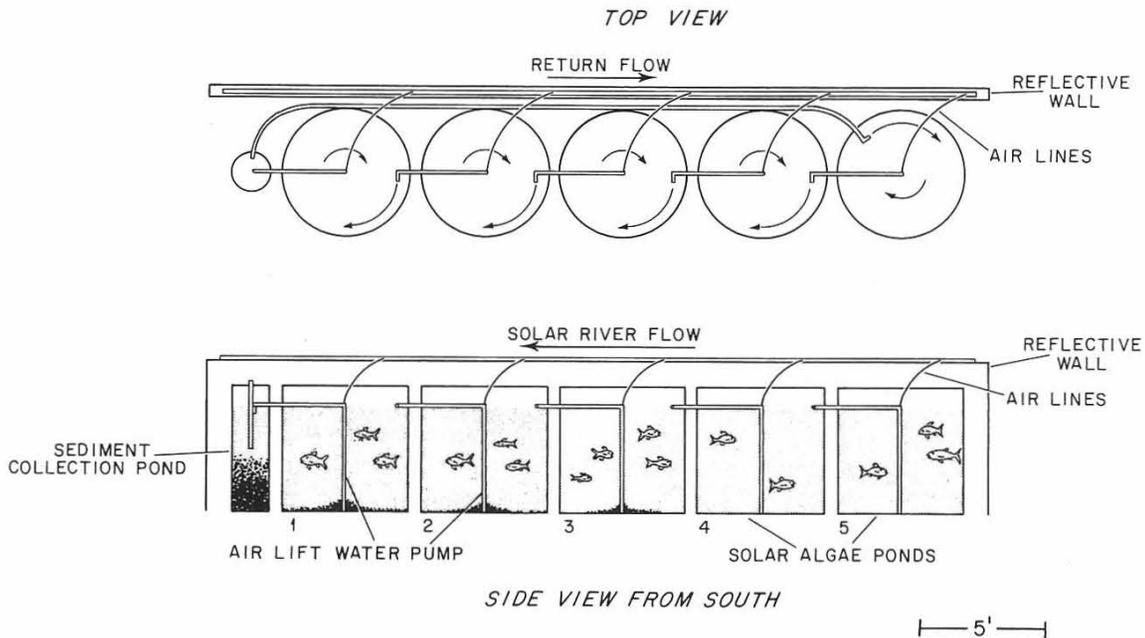
6. Bacterial Denitrification (Anaerobic Transformation of Nitrate into Nitrite and in Turn into Nitrogen Gas)

Denitrification has intentionally not been designed into solar aquaculture because it represents a direct loss of a nutrient source that could be further used in agriculture. However, recent analysis suggests that in the summer under heavy feeding rates, a significant portion of nitrogen in the solar-algae ponds appears to be unaccountably lost, and the most likely removal process is denitrification. Whether denitrification accounts for a predominant loss of nitrogen, and whether this should be

¹Schroeder, 1979. Reference 3.

²For filter sizing and flow rate determination, see Wheaton, 1977. Reference 4.

FIGURE 1
SOLAR ALGAE POND RECIRCULATING RIVER



enhanced for better water quality or discouraged on the basis of lost fertilizer value remains to be answered.

The next section reports the success of an early version of the second water purification approach (enhanced detrital removal) discussed above.

Part 3: A Recirculating Outdoor Solar River with a Settling Pond

Polyculture Feeding Trials in Linked Single-Skin Solar-Algae Ponds in Nonreflective Area (June 16 to October 28, 1979)

The solar river comprised five single-skin solar-algae ponds coupled to a settling tank roughly 5 ft tall, 18 in. in diameter, holding 66 gallons. (Ref. 5 describes another version of a solar river for trout culture). Figure 1 illustrates the arrangement. An airlift tube bubbled water up from the bottom center of each pond to an overflow at the edge of the next tank. The tube outlet faced clockwise to generate a mild circular flow in each tank, which tended to settle out the detritus at the centers of the ponds. After leaving Pond 1 and before re-entering Pond 5, water passed through the 66 gallon settling tank. The effluent from Pond 1 was piped to a point near the bottom of the settling tank to encourage the sedimentation of heavier detritus.

The total volume of the settling tank was drained once a day five times each week. This equals 10% of each pond's volume per week, much less than draining rates for the previous experiments. We hoped that this system would favor detrital removal while actually changing relatively low volumes of the water. This method required much less labor than siphon drain-down techniques.

We stocked the solar river ponds with high densities of tilapia (*Sarotheradon aureus*) and common carp (*Cyprinus carpio*). The carp were added 3½ weeks after the tilapia. Ponds 1 and 2 were each stocked with 600 tilapia, while Ponds 3, 4, and 5 were each stocked with 600 tilapia and 300 carp.

