# Comparative analysis of the environmental costs of fish farming and crop production in arid areas

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**ABSTRACT**

Using published data, 20 crop and 19 fish production systems were compared for efficiency of water and nutrient (nitrogen) use. In agriculture, rain-fed cassava was most efficient, followed by rain-fed beans, pivot-irrigated maize and rain-fed wheat. Intensive vegetable production uses water most efficiently to produce edible dry matter. Maize, wheat and crop legumes are most efficient at producing protein. Cassava produces energy most efficiently. For aquaculture, sharp-tooth catfish in fed raceway-ponds are most efficient, followed by tilapia in fed cages and tilapia in sewage-fed ponds. Herbivorous and omnivorous fish are more efficient to produce than carnivores. Aquaculture is of comparable efficiency to crop production only in terms of edible dry matter output per cubic meter of water and crude protein production per kilogram of nitrogen. Aquaculture in arid areas is of comparable efficiency with agriculture only when it is highly intensive and/or strongly integrated with other farm enterprises.

## INTRODUCTION

The global natural resource base is increasingly under pressure from the food needs and demands for economic growth of expanding human populations. In addition, increasing competition in local, regional and international markets is forcing commercial farmers to reduce production costs while increasing outputs. Together, these factors are driving a global interest in more efficient food production systems.

The importance of improving management of natural resources requires that we find a proportionately robust and straightforward means of measuring the efficiency of farming systems. For most farming businesses, efficiency is measured in economic terms; that is, the amount of money spent on a farming activity (including costs of inputs, labour, management, opportunities on land and capital, etc.) is compared to the amount earned through the sale of produce. In biophysical terms, however, efficiency

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is measured by the amount of water, carbon, nitrogen, phosphorus and energy that a farming system uses to grow food and process waste materials, compared to the weight of food produced. These two sets of criteria may yield very different estimates of efficiency.

When markets are efficient estimators of real prices for inputs, outputs and environmental goods and services, economic efficiency can approximate biophysical efficiency. However, this is seldom the case. Most farming systems especially neglect the costs of many environmental goods and services in their calculation of the bottom line (Berg *et al.,* 1996; Kautsky *et al.,* 1997). These costs may include:

- oxygen requirements for decomposition of organic wastes;
- assimilation of fertilizer runoff, especially phosphorus and nitrogen;
- ecological impacts of pesticides and herbicides;
- human health consequences of antibiotic use in animal feeds;
- production of $CO_{2;}$
- land and natural resources required for feed production;
- biodiversity trade-offs in land and water allocation; and
- negative environmental impacts of introduced alien or genetically modified organisms.

Measuring "efficiency" as a proxy for sustainability may consequently be easier if one looks at the biophysical materials that flow in and out of farming and other natural resource management systems. However, this "materials flow" approach may easily be confounded by the large number of environmental and production system variables that characterize modern farming, including:

- soil (composition, structure, slope);
- solar radiation (intensity, periodicity);
- temperature (extremes, duration);
- wind (direction, intensity, frequency);
- evaporation rate;
- rainfall (timing, intensity, amount);
- water quantity and quality;
- fallowing, crop rotation, intercropping;
- variety or genetic strain; and
- production cycles per year.

The time of cropping, for example, depends upon a number of variables, some of which are more important in certain crops than others (e.g., photoperiod, ambient temperature, timing of rainfall, media type in greenhouses). In addition, a number of crops are rotated or intercropped, making generalizations risky. An example from fish farming is polyculture, in which a mixture of species is grown together at rates determined empirically to conform to the size of the various feeding niches available in the pond. There is no obvious way to correct for so many variables over all crops at all latitudes in which the arid zones are located, so a few critical indicators are needed.

Given the availability of published data, I attempted to find common factors that could be used to compare the wide range of farming systems that need to be looked at. Six key parameters were identified:

- edible or usable dry matter produced per unit of water used
- edible or usable dry matter produced per unit of unit of nitrogen used;
- crude protein produced per unit of water used;
- crude protein produced per unit of nitrogen used;
- digestible energy produced per unit of water used; and
- digestible energy produced per unit of nitrogen used.

The balance of this paper will focus on these six parameters and attempt to relate them to the relative efficiency of various food production systems. The overall aim is to provide a practical means of comparing the efficiency and environmental costs of aquaculture and crop production, with a focus on species cultivated in arid areas.

