EMERGY SYNTHESIS:

Theory and Applications of the Emergy Methodology

Proceedings from the First Biennial Emergy Analysis Research Conference,
Gainesville, Florida, September, 1999.

Edited by
Mark T. Brown
University of Florida
Gainesville, Florida

Associate Editors
Sherry Brandt-Williams
Rookery Bay National Estuarine Research Reserve
Naples, Florida

David Tilley
Texas A&M University
Kingsville, Texas

Sergio Ulgiati
University of Siena
Siena, Italy

December, 2000

The Center for Environmental Policy
Department of Environmental Engineering Sciences
University of Florida
Gainesville, FL

14

Emergy Analysis Of Channel Catfish Farming In Alabama, USA

E. Ortega, J.F. Queiroz, C. E. Boyd, . and José M. G. Ferraz

ABSTRACT

The data concerning the environmental status of channel catfish farming in Central West Alabama, conducted by Auburn University, allow one to describe, for study purposes, a typical catfish farm with 40 ha occupied by ponds. Diagrams and spreadsheets were prepared in order to obtain emergy indexes to evaluate channel catfish production systems. The emergy indexes obtained are the following: Transformity = 650 000 sej/J, Renewability = 24%; Emergy Yield Ratio = 1.32; Emergy Investment Ratio = 3.0 and Environmental Loading Ratio = 3.2; Emergy Exchange Ratio = 1.7. Although these indexes revealed some similarity with USA conventional agriculture systems, catfish production was shown to be less dependent on non-renewable resources and its renewability is greater than other animal meat production systems. Finally, it is discussed how, through the adoption of best management practices, the above indexes for catfish farming may be improved.

Key Words: Aquaculture, Emergy Indexes, Sustainability.

INTRODUCTION

The world must choose between a "New Green Revolution" based on the energy of fossil sources or "Sustainable Agriculture" based on renewable resources (Ortega, 1997 and 1998). Aquaculture, like other biological production systems, depends on external and internal sources of energy that may be regarded as renewable and non-renewable. An appropriate measurement of energy flows in ecosystems could allow the measurement of their sustainability, for that purpose it is suggested to use Emergy, the "available energy used in ecosystems for production of resources" (Odum, 1971, 1983 and 1986). The proportion of renewable emergy used in relation to the total emergy consumed, is the index that measures the renewability of the system (Odum, 1996). This quantitative evaluation of sustainability could help the development of public policies according to the Agenda 21 Agreements (Ortega, 2000). The Emergy Indexes could provide scientific information to support public policies for environmental protection, such as taxes for water consumption and water pollution, in the transition to more sustainable aquaculture systems.

According to data provided by the Food and Agriculture Organization, the maximum sustainable yield for global capture fisheries of traditional aquatic species has already reached the sustainable limit of 100 million of metric tones per year. Initiatives to reduce capture originated a FAO Protocol, signed by more than 120 countries, to decrease progressively the volume of capture fisheries, beginning in 2003 (FAO, 1997). Meanwhile, the world demand for fish continued to grow, due to population growth but also due to health concerns with less fat and cholesterol. Aquaculture is an alternative to supply the increasing demand for good quality aquatic food at competitive prices but, as fisheries, also has limits.

Aquaculture is defined as the culture of aquatic organisms for human consumption and industry use. References of fish culture in China appeared 4,000 years ago. In 1996 world aquaculture contributed with more than 35 million metric tons of fish/year. The Asian countries contribute with more than 80% of the world aquaculture production. Catfish farming in the USA began in the 1940s and became the largest aquaculture activity in the country. In 1993, more than 200,000 tons of catfish were produced in 59,000 hectares of ponds (3,500 kg/ha/year). This activity is concentrated in the Southeast, and in Central West Alabama, catfish farming has had more than three decades of continuous economic success. During the past few years, a great increase in productivity was reached by the use of better feed, higher densities of fish per cubic meter of water, treatment of diseases and more efficient practices to control water quality. These technological developments allowed for more profits through a decrease in production costs and lead to the expansion of cultivated area (Boyd and Tucker, 1995), but public concerns in relation with the environment have recently appeared. Therefore, aquaculture must work towards the development of production systems based on "Best Management Practices" to prevent, mitigate and solve adverse environmental impacts (Boyd and Schmittou, 1999).