After shipping mortality of both species had subsided, heavy feeding was initiated with up to 150 g of trout food daily. Within two weeks, this high feeding rate led to substantial ammonia concentrations. Because the water had a high pH, much of this ammonia existed in its toxic unionized form. Feeding was then reduced until the ammonia disappeared. Water analysis showed that circulation was fast enough to create similar water quality conditions in all ponds.

Growth relationships for the solar river are summarized in Table 2. Final fish weights showed little growth for the carp species in all three polyculture ponds. The poor performance by the carp reinforces the results of earlier carp monoculture and

Table 2. SUMMARY OF GROWTH DATA FOR OUTDOOR SOLAR RIVER EXPERIMENT 4.

Variable	Pond 1	Pond 2	Pond 3	Pond 4	Pond 5
Total Food Input:	5,025 g trout food per pond.				
Tilapia Growth Period:	6/16-9/28.				
Carp Growth Period:	7/09-9/28.				
<i>Tilapia:</i>					
Initial population	600	600	600	600	600
Initial average weight	2.4 g	2.4 g	2.4 g	2.4 g	2.4 g
Final population ^a	361	416	382	399	366
Final average weight	10.9 g	11.3 g	11.9 g	11.3 g	10.9 g
<i>Common Carp:</i>					
Initial population	0	0	300	300	300
Initial average weight			3.0 g	3.0 g	3.0 g
Final population ^a	0	0	95	74	110
Final average weight			7.0 g	5.0 g	5.0 g
Total Growth rate (g/day)	49.6	50.7	48.9	45.3	40.3
Total Growth rate (lb/yr)	39.9	40.9	39.4	36.5	32.0
Nitrogen assimilation Efficiency (%)	39	40	39	36	32

^aThe one-third mortality of tilapia and the two-thirds mortality of carp occurred soon after stocking and was probably due to stress during shipping.

carp/tilapia polyculture experiments in solar-algae ponds.³ Nitrogen assimilation efficiencies represent primarily nitrogen assimilation by tilapia. The efficiencies of 32% and 40%, lower than the 44.50% efficiencies reported in Table 1, are expected on the basis of an early increase in ammonia concentration as well as the poor assimilation of food by the carp. Growth rates, however, gave a projected respectable yield of 14.7–18.5 kg per pond annually.

The method of draining small amounts of water from an auxiliary settling tank proved quite successful when the results were compared with the growth relationships found with 20% siphoning (Table 1). From Table 1, a decline in fish assimilation efficiency because of accrual of excess nitrogen would have been predicted at about six weeks. Instead, good water chemistry conditions and rapid growth continued for 20 weeks. Total food input to each pond was 5,025 g trout food, twice the feeding limit found in the ponds siphoned 20% weekly.

In conclusion, the settling tank system appears capable of selectively removing substantial quantities of detrital material containing nitrogen. Since the design is relatively easy to construct and its function is very effective, it holds great promise as one approach to enhancing solar-algae pond productivity.

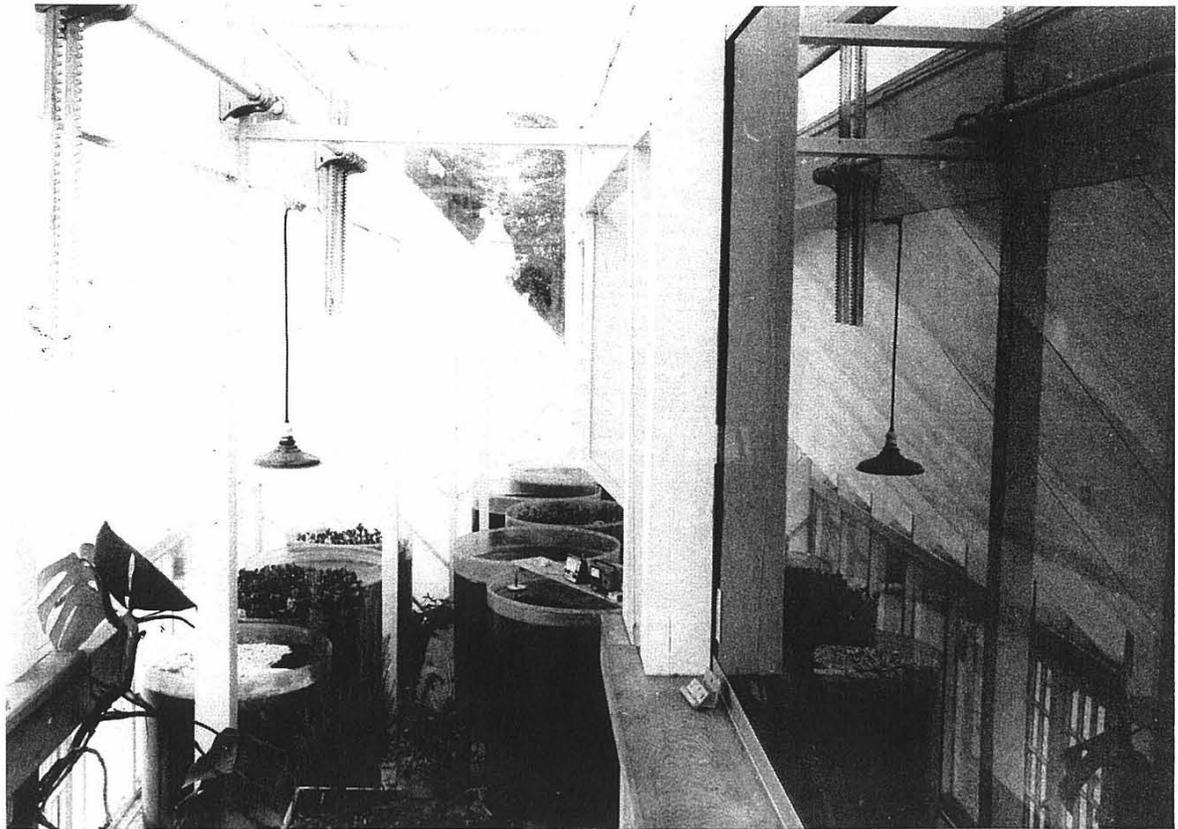
³Reference 1.

