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Emergy Evaluation of Salmon Pen Culture

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Abstract. *Emergy* (spelled with an "m") and its economic equivalent *emdollars* evaluate the work done by the environment and by the human economy on a common basis. Making choices that maximize emdollar contributions of environment and economy is a useful public policy.. Emergy-emdollar evaluation of salmon pen culture is presented in this paper as an example of the calculations and interpretation. The procedure evaluated the estuarine contribution as well as those made by the pen operators. Like other environmental products, salmon contribute more emdollars to the economy than are recognized with market values. The buyer receives 2 times more emdollars than is paid in dollars. After the salmon are processed and used by the consumers, more emergy values are added directly and indirectly from the fuels and other resources operating the rest of the economy. In the United States, 7 emdollars from the outside economy are attracted to each emdollar of local environmental product. The solar transformity of salmon = emergy/energy = 1.7×10^7 solar emjoules/joule, a high value compared to most fish. A similar value was obtained from evaluating the natural salmon life cycle in the Umpqua River, Oregon. However, the emdollar value of the original salmon run was less than that of the hydroelectric potential.

Keywords: salmon, emergy, valuation, aquaculture, estuaries

1. INTRODUCTION

Emergy valuation (spelled with an "m") is the work of one kind required to produce a product or service. Emdollars, abbreviated Em$, is the part of the gross economic product whose buying power was contributed by the product. Emergy and emdollars measure human service and environmental services on a common basis. The method externalizes the internalities. At this conference the author reviewed emergy valuation concepts and examples, summarizing the book, Environmental Accounting (Odum, 1996). However, for this proceedings, the method may be explained best by presenting a sample evaluation, emergy of aquaculture of salmon in floating pens.

1.1. Concepts and Definitions

Real wealth is defined here to mean any product or service that requires available energy to create and maintain such as food, clothing, housing, information, art, culture, landscape, forests, aesthetics, etc. In any local area real wealth is generated by the landscape system interacting with the economy (Figure 1). The diagram shows inputs of two kinds. Local free environmental inputs come from the left, and purchased inputs brought into the area from the economy elsewhere are shown from the right. Note that money only circulates to pay for the services part of the real wealth from the right.

Money cannot be used to evaluate environment completely because money is paid only to people. People are paid for the work they do, but the environment is not paid for the necessary work that nature does such as processing waters, building soils, and cleansing air. When the contribution of the real wealth of fisheries, timber, fertile soils, and aesthetic nature is abundant, prices are low and the economy gives it little market value. When environmental inputs are scarce and contributing very little, prices are high. Market values of environment are inverse to real wealth contributions to public life support.

Emergy, a measure of real wealth, is defined as the sum of the available energy (exergy) of one kind previously required directly and indirectly through input pathways to make a product or service (unit: emjoules). In this paper solar emergy is used with the unit solar emjoule (abbreviation: sej).

Empower (J_{ems}) is the emergy flow per unit time (units: solar emjoules per year (abbreviation: sej/yr).

Figure 1 shows the essence of interfaces between economy and environment, money circulation, and the pathways evaluated by emergy.