MATERIALS

Catfish (*Ictalurus punctatus)* farming is generally done in large man made ponds, in former croplands or pastures. According to Boyd and Tucker (1995) the ponds most frequently used in West Alabama are watershed and levee types. The ponds use runoff water and water pumped from wells or adjacent streams. The ponds have steel tubes that, in the periods of intense rain, allow for drainage of excess water. Complete drainage of ponds is done only every 6 to 10 years. The renewal of pond water is avoided for economic reasons. The size of the catfish farms varies from 4 to 60 hectares and the flooded area usually occupies 85% of farm. An economical size, for optimum benefit was estimated to be around 40 ha. The area of the ponds varies from 0.1 to 15 ha (average 5.4 ha) and pond depth from 1.2 to 1.5 meters. The basin drainage area that delivers water to watershed ponds is 6.32 ha per 1 ha of pond. The characteristic topography is gently rolling prairie and the source of water is rain, run off, wells and water streams.

Net seepage from ponds averages 1.5 mm/day (0.556 m^3/m^2/day) which does not represent risk of contamination of ground water by percolation of the compounds added to the ponds like lime, salt, chemical fertilizers and feed. Phosphate is usually adsorbed by pond soils and sediments and bound in largely unavailable form. Masuda and Boyd (1994), working with experimental channel catfish ponds at Auburn University, found that more than 66% of the phosphate added to feeds was bound in bottom soils. In a recent study (Boyd et al., 2000) demonstrated that adding salt to reduce problems of nitrite intoxication, does not appear to be a significant problem down stream. The amounts added do not raise chloride concentrations above levels tolerated by freshwater species endemic to the region. Therefore, since the chloride concentration in pond water is not high, its concentration in ground water produced by seepage might be low.

Every year the ponds are stocked with fingerlings, 10 to 15 cm long, produced in 7 to 10 months by hatchery farms. The type of feed used by the catfish industry consists of commercial pellets with 28-36% crude protein. The ratio between the weight of feed and fish produced in the pond is known as food conversion rate (FCR) and generally decreases with the increase of stocking density and feeding rates. Catfish are grown in ponds with stocking densities of 10,000 to 12,000 fish/ha and after 6 to 8 months they reach 400 to 600 grams. Then the catfish are seined, usually without draining ponds, and taken out of the ponds with a crane and placed alive in special trucks for transportation to fish processing plants, located in the area.

Aerators are used to maintain good levels of dissolved oxygen in the ponds. Aeration power applied to ponds varies from 1.5 up to 6 H.P./ha. Most catfish farmers do not use more than 3 H.P./ha (Boyd and Tucker, 1995). Normally, neither water exchange nor effluent treatments in settling basins or wetlands are used. Reconstruction of embankments is done when necessary and sediments are not disposed outside the ponds. Chemical products, such as lime, fertilizers, salt and algaecides are frequently used. Culture of another fish species, such as grass carp, is a common practice for macrophyte control. In many cases, the infiltration of water compensates the amount of water that is being pumped from the aquifers to supply the levee ponds. Electricity for pumping and aeration consumes 1,200 to 9,000 kWh/ha per crop. Representative values are 3,000 and 4,000 kWh/ha for humid and arid climates, respectively. Depending on humidity of climates (evaporation rate), infiltration, and draining frequency the electricity used for water supply and level maintenance varies from 500 to 2,000 kWh/ha (Shelton and Boyd, 1993).

Catfish farmers normally received US$ 1.76 per kg of catfish and the electricity usually costs US$ 0.06 to 0.10 per kWh in the Southeast of the USA. Electricity expenses constitute a small portion of catfish production cost (Boyd et al., 2000). The farm budget includes construction and maintenance of ponds, fingerlings production, mechanized fish feeding with trucks, mechanized fish seining, transport of supplies and other products, and farmer's family consumption.

The labor force is small and usually consists of a manager and some field workers to feed the fish on farms bigger than 80 ha. In smaller farms, the family assumes direct responsibility for maintenance, production and control of ponds. The intensity of work is larger during summer due to greater feed consumption and also due to problems with water quality - mainly eutrophication -, which requires aeration. Normally, families involved with catfish farming in Alabama have a good living standard. Small children – usually two per family – live with their parents until 17-18 years old, when they leave their homes to go to College.