ACKNOWLEDGMENTS

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Modeling Algal Growth and Decline in Solar-Algae Ponds

John Wolfe, Ron Zweig, and David Engstrom

During the summer of 1978 the algae in the various solar courtyard ponds fluctuated in a remarkably similar pattern (see Figure 1; the darkest line indicates algal volume on each graph). All the algae peaked 24 to 30 days after the experiment's inception, then flocculated (clumped together) and declined rapidly to very low densities. The growth-and-collapse pattern occurred in all ponds, even though the dominant algal species differed: *Sphaerocystis Schroeteri* and a large *Chlorella* species in Pond J; *Scenedesmus quadricauda* in Pond L; *Micractinium pusillum* in Pond H. After about 80 days the algae tended to cycle upward slightly again. Since algal growth and decomposition strongly affect water chemistry, it is critical to understand the cause of algal fluctuations.

Why did the algae crash suddenly? Several hy-

potheses have been offered by biologists in our group and elsewhere. They include the following:

1. A period of sunny weather was followed by a period of cloudy weather.
2. The algae grew to a point at which they shaded each other's incoming light.
3. Shading occurred not only from live algal cells, but also from dead algal cells still suspended in the water column.
4. The algae depleted a nonrenewable micronutrient (the macronutrients phosphorus and nitrogen were in soluble form in sufficient concentrations in all cases at the time of collapse).
5. The algae released a toxin that accumulated as their numbers increased.
6. The algae were attacked by predatory bacteria with an exponentially growing population.