In terms of nutrient inputs, fish are generally the most efficient animals to produce (Olah and Sinha, 1986). As poikilotherms, fish do not use energy to heat their bodies. Since they excrete ammonia, fish use minimal energy in protein catabolism and excretion (Goldstein and Forster, 1970). Also, because they are generally neutrally buoyant, fish do not need heavy bones (Tucker, 1969). Channel catfish (*Ictalurus punctatus*), for example, gain 0.85 g of weight for every gram of feed consumed, compared to 0.48 g in chickens, the present most efficiently farmed warm-blooded animal, and 0.13 in beef cattle (NRC, 1983, Lovell, 1989). In terms of consumptive water use, fish use no more, and in many cases less, than do other animals (Brummett 1997).

For plant crops, with which fish production competes both for nutrient inputs and for fresh water, the situation is less clear. This review is aimed at illuminating the differences in biophysical efficiency of fish farming as compared to crop production in dryer parts of the world, where water and other critical inputs are often in short supply. The main comparators used for inputs are water and nitrogen; for outputs, dry matter of human food, crude protein and energy are used.

## EFFICIENCY AND ENVIRONMENTAL COSTS OF CROP PRODUCTION

Agriculture is highly variable in its scale and intensity, making generalizations difficult. Very small-scale, artisanal systems often use no fertilizers or irrigation, resulting in minimal production and generally low efficiency. Larger-scale systems rely on more inputs, but produce disproportionately more outputs per unit of input, thus making them more efficient. Also, larger-scale cropping systems are more uniform throughout the world, facilitating generalization. These more efficient, larger-scale systems are thus used for purposes of comparing crop agriculture with aquaculture.

Table 1 shows the amounts of water and nitrogen necessary to achieve average yields from a representative variety of dry zone crops produced under a range of irrigation and input regimes. Table 2 shows the estimated efficiency of production in terms of water and nitrogen use per kg of edible dry matter, kg of crude protein and kcal of digestible energy available to humans. In terms of edible dry matter output per unit of water, drip-irrigated cucumber is the most efficient, followed by drip-irrigated tomato and furrow-irrigated onion. Per unit of nitrogen, rain-fed cassava, rain-fed wheat and pivot-irrigated sorghum are the most efficient. In terms of crude protein production per unit of water consumed, pivot-irrigated maize ranks highest, followed by rain-fed beans and rain-fed soya bean, while in terms of nitrogen, rain-fed beans are better than pivot-irrigated maize which in turn is better than rain-fed wheat. In terms of digestible energy per unit of water, rain-fed cassava, pivot-irrigated maize and rain-fed beans seem most efficient; in terms of nitrogen, rain-fed cassava, rain-fed wheat and rain-fed beans are the best.

The crops most frequently in the top three for each category are rain-fed beans (four times), rain-fed cassava (three times) and pivot irrigated maize (three times). With a simple proportional weighting index (three points for first place, two for second and one for third), rain-fed cassava might be considered the most efficient overall with nine points, rain-fed beans and pivot-irrigated maize tie for second with seven points and rain-fed wheat comes third with five points.

In general, intensive vegetable production, especially in greenhouses with drip irrigation, are the most efficient way to use water to produce edible dry matter. Maize, wheat and crop legumes (beans and soya bean) are most efficient at producing protein. Cassava is by far the most efficient crop in terms of energy production.

## EFFICIENCY AND ENVIRONMENTAL COSTS OF AQUACULTURE

Fish production systems are different from agriculture systems in that the water necessary to fuel the system is not completely consumed. Consumption is highest

TABLE 1

**Water and nitrogen inputs compared to outputs of dry matter, crude protein and energy, under various production systems for representative row crops produced in dry areas. Values are based on reported use in larger-scale commercial farming systems (generally >50 ha) except for pearl millet, which is almost exclusively a smallholder crop. Data from: NRC (1983); ARNAB (1989); Göhl (1992); Adeola, King and Lawrence (1996); Martin, Slack and Pegelow (1999); Cavero *et al*. (2001); Raemaekers (2001); Broner and Schneekloth (2003); Fasuyi and Aletor (2005)**