Nowadays, catfish farming is being questioned from the ecological point of view. Main concerns are the large amounts of feed with high protein levels required to produce catfish in ponds, the chemical substances added to ponds and electric power demand for pumping and aeration. If seining is not done properly, sediments could be suspended and go down-stream, causing problems with water quality. Besides the adoption of the best management practices, such as those proposed by Boyd and coworkers (1995, 1999, and 2000), it will be necessary to develop more sustainable systems according to Agenda 21 Agreements. New production models must be discussed between the research centers, governmental agencies and producers, in order to reduce environmental impacts. In this study, Emergy Analysis is used to understand aquaculture systems performance and, in future research and it will be used to quantify the cost/benefit ratio of issues promoted by environmental regulations. If these efforts are successful, this technique could induce progressive environmental advances leading to more sustainable aquaculture systems.

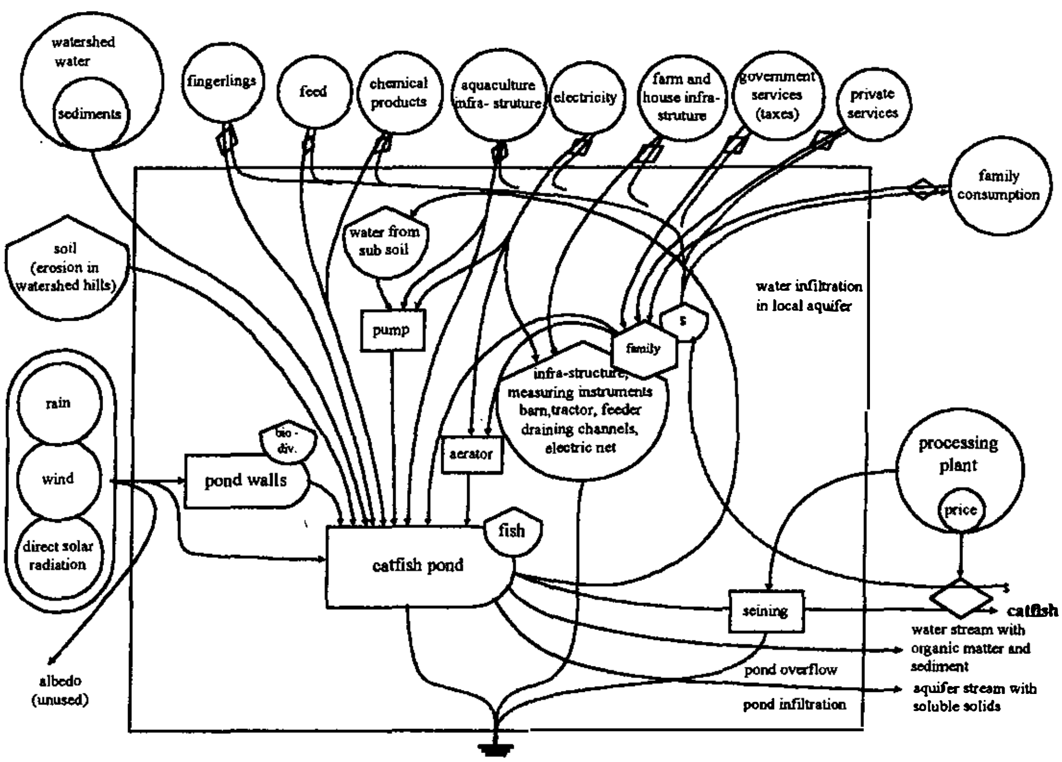

***Figure 1.** Energy flows diagram of a catfish farm in Central West Alabama, USA*

A graphical description of catfish farming in West Alabama is provided in Figure 1. All inputs of a typical catfish farm with 40 ha of grow-out ponds were considered, including contributions from nature and inputs from main economy. The flows can be transformed into emergy flows using "transformities" (Odum, 1996) and could be aggregated (Figure 2) as renewable (R) and non-renewable (N) nature resources; materials (M) and services (S) from economy and interpreted using emergy ratios (Odum, 1996), listed below.

Transformity: Tr = (Y/Qp) – it expresses how much resources are needed to outcome a specific product. Y is the emergy used to obtain a certain product. Qp is the energy of product.

Renewability: %R = 100 (R/Y) - it evaluates the sustainability of any kind of production system. It is expressed in percentage (%R), and is defined as the relationship between the emergy of renewable resources (R), such as, rain, sediments, superficial and ground water, biodiversity and soil, divided by total emergy used to produce a product (Y).

Emergy Yield Ratio: EYR = (Y/F) - it measures the incorporation of emergy from nature and it is expressed as the ratio of total emergy invested (Y), from nature (I) and economy (F), per unit of economy feedback (F), that considers material and services used.