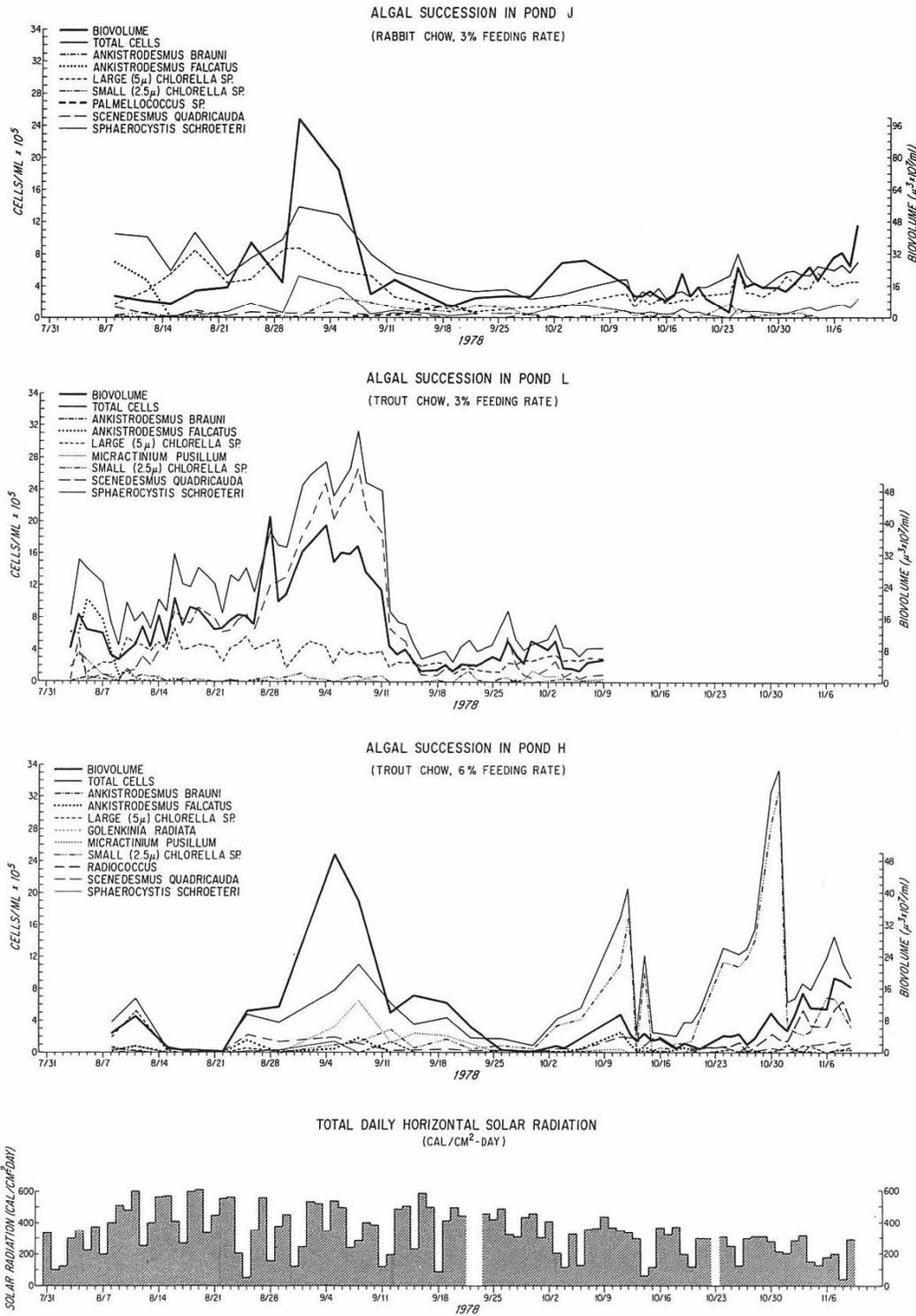


Figure 1. Modeling algal growth.

Most biologists would suspect that the last three hypotheses would be species-specific. We reject all three here because each pond displayed a different dominant species. An experiment has been devised to test Hypotheses 4, 5, and 6 (the experiment is scheduled to be carried out in the spring or summer of 1981).

The first three hypotheses all involve sunlight starvation. To compare these three hypotheses we expressed each hypothesis mathematically, and incorporated it into a computer simulation of solar-algae pond growth dynamics. To express the first hypothesis correctly, the solar radiation actually penetrating the walls and tops of the ponds, rather than the daily totals of horizontal solar radiation that we had recorded, had to be determined. A computer model, SOLAR6,¹ was devised to convert horizontal radiation measurements into the amounts of sunlight entering the solar-algae ponds.

Using SOLAR6, we put in horizontal solar mea-

surements in calories per square centimeter per day (cal/cm²/day) and got back the calculated solar energy entering the ponds (in cal/day).

These new data were the foundation of our first algal growth model. To express Hypothesis 1 mathematically, we can say the algae grew or declined according to Equation 1.

$$dA/dt = A(S - E)/T \quad (1)$$

where

- A = algal density
- S = solar energy reaching the water column
- E = the level of sunlight at which the algae neither grow nor decline
- T = a constant (units: energy × time)

Equation 1 states that external light levels entirely control algal growth. A simple computer program, written in the system dynamics language DYNAMO, was constructed around the preceding equation and solar input data generated by SO-

¹Wolfe, Engstrom, and Zweig, 1979. (Reference 5.) This article describes the principles and assumptions on which SOLAR6 is based.