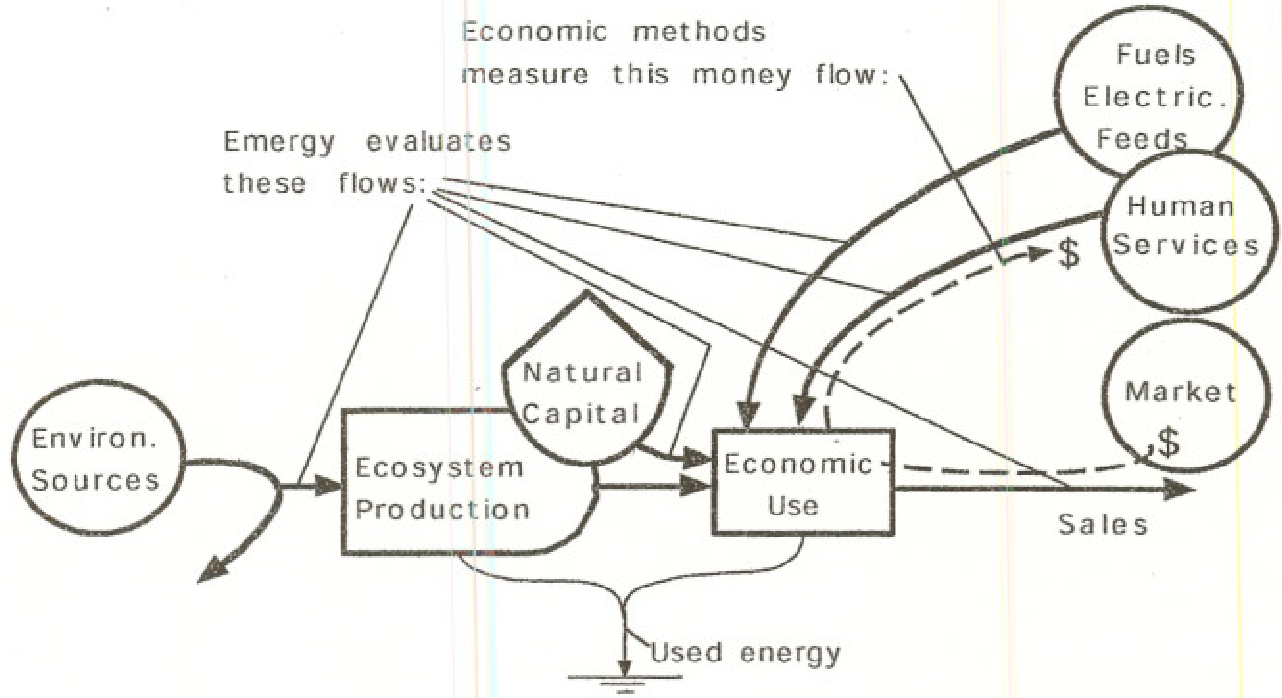


Figure 1. Interface between local environmental production and the human economy.

Figure 2 explains the way energy transformations form a series with energy decreasing at each step. In this simplified example solar emergy (solar emjoules) on the left drives the series and is constant along the series.

<u>Transformity</u> of a product or service is defined as the emergy divided by the energy. In Figure 2 the ratio of the driving solar emergy to the remaining energy (the solar transformity) increases from left to right, a measure of the quality of the energy at the higher levels on the right. Tables of transformities are very useful in valuations. Energy flows (power) can be multiplied by transformities to get emergy flows (empower).