Emergy Investment Ratio: EIR = (F/I) – it shows the relationship between the sum of materials and services (M + S) involved in the production process, expressed as economy feedback (F), and the sum of renewable and non-renewable natural resources expressed as (I). I is equal to R + N.

Environmental Loading Ratio: ELR = ((N+F)/R) – it represents the relationship between the non-renewable resources (N+F), divided by the renewable resources (R).

Emergy Exchange Ratio: EER = Y/[($).(sej/$)] – it shows the relationship between the emergy of product divided by emergy contained in the money received by its selling.

Transformity of human labor - In Alabama catfish farms usually the family takes care of the system operation. It was possible to estimate family consumption (material and services) and the work done by one person dedicated full time to carry out all production activities.

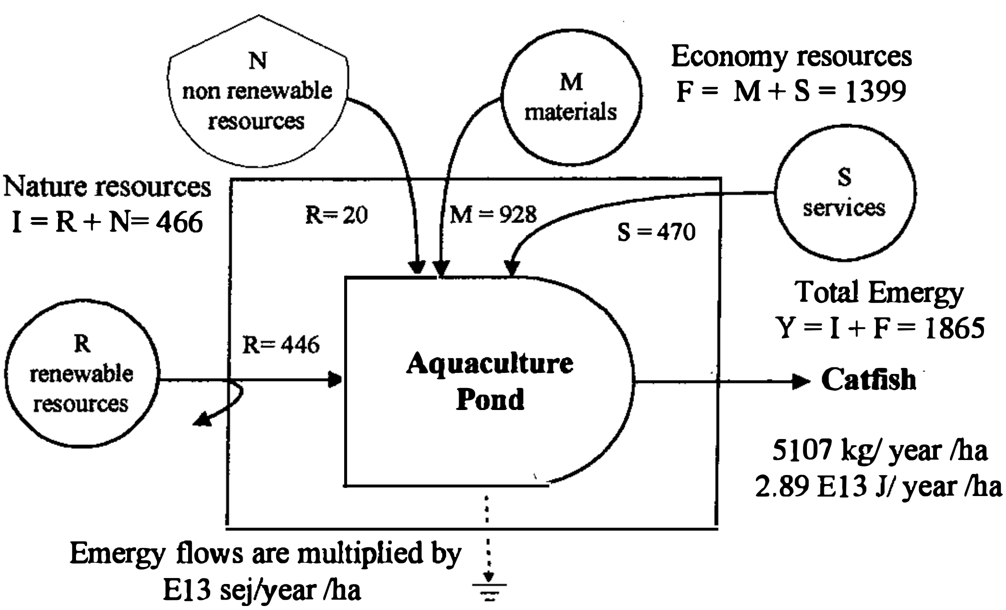

***Figure 2.** Aggregated Emergy flows diagram of a catfish farm in Central West Alabama.*

Sustainable Fish Farming Practices - Emergy indexes could be improved by the adoption of **Best Management Practices (BMP's)** described by Boyd et al., (2000). Their use may reduce impacts caused by site limitations, bad design, and poor management. For example:

Reduction of erosion and deterioration of water quality

It can be avoided (a) protecting the adjacent areas of catfish ponds with grass cover on denuded areas, (b) providing grass cover on the interior and exterior of pond embankments, (c) diverting excess water flow of large watersheds away from ponds, (e) minimizing erosion of pond bottoms and embankments caused by aerators placed at wrong sites.

Reduction of down stream pollution

It can be mitigated through: (a) avoiding discharge of water during final seining, (b) avoiding leaving ponds empty during winter, (c) shutting valves when ponds are empty, (d) closing valves when renovating inside earthwork, (e) using sediment removed from pond to repair the embankments, (f) extending drain pipes beyond the base of the embankments, (g) constructing ditches to minimize erosion, (h) using concrete structures to reduced the water current along the drainage channels, (i) extending drainage pipes until the streams to avoid bank erosion and releasing pond effluents into natural wetlands.

Overcome of pond support capacity

It can be prevented by avoiding (a) excessive fish density and (b) excessive feed use.

RESULTS

Emergy evaluation of channel catfish farming is given in Table 1. A summary of monetary costs and emdollar values of the resource use in channel catfish farming is given in Table 2. Emergy flows supporting channel catfish farming are summarized in Figure 2.