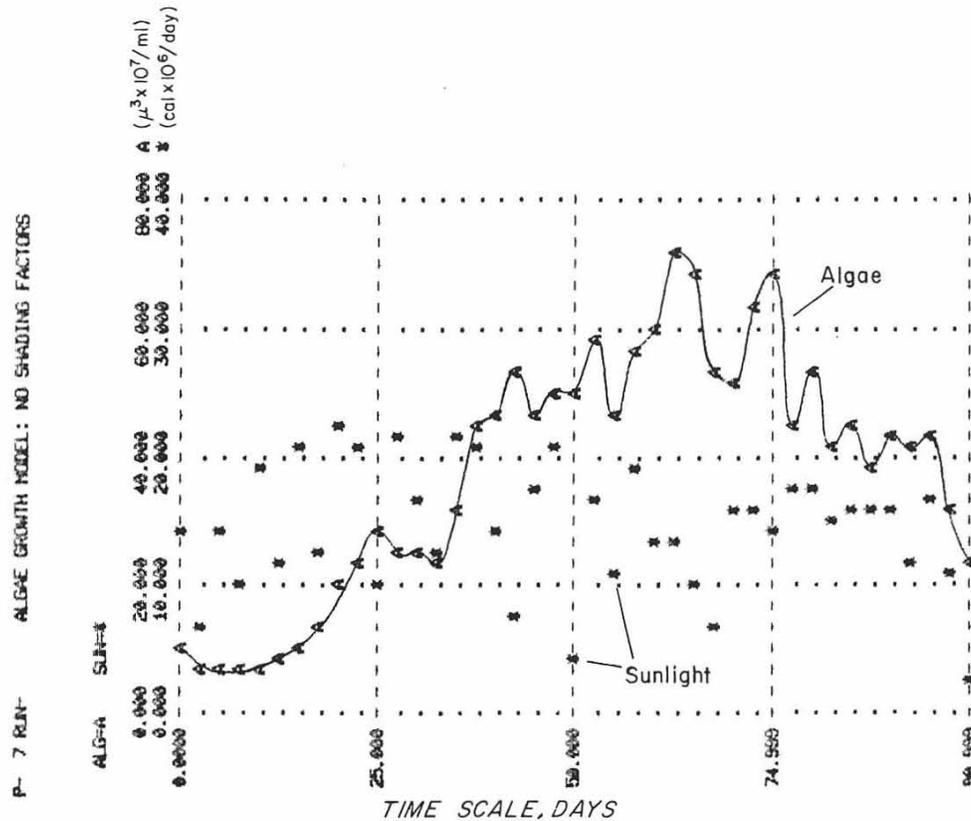


Figure 2. A run of the simple algal growth model based on solar energy fluctuations, with no shading factors. (Hypothesis no. 1)

LAR6. (For more information on system dynamics and DYNAMO, see the Bibliography.)

A run of the model is shown in Figure 2. The horizontal axis of the graph is time (in days). On the vertical axes, A represents algae volume and has the units ten million cubic microns per milliliter, and S stands for sunlight (measured in million calories per day). Unlike the algae curve, the points of sunlight on the plot remain unconnected because the time scale only shows a "snapshot" of light intensity every third day. Do not worry, though; the computer is using a complete daily sunlight data series and steps through time in tenth-of-a-day increments.

It is clear from inspecting Figure 2 that this model in no way approximates the early steep growth and decline of algae documented in Figure 1. No change in any of the model's parameters (excluding sunlight) created an output significantly closer to the real data than Figure 2. A more sophisticated model is needed.

Hypothesis 2, the self-shading of the algae, adds a limiting factor to the model's structure. Ex-

pressed mathematically, Hypothesis 2 might be written

$$dA/dt = A(b - bA/Sk_1) - Ad_1; \quad Sk_1 \geq A \quad (2)$$

where (in addition to terms defined for Equation 1)

- b = maximum algal growth rate (units: per day)
- d_1 = death rate of the algae (units: per day)
- k_1 = sunlight constant (units: algae volume/solar energy)

When solar inputs are very great, bA/Sk_1 approaches zero and $b - bA/Sk_1$ approaches b , the maximum growth rate. When the sunlight factor Sk_1 is smallest it equals A , and the growth term $b - bA/Sk_1$ equals zero and falls out, leaving only the death rate.

Figure 3 depicts the output using Equation 2 to express Hypothesis 2. As shown, the model generates an overall pattern of sigmoidal growth to a maximum limit. Random fluctuations in sunlight causes the output to oscillate around the general