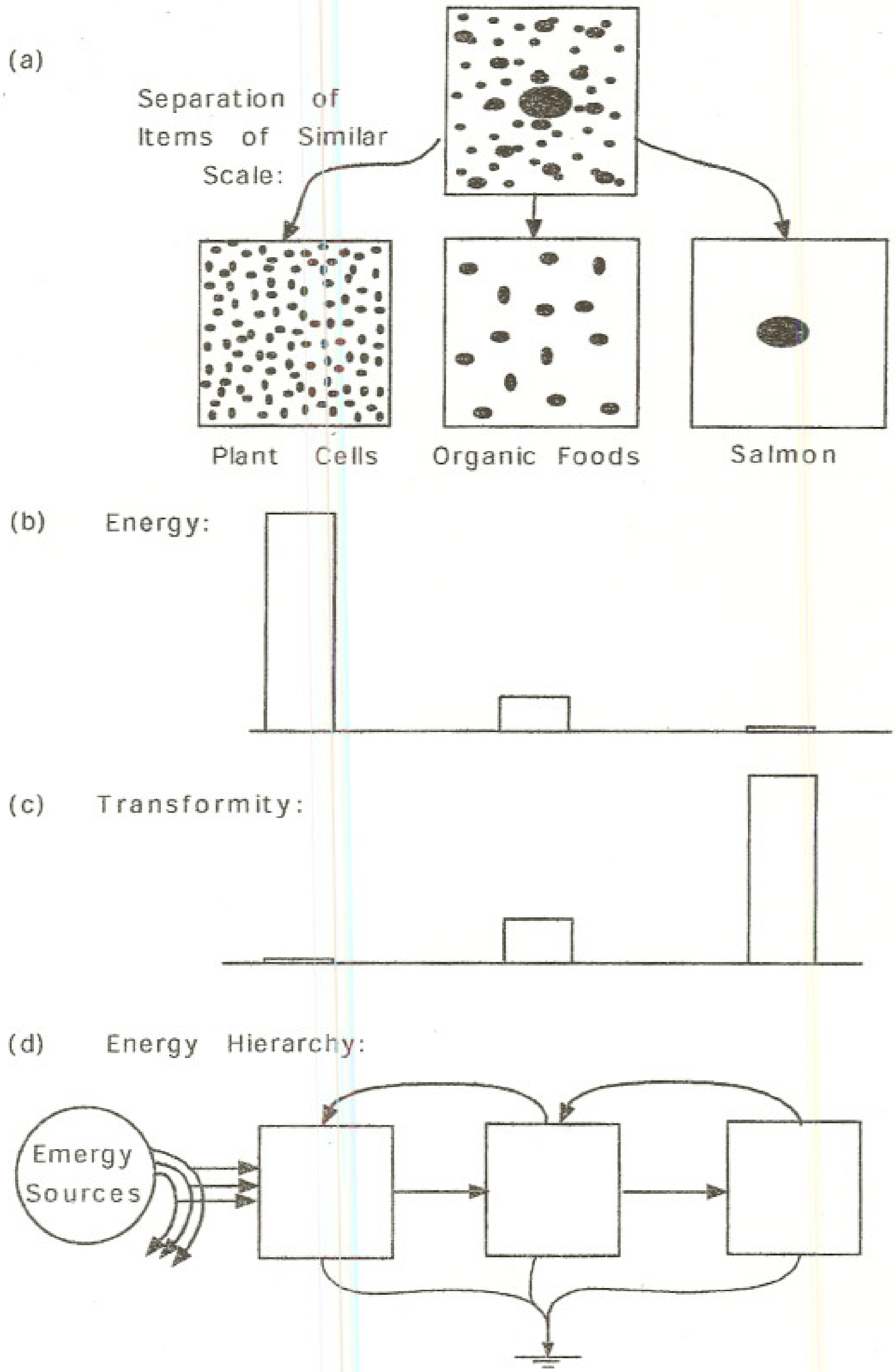
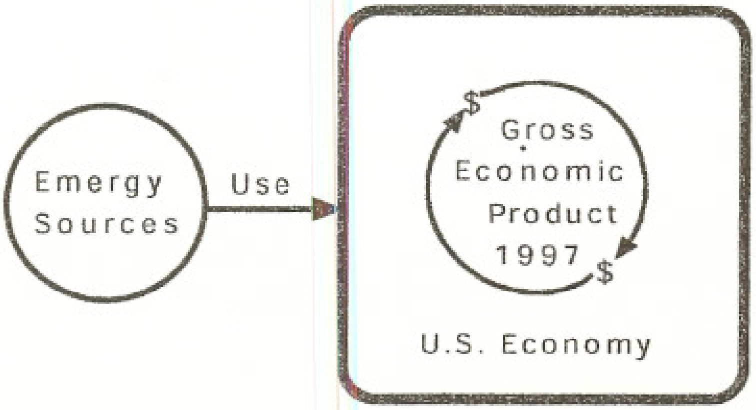


Figure 2. Energy hierarchy concept: (a) Increasing sizes and territories; (b) energy flow; (c) transformity = emergy/energy; (d) Energy systems diagram showing emergy inflows supporting the energy transformation series.