Transformity was calculated dividing the emergy used (Y = 1.865 E16 sej/y/ha) by the energy that catfish supplies when it is consumed as food (Qp = 2.89 E10 J/y/ha). The value obtained, 646,152 sej/J is similar to vegetable products transformity, which vary from 100,000 to 1,000,000 and slightly lower than other animal production systems in USA, such as, confined poultry and pigs (1,500,000).

The **renewability** (%R) obtained for catfish production in West Central Alabama is 24%. In other words, 76% of the emergy to produce a catfish comes from non-renewable resources (fossil fuels), which could characterize a non-sustainable system. Through the use of ecological techniques, regional planning and environmental policy this index could increase. Natural systems have renewability values close to 100%. The adoption of more sustainable techniques by catfish farmers, which might take profit from the use of natural energy sources, such as, run-off and biodiversity, could improve this system. Solar and also wind energy could be used for aerators and water pumps. Integration of animal breeding like, poultry and pigs, combining agriculture and forestry with aquaculture systems could provide ways to reduce the input of commercial feed in a polyculture fish production. Nowadays, fossil fuels supply the energy used in production systems all over the world. If they begin to decrease in the next decades the systems with lower percentage of renewability will face serious problems.

The **emergy yield ratio** obtained for catfish farming in West Central Alabama (1.33) is better than farm production systems using conventional agriculture, which are normally lower (1.10). This index could increase, from a minimum of 1.0 to values around 2 to 3 through the incorporation of ecological procedures, such as the integration of forestry and catfish systems.

The **emergy investment ratio** and the **environmental loading rate** have very close values. The EIR and ELR values obtained for the catfish industry in West Alabama varies from 3.0 to 3.2, values which are lower than the average for agriculture (7) and for animal breeding (8). Thus, when these indexes are compared to other animal production systems in use in the USA, the catfish industry appears to show better ecological behavior than poultry, pigs and cattle breeding whose values, on average, bigger (12.0).

The **emergy exchange ratio** shows that catfish production systems are losing emergy through exchange with the external system, which is composed of owners of the processing plants – their main fish buyers. Catfish systems in West Alabama spend 1.7 times more emergy to produce their fish than the value received in sales.

Table 1. Emergy Accounting Table

Resource	Quantity	Units	Conversion factor	SI flow	Units	Transformity (sej/unit)	Empower x E+13 sej/y/ha	%
Renewable								
Rain	1.33	m³/m²/ yr	4.94E+10	6.57E+10	J/y/ha	1.83E+04	119.9	6.43
Watershed water	0.42	m³/m²/ yr	4.94E+10	3.16E+10	J/y/ha	4.85E+0	153.2	8.22
Water from well	0.72	m³/m²/yr	4.94E+10	3.56E+10	J/y/ha	4.85E+04	172.4	9.24
Non-renewable								
Watershed sediment	3076.00	kg/y/ha	9.04E+05	2.78E+09	J/y/ha	7.38E+04	20.5	1.10
Materials								
Ponds and channels	160.0	$/y/ha		160.0	$/y/ha	1.25E+12	20.0	0.67
House and barn	160.0	$/y/ha		160.0	$/y/ha	1.25E+12	20.0	0.67
Machinery	160.0	$/y/ha		160.0	$/y/ha	1.25E+12	20.0	0.67
Fingerlings	3500	fish/y/ha		1.75E+02	$/y/ha	1.25E+12	21.9	1.17
Feed	6250.0	kg/y/ha	3.39E+06	2.12E+10	J/y/ha	2.00E+05	423.8	22.73
Lime	113.0	kg/y/ha		113.0	kg/y/ha	1.00E+12	11.3	0.61
Fertilizers	12.0	kg/y/ha		12.0	kg/y/ha	1.10E+12	1.3	0.07
Herbicide	0.5	kg/y/ha		0.5	kg/y/ha	8.24E+14	42.8	2.30
Algaecide -CuSO4	30.0	kg/y/ba		30.0	kg/y/ha	1.25E+12	3.8	0.20
Nitrite control -NaCl	800.0	kg/y/ha		800.0	kg/y/ha	1.25E+12	100.0	5.36
Other products	15.0	$/y/ha		15.0	$/y/ha	1.25E+12	1.9	0.10
Electricity	3000.0	kWh/y/ha	3.60E+06	1.1E+10	J/y/ha	2.00E+05	216.0	11.58
Fuel	230.0	kg/y/ha	4.48E+07	1.03E+10	J/y/ha	6.60E+04	68.0	3.65
Services								
Family labor	9.1	days/y/ha	1.23E+07	1.15E+08	J/y/ha	3.65E+07	417.9	22.41
External labor force	50.0	$/y/ha		50.0	$/y/ha	1.25E+12	6.3	0.33
Extern. management	120.0	$/y/ha		120.0	$/y/ha	1.25E+12	15.0	0.79
Public services	100.0	$/y/ha		100.0	$/y/ha	1.25E+12	12.5	0.66
Insurance	50.0	$/y/ha		50.0	$/y/ha	1.25E+12	6.3	0.33
Suhsidy	0.0	$/y/ha		0.0	$/y/ha	1.25E+12	0.0	0.00
Loan	100.0	$/y/ha		100.0	$/y/ha	1.25E+12	12.5	0.66