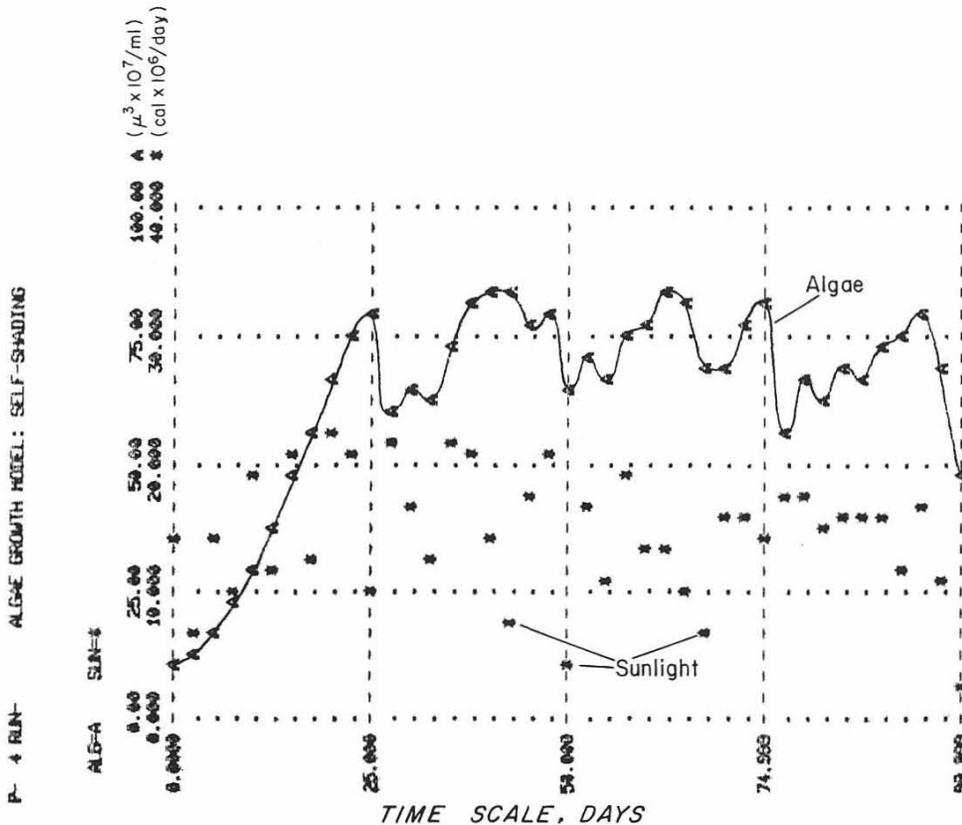


Figure 3. A run of the algae growth model with solar fluctuations and self-shading factors. (Hypothesis no. 2)

growth-to-a-plateau curve. This too, is not the general behavior displayed by the algal populations in the summer of 1978.

A third factor, shading from dead algal cells (Hypothesis 3) was then added to the model. As any microscopic examination of the pond water after the first month of an experiment will show, midwater detritus (largely dead algae) is a common element in the ponds—often more prevalent than the algae themselves. Mathematically, their influence can be expressed as

$$dA/dt = A[b - b(A + OK_2)/Sk_1] - Ad_1 \quad (3a)$$

$$dO/dt = Ad_1 - Od_2 \quad (3b)$$

where (in addition to terms defined for Equations 1 and 2):

O = dead midwater organics

k_2 = shading impact of organics relative to algae

d_2 = disappearance rate (settling and decomposition) for midwater organics

A DYNAMO flow diagram of the resulting model is shown in Figure 4. Figure 5 shows a run of the model.

As illustrated in Figure 5, this model produces a growth and collapse curve quite similar to the real summer, 1978, data for Ponds J, L and H. In the mathematical simulation the algae do peak at about the twentieth day rather than the twenty-fifth to thirtieth day as in the real data. However, unique start-up conditions, if included in the model, would delay the peak for a more precise fit. These start-up conditions are: 1) the heavy successful predation of the algae when the tilapia are first introduced, before inedible algae species are selected for, and 2) moderate nutrient limitations, before feed inputs cycle through the fish and are transformed by the bacteria to generate the nutrients phosphate, ammonia and nitrate.

How can the algal crash, with its eventual negative impact on water quality, be avoided? The model can easily assess one approach: increasing the settling rate of the midwater particulates. Min-