Figure 3 summarizes the annual emergy use by a state. The total emergy used in a year is divided by the gross economic product to get the emergy/money ratio (emjoules/$) for that year. Monetary data on goods and services given in $ can be converted to emergy with the average emergy/ money ratio.



$$\text{Emergy/Money Ratio} = \frac{\text{Emergy Used}}{\text{Gross Economic Product}} =$$

$$\frac{9.1 \times 10^{24} \text{ solar emjoules/year}}{8.1 \times 10^{12} \text{ \$/year}} = 1.12 \times 10^{12} \text{ solar emjoules/1997 \$}$$

Figure 3. Relation of emergy use and money circulation

1.2. Evaluation Procedure

The following are the steps for evaluating a system with an emergy evaluation table. The procedure is used in this paper for evaluating an example of salmon pen aquaculture.

A. Draw an energy systems diagram that helps convert verbal models to quantitative energy and mathematical systems languages.
B. Set up an emergy evaluation table with a line item for each input, for each product, and each sale.
C. Evaluate flows with usual units, joules, grams, dollars, individuals, etc. Multiply each rate of flow by the emergy/unit to get annual emergy flow (empower).
D. Divide annual emergy flows by emergy/money ratio of the surrounding economy to find the gross economic product equivalent of the emergy contribution.
E. Sum the emergy inputs to evaluate the products.
F. For interpretation, calculate emergy indices: transformities of products, exchange ratios, net emergy ratios, investment ratios, etc.

To evaluate the quality of a yielded product, a transformity can be calculated and compared with that of other products.

<u>Net emergy ratio</u> is calculated to determine the net benefit of an economic use of an environmental resource. It is the ratio of emergy yield to the economy divided by the emergy used from the economy.

To anticipate whether inputs from the economy are well matched with free resources, <u>the emergy investment ratio</u> is calculated. It is the ratio of emergy used from the economy divided by the emergy supplied free from the environment.

The <u>exchange ratio</u> indicates the advantage to the buyer in real wealth received. It is the emdollars in product received divided by the dollars paid by the buyer.

2. EVALUATION OF A SALMON PEN

The main contributions to salmon pond culture from nature and from the economy are shown in the energy systems diagram in Figure 4, using energy systems symbols. Full explanations of the energetic, mathematical, and hierarchical meanings of the symbols are available in many places (Odum, 1971, 1983, 1996, 2000). Each of the main pathways carrying emergy into the process across the selected boundary is a line item in the annual emergy evaluation Table 1.

The estuary contributes support and flushing of low nutrient waters, well aereated with dissolved oxygen. Salmon in pens generate nutrients from consumption and respiration which the waters remove and dilute. To prevent eutrophic conditions that would be unhealthy for the salmon and interfere with other marine life, the water exchanges should keep low nutrient concentrations in the estuarine waters. Phosphorus less than 50 parts per billion was used for the calculation of the necessary exchange rate, with the expectation that other nutrients will be similarly limited).