Catfish farm production

Total mass produced	5107	kg/y/ha			
Conversion factor	5.65E+06	J/kg	Price	1.76	US $/kg
Energy	2.89E+10	J/y/ha	Sales	8999	US $/y/ha
Emergy of product	1.86E+16	sej/y/ha	Emergy of sales money	1.1E+16	sej/y/ha

Results

Aggregated Emergy Flow	x E+13 (sej/y/ha)	Emergy Indexes	Shorten	Value
R	445.5.0	Transformity	Tr	646152
N	20.5	Emergy Yield ratio	EYR	1.33
I	**466.0**	Emergy Investment Ratio	EIR	3.00
M	928.3	Environmental Loading Ratio	ELR	3.19
S	470.4	Renewability (%)	%R	23.89
F	**1398.7**	Emergy Exchange Ratio	EER	1.66
Y	1864.7			

Table 2. Monetary costs and emdollar values of resources flows in channel catfish farming

Resource	Quantity	Units	Unitary price	Monetary cost (US$/y/ha)	**Emdollars (US$/y/ha)**
Rain	1.33	m^3/m^2 year	0	0	**959.2**
Watershed water	0.42	m^3/m^2 year	0	0	**1,225.7**
Water from well	0.72	m^3/m^2 year	0	0	**1,378.9**
Watershed sediment	3076.0	kg/y/ha	0	0	**164.1**
Ponds and channels	100.0	$/y/ha	1.00	100.0	**100.0**
House and barn	100.0	$/y/ha	1.00	100.0	**100.0**
Machinery	100.0	$/y/ha	1.00	100.0	**100.0**
Fingerlings	3500	fish/y/ha	0.050	175.0	**175.0**
Feed	6250.0	kg/y/ha	0.400	2,500.0	**3,390.7**
Lime	113.0	kg/y/ha	0.015	1.7	**90.4**
Fertilizers	12.0	kg/y/ha	0.270	3.2	**10.6**
Herbicide	0.5	kg/y/ha	8.850	4.6	**342.8**
Algaecide -CuSO4	30.0	kg/y/ha	1.800	54.0	**30.0**
Nitrite control -NaCl	800.0	kg/y/ha	2.130	1,704.0	**800.0**
Other products	15.0	$/y/ha	1.000	15.0	**15.0**
Electricity	3000.0	kWh/y/ha	0.070	210.0	**1,728.0**
Fuel	230.0	kg/y/ha	0.700	161.0	**544.1**
Family labor	77.0	h/y/ha	15.79	1,216.4	**3343.5**
External labor force	50.0	$/y/ha	1.00	50.0	**50.0**
External management	120.0	$/y/ha	1.00	120.0	**120.0**
Public services	100.0	$/y/ha	1.00	100.0	**100.0**
Insurance	50.0	$/y/ha	1.00	50.0	**50.0**
Subsidy	0	$/y/ha	1.00	0	**0.0**
Loan	100.0	$/y/ha	1.00	100.0	**100.0**
Total				6,764.9	**14,917.6**

Economic rentability:

$$\frac{\text{Net income}}{\text{Annual expenses}} = \frac{\text{Sales - Economic Cost}}{\text{Economic Production Cost}} = \frac{3270}{5729} = 57{,}1\ \%$$

DISCUSSION

Levee ponds probably have worse emergy indices than watershed ponds because they have fewer contributions from nature and demand more construction efforts.