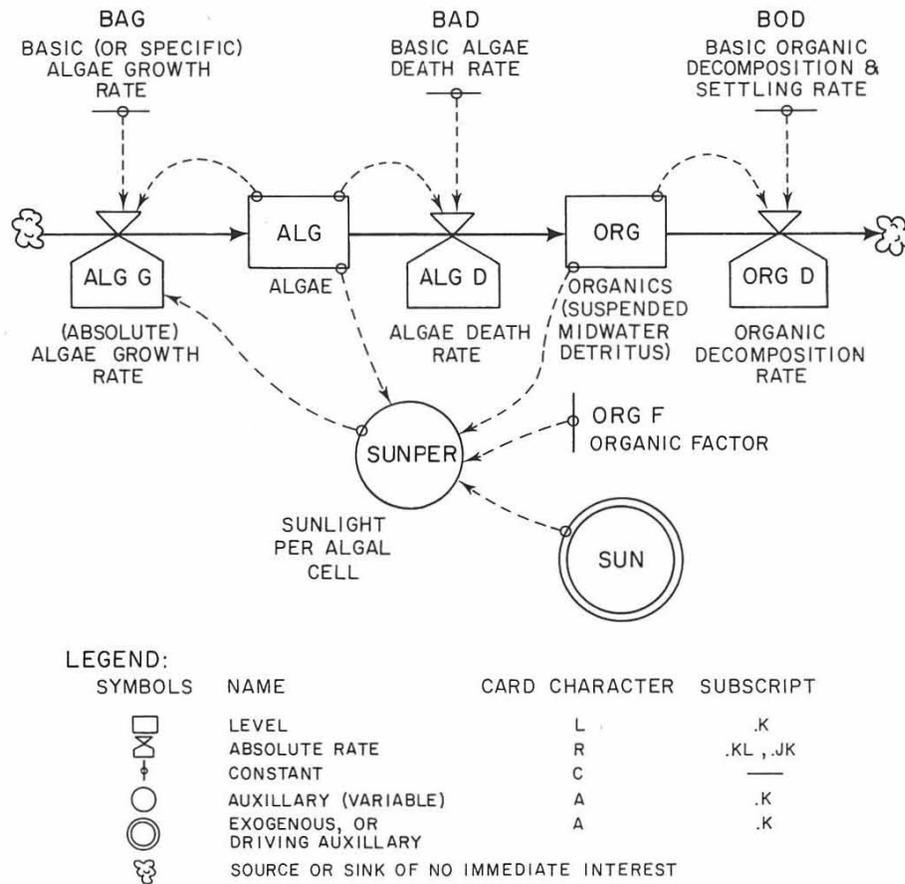


Figure 4. DYNAMO flow diagram of algae growth model.

imizing water turbulence from aeration and installing separate settling ponds can both increase the settling rate. Figure 6 shows a run of the model where the settling rate is raised from 3% to 10% of the organics per day. The algae peak slightly higher and do not decline nearly as far—their final equilibrium level exceeds the baseline run of Figure 6 by roughly three times.

The higher resulting standing crop of algae does not necessarily mean better water quality, however. Good water quality derives from algal growth rates—not algal density directly. Algal growth removes toxic ammonia and carbon dioxide from the water and releases beneficial oxygen. To tell whether the algal growth rate, as well as the algal standing crop, had increased with faster particulate settling rates, the algal growth and death rates were plotted. The plots (not shown) proved that faster settling rates increased both growth and death rates. The increased algal growth rate would have an

immediate beneficial impact on water quality. The increased death rate would eventually lead to decomposition and a loss of the gains made in water quality—unless the dead cells were removed in time.

This insight into the benefit of increasing the settling rate of particles suspended in the water column has inspired several new experimental designs. The new designs vary from adjacent settling or filtering units through which pond water cycles, to quiet zones within the pond created by vertical barriers across the bottom. Management solutions may include turning off water-churning aeration consistently during the day, or by relocating the air bubblers permanently from the pond bottom to halfway up the side of the pond, creating an undisturbed zone underneath. These methods should foster stronger, stabler algal growth, hence healthier water chemistry conditions and ultimately faster fish growth over longer periods.