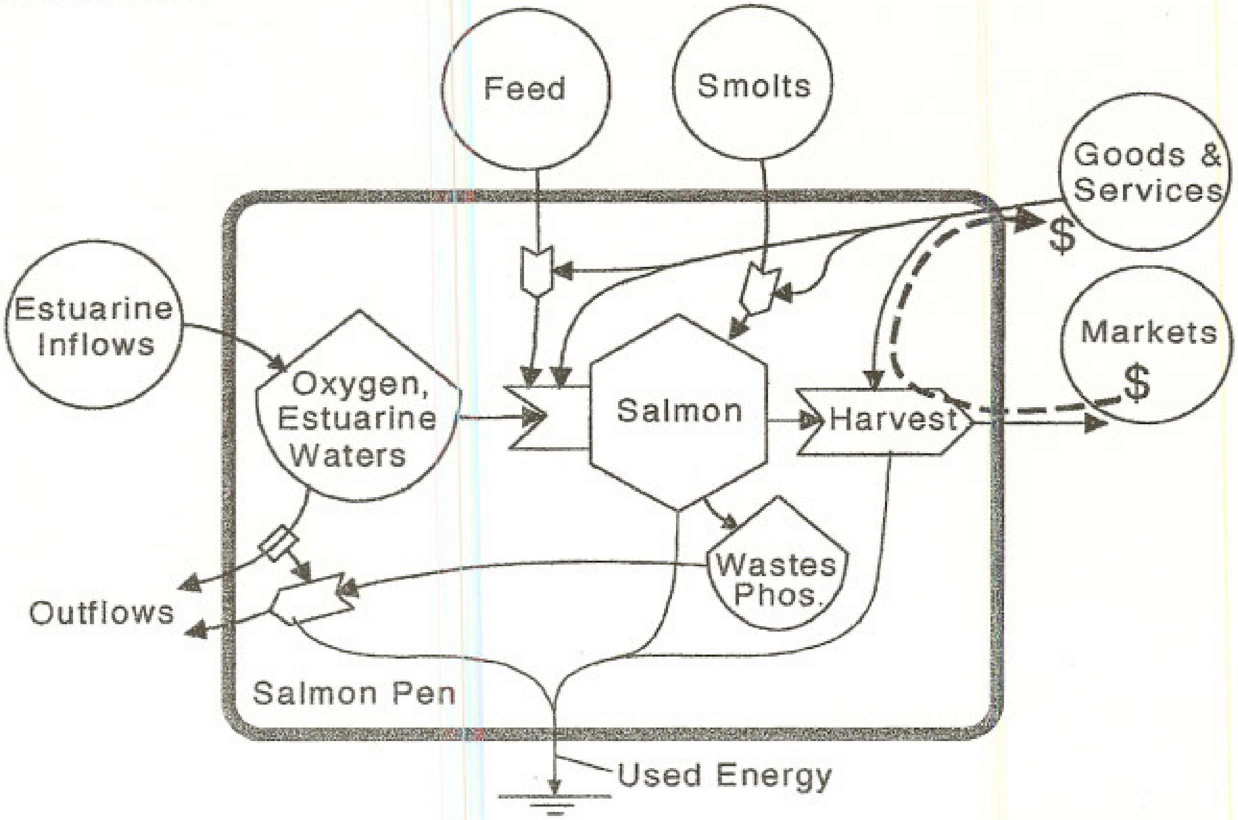


Figure 4. Energy systems diagram of the main inputs and products of a salmon pen operation.

Table 1
Emergy Evaluation of a Salmon Pen in British Columbia*

Note	Inputs & Units	Inflow units/yr	Emergy/Unit sej/unit	Empower E18 sej/yr
1	Estuarine support, m2	5.6 E5	6.65 E12	3.7
2	Smolts, individuals	1.53 E5	2.4 E13	3.7
3	Feed, kg	4.7 E5	2.09 E13	9.8
4	Goods and services, $	1.63 E6	1.35 E12	2.2
5	Salmon produced, sum items 1-4:	-	19.4	
6	Received for sales, $	7.4 E6	1.35 E12	10.0

* Data from Bjorndal (1990).
# Based on pen producing 130,000 salmon after starting 180,000 smolts; volume of pen: 6.2 E3 m3
$ = Canadian $ 1989 = 0.83 US 1989 $; 1.63 E12 sej/1989 US $ (Odum, 1996 Appendix D)
(0.83 US 1989 $/Canadian 1989 $)(1.63 E12 sej/1989 US $) =
1.35 E12 sej/Canadian $ Footnotes for Table 1 Emergy Evaluation of a Salmon Pen

1 Water support from the volume of enclosure times necessary to keep the concentration of nutrients below that which could cause algal blooms that displace normal oligotrophic conditions. Flushing required to keep phosphorus less than 50 mg/m3 is used to estimate the area of estuary required and the annual emergy of sun, tide, and river supporting that area.