| Production System | | Inputs | | Outputs | | | |
|---|---|---|---|---|---|---|---|
| | | Water ($m^3/m^2$) | Nitrogen ($g/m^2$) | Edible yield ($kg/m^2$) | Edible dry matter (percent) | Crude protein (percent) | Digestible energy (Kcal/kg) |
| Pearl millet (*Pennisetum glaucum*) | Rainfed | 0.5 | 1.6 | 0.05 | 92 | 11.0 | 3 400 |
| Maize (*Zea mays*)* | Rainfed | 0.66 | 15.0 | 0.12 | 89 | 9.6 | 3 800 |
| | Furrow irrigated | 1.2 | 15.0 | 0.36 | 89 | 9.6 | 3 800 |
| | Pivot irrigated | 0.83 | 15.0 | 0.6 | 89 | 27 | 3 800 |
| Rice (*Oryza sativa*) | Flooded | 1.5 | 20.0-60.0 | 0.9 | 89 | 7.9 | 2 600 |
| | Upland | 1.0 | 5.0-10.0 | 0.2 | 89 | 7.9 | 2 600 |
| Sorghum (*Sorghum bicolour*) | Rainfed | 0.8 | 2.4 | 0.2 | 90 | 13 | 3 300 |
| | Furrow irrigated | 1.3 | 13.4 | 0.6 | 90 | 13 | 3 300 |
| | Pivot irrigated | 1.2 | 11.9 | 0.7 | 90 | 13 | 3 300 |
| Wheat (*Triticum* spp.) | Rainfed | 0.5 | 0.9 | 0.07 | 88 | 13 | 3 400 |
| | Furrow irrigated | 0.9 | 18.0 | 0.6 | 88 | 13 | 3 400 |
| Cassava (*Manihot esculenta*) | Rainfed | 1.25 | 4.4 | 2.2 | 39 | 1.2 | 11 000 |
| Beans (*Phaseolus vulgaris*) | Rainfed | 0.7 | 7.0 | 0.4 | 90 | 22.6 | 3 470 |
| Soya bean (*Glycine max*) | Rainfed | 0.85 | 20.0 | 0.25 | 90 | 40 | 1 390 |
| Cucumber (*Cucumis sativus*) | Greenhouse (drip irrigation) | 0.2 | 13.1 | 7.9 | 3.8 | 0.6 | 120 |
| Tomato (*Lycopersicon esculentum*) | Greenhouse (drip irrigation) | 1.6 | 104.0 | 34.6 | 6.2 | 1.2 | 200 |
| | Furrow irrigated | 3.6 | 9.0 | 3.0 | 6.2 | 1.2 | 200 |
| Onion (*Allium cepa*) | Furrow irrigated | 0.5 | 10.2 | 2.4 | 19.7 | 1.6 | 380 |
| Citrus (*Citrus* spp.) | Furrow irrigated | 1.8 | 4.2 | 3.0 | ~35percent juice | <1percent | 35 000 |
| Groundnut (*Arachis hypogaea*) | Rainfed | 0.6 | <2.0 | 0.084 | 91 | 22 | 2 600 |

* Refers to grain maize, which is more commonly produced in less developed countries than sweet corn.

in earthen ponds where seepage and evaporation can sometimes be considerable, especially in hot, dry, windy areas. Flow-through raceways must pass large quantities of water through the production unit, but the quality of water released from these systems is good and readily available for other uses, especially crop irrigation. Cages and recirculating systems consume virtually no water. Fish average about 76 percent water and this value was used as the consumptive use for those systems where water was not consumed by the production system (Lovell, 1989). For systems receiving pelleted feeds, the water requirements of the crops grown to produce those feeds is added to the amount used during the culture cycle (Piemental *et al.*, 1997).

While the proximate analysis of fish is dependant upon the feed or fertilizer used in the system, the composition of fish flesh in terms of protein and energy varies within a relatively narrow range compared to plant crops. For purposes of this paper, an average crude protein value of 18.7 percent and energy value of 300 kcal/kg, calculated on the basis of proximate analyses of 77 fish species, were used (Herzberg and Pasteur, 1981; Hepher, 1988; Tidwell *et al.*, 2000; Garduño-Lugo *et al.*, 2003).