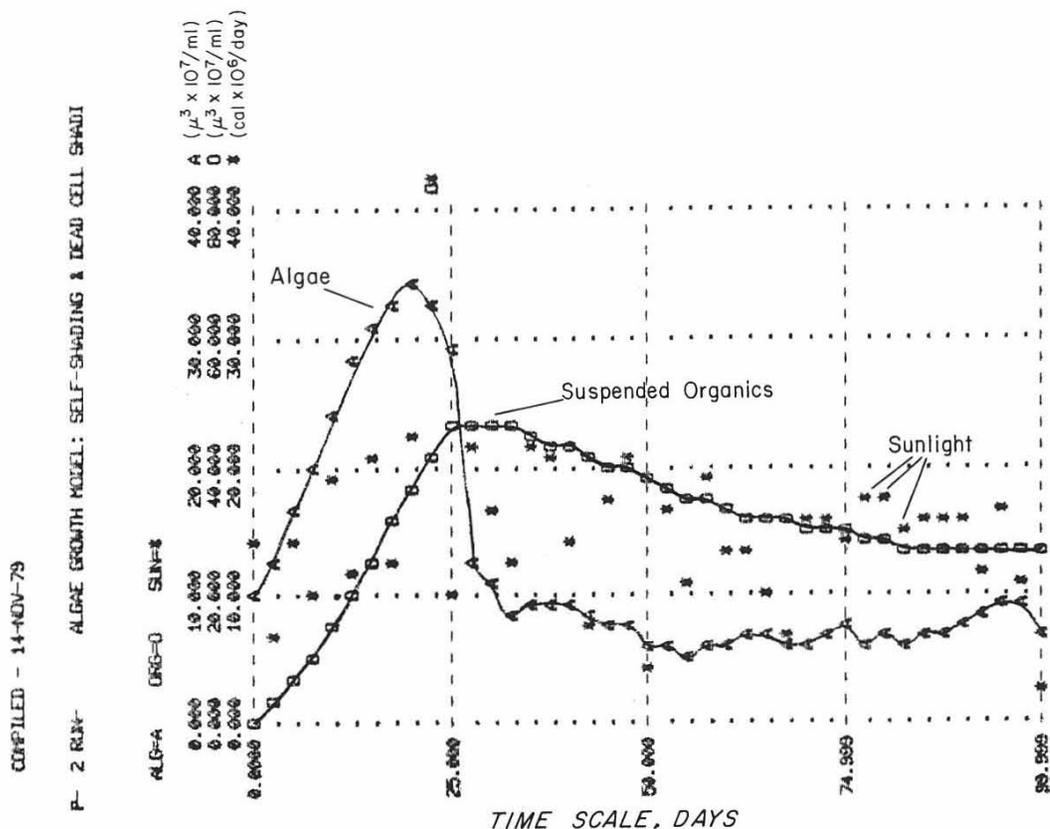


Figure 5. A run of the algae growth model with solar fluctuations, self-shading and mid-water particulate shading factors. (Hypothesis no. 3)

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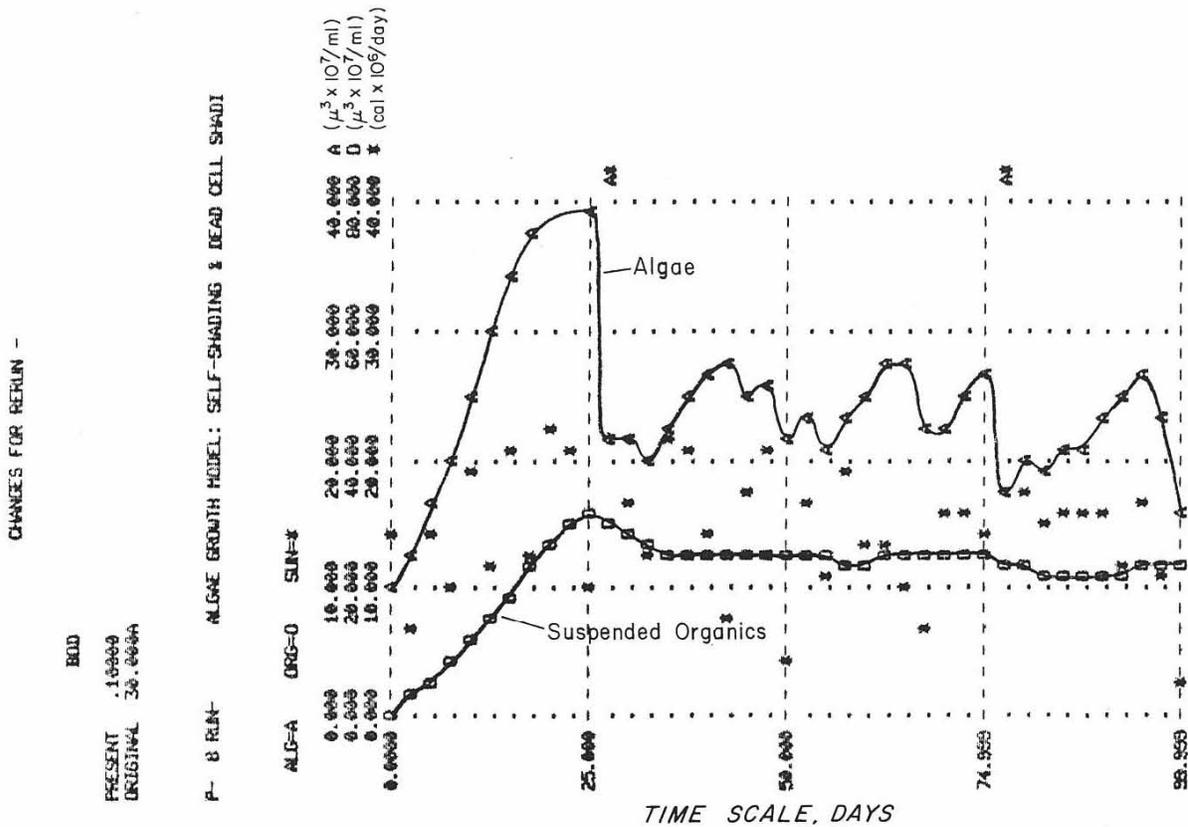


Figure 6. A run of the algae growth model based on hypothesis no. 3, with an increased midwater organics settling rate.