Phosphorus released by salmon estimated from metabolic rate 81.8 mg/kg/hr from Jorgensen et al. (19) and 1% phosphorus
(130,000 fish)(1.5 kg fresh weight/fish)(0.0818 g phos/kg fish/hr)(0.01) = 160 g phosphorus/hour

Water volume per hour = (160 g phos/hr)/(0.050 g/m3) = 3200 m3/hr

Estuarine support area required
(3200 m3/hr flushing)(365 d/yr)(24 hr/day)/(50 m depth) = 5.6 E5 m2/yr

Estuarine Emergy Contribution to the area required:
Empower per area from available energies of sun, tide and freshwaters.
Solar energy: (3 E9 J/m2/yr)(5.6 E5 m2)(1 sej/J) = 1.69 E15 sej.yr

Emergy from 5 m tidal energy absorption; transformity of tidal absorption 7.39 E4 sej/J and for river flow 4.0 E5 (Odum, 2000)
(5 m)(1.025 E3 kg/m3)(5.65 E5 m2)(2.5 m center of gravity)(9.8 m/sec2 gravity)(706 tides per year)(7.39 E4 sej/J) = 3.7 E18 sej/yr

Freshwater runoff contribution assumed 0.3 m/yr
(0.3)(5.6 E5 m2)(1 E6 g/m3)(4.0 E5 sej/g) = 6.7 E16 sej

Sum (sun, tide, freshwater): 1.69 E15 + 3.7 E18 + 6.7 E16 = 3.76 E18 sej
per area: (3.76 E18 sej/yr)/(5.65 E5 m2) = 6.65 E12 sej/m2/yr

2	180,000 smolts @ 0.85/smolt = \$153,000 @ 1.35 E12 sej/\$ = 2.06 E17 sej 300,000 eggs @ 1.4 E13 sej/egg(Umpqua table) = 4.2 E18 sej Sum: (2.06 E17) + (42 E17) = 44.1 E17 sej Per individual smolt: 44.1 E17 sej)/(180,000 ind) = 2.4 E13 sej/ind
3	Feed: \$850,000/(\$1.30/kg)/(1.8 E5 fish) = 3.63 kg/ fish (1.3 E5 fish)(3.63 kg/fish) = 4.7 E5 kg Organic feed: (5 kcal/g)(1000 g/kg)(4186 J/kcal)(1 E6 sej/J) = 2.09 E13 sej/kg
4	Production cost including fixed capital costs: \$4.10/kg; (\$4.10 /kg)(3.06 kg/fish at harvest) = \$12.55/fish (1.3 E5 fish)(\$12.55/fish) = \$1.63 E6
5	400 tons yield/year; 3.06 kg/fish (400 ton/yr)(1 E3 kg/ton)/(3.06 kg/fish) = 1.30 E5 fish/yr
6	Money received for 130,000 fish: (\$7.71 per pound)(2.2 pounds/kg) (3.63 kg/fish) = \$61.6 /fish (\$61.6 /fish)(1.3 E5 fish) = \$7.4 E6 Canadian 1989\$

The necessary flushing volume per time is equal to the phosphorus respired per time by the salmon divided by the acceptable phosphorus concentration.

The capacity of the estuary to flush the pens depends on the depth. Estuarine area required to support the pen is the volume per time divided by the depth. The empower supporting the estuary is estimated from the sun, tides, and freshwater energies per area.

The pellets of food carry the emergy of the food chain that produced the organic matter plus the emergy of the human services. The smolts used to start the population include emergy of human services plus the emergy in the eggs used in the nursery. The rest of the costs are in a line item that includes the capital investments, interests, operational costs, etc. All of these items appear to be important. The total emergy value of the product is the sum of these independent inputs.

Also included in Table 1, line 7 is the money received for sale of the harvest. This money is multiplied by the emergy/money ratio of the economy which is purchasing the salmon. The product is put on an emdollar basis by dividing the emergy by the emergy money ratio of the economy.

Because of the large inputs from the economy, the emergy yield ratio is small. There is very little net emergy. Like other intensive aquaculture and agriculture, the products are not primary energy sources capable of supporting other enterprises.

3. EMERGY INDICES OF THE SALMON PEN

Emergy indices calculated from the results in Table 1 are given in Table 2.