The intensification of catfish production systems through the development of more sophisticated techniques over the last years provided better economic yields but reduced ecological performance. In order to achieve better economic yields farmers invested in machinery that led to higher inputs and costs per area of production. The increase of fish stocking will demand the increase of feed supply to the ponds, and this situation could lead to the accumulation of greater amounts of uneaten feed and faeces on the pond bottom. In this case the organic matter decomposing rate could be overcome causing the increasing of BOD and the reduction of FCR. Boyd et al (2000) suggests the adoption of lower stocking and feeding rates which will improve emergy yield rate, due to the reduction of fingerling acquisition, feed consumption and environmental loading rate. These measures will promote better water quality conditions, recovery of food conversion rate and less stress to culture fish reducing disease occurrence. This approach will directly improve the survival and the productivity rates.

USA aquaculture could face problems due to market opening in consequence of globalization. Thus, production systems based on non-renewable natural resources may not be able to compete with systems characterized by lower economic investment (F) and greater contribution by nature (I), and may become uneconomical. New technical designs combined with regional planning and trade rules must be considered to evaluate and conduct development strategies for systems, which now demand higher non-renewable inputs.

CONCLUSIONS

Agriculture systems currently used in the USA are dependent on non-renewable resources, such as fertilizers, pesticides and chemical products, involved in the manufacture of basic ingredients and services. The emergy indexes obtained for the catfish industry in West Alabama confirms that dependence, but it is smaller compared to other animal protein production systems.

The price of petroleum is kept below its real value, creating a subsidy to the products, directly and indirectly obtained from it. Nevertheless, this resource is limited and according to specialists like Campbell (1997), oil crises cannot be avoided in the near future and strategies to reduce the dependence on fossil fuels must be taken into consideration for further development planning.

The applications of the BMP's will allow some improvement of the efficiency of aquaculture systems in general by reducing loses of soil by erosion and water by overflow, run off, seepage, evaporation and harvest. As materials and services also count in the calculations of the total emergy used to produce a certain product, they need to be well managed. For example, by using better fish feeds with lower concentrations of protein of animal origin there will be a lower potential to pollute the water in the fishponds.

Better fish feeds means better food conversion rates, which also means better water quality, effluents with lower concentrations of nitrogen and phosphorous and minor eutrophication of water streams. This also implies in lower costs of production, due to better efficiency of feed uptake by the fish which has a direct impact on the quantity of materials needed for fish production, like mechanical aerators and fish feed. Where a low quality fish feed is used combined with poor pond management, an increase in services such as the amount of aeration, disease control and algae bloom control, will occur.

Besides this, the recommendations for more sustainable agricultural systems, suggested by the Agenda 21 Documents, at global and national levels, could be a guidance to make progressive adjustments to reduce environmental and social impacts caused by the production systems presently in use all over the world.

Catfish farming in West Alabama has already proved its profitability over the last decades and its benefits in improving the standards of life in that particular region in the USA. The biggest challenge for the catfish industry will be the development and adoption of culture systems and management techniques less dependent on non-renewable resources. Further studies need to be realized in order to answer these questions.

Suggestions For Future Studies

Some innovations in relation emergy methodology were achieved, such as identification of family consumption and calculation of labor transformity and inclusion of economical accounting side by side with emergy flows in the same spreadsheet. However new achievements will be necessary for future emergy calculations regarding the description and measurement of water, phosphorous and sodium cycles, estimation or measurement of seepage water (quantity and quality), discussion of how to consider NaCl (as renewable or not). As well as the substitution of money flows by material or energy flows when possible. Better description of the correspondence between BMPs and Emergy Indexes is necessary. A complete study of liquid, gaseous and solid effluents, estimation of emergy needed for effluent treatment. The application of mathematical models and computer simulation to verify the positive effects of the adoption of sustainable practices will be done in further studies.

ACKNOWLEDGEMENTS

We express our gratitude to Ms. Hilary Castle de Menezes, Carla Lanzotti, Mara Cornelio and Maria Conghos of FEA-Unicamp for their kind support in the preparation of this paper.

REFERENCES

Boyd, C. E. 1995. Bottom Soils, Sediment and Pond Aquaculture. Chapman and Hall, New York. 348 pages.

Boyd, C. E., Queiroz, J. F., Whitis, G. N., Rowan, M., Lee, J., and Amit Gross. 2000. Environmental Assessment of Channel Catfish Farming in Alabama. Journal of world Aqua culture sociaty. Vol. 31, No.4 p 511-544.