A large part of the emergy value is from the economy (feed, services, smolts). When compared to the environmental flushing contribution the investment ratio 4.2 is moderately high, but less than the average for the United States and other developed economies.

Table 2
Emergy Indices for the Salmon Pen System

1	Emergy Yield Ratio	1.23
2	Emergy Investment Ratio	4.2
3	Emergy per Fish	1.49 E14 sej/ind.
4	Emdollars per Fish	149 US 2000 \$

5	Solar Transformity:	9.7 E6 sej/J
6	Emdollar of Harvest	19.7 million US 2000 $
7	Exchange Ratio for Buyer	1.94

Footnotes for Table 2, Emergy Indices

1 Feedbacks from the economy: (3.7 + 9.8 + 2.2) = 15.7 E18 sej
(19.4 E18 sej)/(15.7 E18 sej) = 1.23

2 (15.7 E18 sej)/(3.7 E18 sej) = 4.2

3 Per fish: (19.4 E18 sej)/(130,000 fish) = 1.49 E14 sej/fish

4 (1.49 E14 sej/fish)/(1.0 E12 sej/US 2000 $)

5 (3.06 kg/fish)(1000 g/kg)(0.2 dry)(6 kcal/g)(4186 J/kcal) = 1.54 E7 J/fish
(1.49 E14 sej/fish)/(1.54 E7 J/fish) = 9.7 E6 sej/J

6 (19.4 E18 sej)/(1.0 E12 sej/US 2000 $) = $1.94 E7

7 (19.4 E18 sej)/(10.0 E18 sej) = 1.94

The emergy and emdollars per fish are much larger than the costs and sale price. The total emdollar value of the harvest is much greater than its market value. More real wealth comes to the people using the product than from selling it.

The solar transformity of the salmon product is 9.5 E6 solar emjoules/joule, a value comparable with other choice protein foods. Economic market values tend to increase with transformities, as you might expect for products with more economic inputs and higher costs. The value is similar to the transformity estimated for the natural salmon emergy in the Umpqua River, Oregon (7.6 E6 sej/J for fish maturing at sea and 1.5 E7 sej/J for returning salmon).

With 400,000 returning salmon, the emdollar value of the original salmon runs in the Umpqua River was large:
(4 E5 fish/yr)(9 E 14 sej/fish)/(1 E12 sej/$)
= 360 million US 2000 emdollars:

However the emdollar value of the hydroelectric potential of the river is even greater.# Electricity may be expected to take priority in an information age facing times of short electric power ahead. The challenge is managing for both salmon and information.

Geopotential of Umpqua River 200 m3/sec upper river; 350 m3/sec lower river.
(200 + 350 m3/sec)(1 E3 kg/m3)(500m)(9.8 m/sec2)(3.14 E7 sec/yr) = 8.5 E16 j/yr
Annual empower:
(8.5 E16 J/yr)(1.04 E4 solar emjoules/joule)
= 51.8 E20 solar emjoules/yr
Potential contribution to economy:
(51.8 E20 sej/yr)/(1 E 12 sej/$ 2000)
= 5.2 billion emdollars/year

The emergy exchange ratio indicates more emergy in the salmon product than in the buying power of the money received. The emergy-emdollars are twice as large as the money paid for the salmon.

The exchange ratios may be different when a product is sold abroad and the emergy/money ratios differ. The net emergy benefit to buyer and sellers not only depends on the emergy exchange ratio in the economy where the pens were operating but also on the difference in emergy/money ratios between the seller's economy and buyer's economy. Buying from a less developed economy, where emergy/money ratios are higher, amplifies the emergy benefit to the buyer. See chapter 11 on international trade in the Environmental Accounting book (Odum, 1996).

For products of agriculture, fisheries, and forestry, high contributions of free emdollars from the environment are typical. Because economic analysis doesn't include inputs from the environment, it underestimates the contribution to buying power and economic wealth. Emergy-emdollar evaluation should be used to evaluate all choices and impacts affecting fisheries and water resources.

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