Boyd, C. E. and C. S. Tucker. 1995. Sustainability of channel catfish farming. World Aquaculture 26:45-53.

Boyd, C. E. and H. R. Schmittou. 1999. Achievement of sustainable aquaculture through environmental management. Aquaculture Economics and Management. Volume 3, No. 1. 1999. 59-69 pp.

Campbell, C. J. 1997. "The Coming Oil Crises", Multi-Science Publishing Company & Petroconsultants.

FAO. Food and Agriculture Organization of the United Nations. 1997. Aquaculture Production Statistics – 1985-1994, 1997. Fisheries Circular No. 815. Revision 8. Fishery Information, Data and Statistics Unit, FAO Fisheries Department, Rome, Italy.

Masuda, K. and C. E. Boyd. 1994. Effects of aeration, alum treatment, liming and organic matter application on phosphorus exchange between pond soil and water in aquaculture ponds at Auburn, Alabama. Journal of the WorldAquaculture Society 25:405-416.

Odum, H. T., 1971. Environment, Power and Society. John Wiley & Sons, New York.

Odum, H.T. 1983, 1993. Ecological and General Systems (formerly Systems Ecology). Univ. Press of Colorado, CO.

Odum, H.T. 1986. Emergy in ecosystems. pp. 337-369 in Environmental Monographs and Symposia, ed. by N. Polunin, John Wiley, NY.

Odum, H.T. 1996. Environmental Accounting, Emergy and Decision Making. John Wiley, NY. 370 pp.

Odum, H. T., 1998. Emergy Evaluation, in "Advances in Energy Studies: Energy Flows in Ecology and Economy", Proceedings of International Workshop held at Porto Venere, Italy, May 26-30, 1998, ed. by Ulgiati, S.; Brown, M. T., Giampietro, M.; Mayumi, K. & Henderson, R. MUSIS, Rome, Italy, pages 99 -112.

Ortega, E., 1997. "Sustainable Development and Integrated Systems for Food and Energy Production". First Workshop on New Paradigms of Science, Federal University of São Carlos, SP, Brazil, October 26. http://www.unicamp.br/fea/ortega/sustain/slide1.htm

Ortega, E., 1998. "Contabilidade Ambiental e Econômica de Projetos Agro-industriais", Conference at XVI Brazilian Food Science and Technology Congress, RJ. http://www.unicamp.br/fea/ortega/sustain/slide01.htm

Ortega, E., 2000. "A sustentabilidade na produção de alimentos e a Agenda 21 do Brasil", Conference at XVII Brazilian Food Science and Technology Congress, CE. http://www.unicamp.br/fea/ortega/agenda21/index.htm

Shelton, J. L. Jr. and C. E. Boyd. 1993. Water budgets for aquaculture ponds supplied by runoff with reference to effluent volume. Journal of Applied Aquaculture 2(1): 1-27.

Appendix Table. Calculation of transformity of labor used in channel catfish farming

Family consumption

Resource	Quantity	Units	Factor	Flow	SI units	Tr (sej/unit)	Emergy (sej/y/ha)	%
Water	36000.0	kg/y/ha	4940.00	1.78E+08	J/y/ha	1.00E+05	1.8	0.10
Electricity	4000.0	kWh/y/ha	3.6E+06	1.4E+10	J/y/ha	2.00E+05	288.0	15.44
Food	116.8	kg/y/ha	1.02E+07	1.2E+09	J/y/ha	5.00E+05	59.4	3.19
Clothes	80.0	$/y/ha		80.0	$/y/ha	1.25E+12	10.0	0.54
Health	80.0	$/y/ha		80.0	$/y/ha	1.25E+12	10.0	0.54
Education	80.0	$/y/ha		80.0	$/y/ha	1.25E+12	10.0	0.54
Leisure	80.0	$/y/ha		80.0	$/y/ha	1.25E+12	10.0	0.54
Telephone	30.0	$/y/ha		30.0	$/y/ha	1.25E+12	3.8	0.20
Fuel	200.0	$/y/ha		200.0	$/y/ha	1.25E+12	25.0	1.34

Family labor transformity

Emergy consumed by family	4.18E+15	sej/ha/year
Energy of farm local labor	1.15E+08	J/ha year
Energy per day	1.23E+07	J/day
Transformity (energy basis)	3.65E+07	sej/J
Transformity (time basis)	45.8E+14	sej/day
Transformity (time basis)	5.70E+13	sej/hour