Table 3 shows output of dry matter in terms of water and nitrogen inputs for a variety of fish species and production systems. Table 4 shows the efficiencies of various fish production systems. In terms of edible dry matter per $m^3$ of water, fed carp polyculture

TABLE 2
**Efficiency of various crop production systems as measured by edible output, crude protein production, and digestible energy**

| Culture species | Production system | Edible output (kg dry matter) | | Crude protein (kg) | | Digestible energy (kcal) | |
|---|---|---|---|---|---|---|---|
| | | per m³ water | per kg N | per l water | per kg N | per m³ water | per kg N |
| Pearl millet (*Pennisetum glaucum*) | Rainfed | 0.09 | 28.75 | 10.12 | 3.16 | 313 | 97 750 |
| Maize (*Zea mays*)* | Rainfed | 0.16 | 7.12 | 15.53 | 0.68 | 615 | 27056 |
| | Pivot Irrigated | 0.65 | 35.60 | 174.76 | 9.61 | 2460 | 13 5280 |
| | Furrow Irrigated | 0.27 | 21.36 | 25.63 | 2.05 | 1015 | 81 168 |
| Rice (*Oryza sativa*) | Flooded | 0.53 | 20.03 | 42.19 | 1.58 | 1388 | 52 065 |
| | Upland | 0.18 | 23.73 | 14.06 | 1.87 | 463 | 61 707 |
| Sorghum (*Sorghum bicolour*) | Rainfed | 0.23 | 36.00 | 24.75 | 3.96 | 743 | 118 800 |
| | Pivot Irrigated | 0.53 | 52.94 | 68.25 | 6.88 | 1733 | 174 706 |
| | Furrow Irrigated | 0.42 | 40.30 | 45.64 | 4.43 | 1371 | 132 985 |
| Wheat (*Triticum* spp.) | Rainfed | 0.12 | 68.44 | 16.02 | 8.90 | 419 | 232 711 |
| | Furrow Irrigated | 0.59 | 29.33 | 76.27 | 3.81 | 1995 | 99 733 |
| Cassava (*Manihot esculenta*) | Rainfed | 0.69 | 195.00 | 8.24 | 2.34 | 7550 | 2 145 000 |
| Beans (*Phaseolus vulgaris*) | Rainfed | 0.51 | 51.43 | 116.23 | 11.62 | 1785 | 178 457 |
| Soya bean (*Glycine max*) | Rainfed | 0.26 | 11.25 | 105.88 | 4.50 | 368 | 15 638 |
| Cucumber (*Cucumis sativus*) | Greenhouse (Drip Irrigated) | 1.50 | 22.92 | 9.01 | 0.14 | 180 | 2 750 |
| Tomato (*Lycopersicon esculentum*) | Greenhouse (Drip Irrigated) | 1.34 | 20.63 | 16.09 | 0.25 | 268 | 4 125 |
| | Furrow Irrigated | 0.05 | 20.67 | 0.62 | 0.25 | 10 | 4 133 |
| Onion (*Allium cepa*) | Furrow Irrigated | 0.95 | 46.35 | 15.13 | 0.74 | 359 | 17 614 |
| Citrus (*Citrus* spp.) | Furrow Irrigated | 0.01 | 2.50 | 0.00 | 0.00 | 204 | 87 500 |
| Groundnut (*Arachis hypogaea*) | Rainfed | 0.13 | 38.22 | 28.03 | 8.41 | 331 | 99 372 |

TABLE 3
**Water and nitrogen inputs and average outputs of dry matter under a variety of production systems for representative fish species produced in dry areas. Values are based on reported use in larger-scale commercial farming systems (generally >100 tonnes per annum) except for fertilized pond tilapia, which is almost exclusively a smallholder crop. Data from: Little and Muir (1987); Hepher (1988); Lovell (1989); Phillips, Beveridge and Clarke (1991); Brummett and Noble (1995); Jarboe and Grant 1996; Mahboob, Sheri and Raza (1996); Brummett (1997); Hecht (1997); Hertrampf and Piedad-Pascual (2000); Boyd (2005)**

| Culture species | Production system | Consumptive water use (m³/tonne) | Nitrogen (g/m³) | Average yield (kg/m³) |
|---|---|---|---|---|
| Tilapia (*Oreochromis* spp.) | Fertilized ponds | 2 000 | 7 | 0.14 |
| | Sewage-fed ponds | 1 750 | 20 | 0.68 |
| | Fed ponds | 2 800 | 12 | 0.25 |
| | Fed aerated ponds | 21 000 | 84 | 1.7 |
| | Fed cages | 760 | 3 400 | 50 |
| | Fed biofilters | 906 | 2 000 | 25 |
| Common Carp (*Cyprinus carpio*) | Fed ponds | 4 032 | 360 | 0.6 |
| | Fed raceways | 740 000 | 11.5 | 0.14 |
| Sharptooth Catfish (*Clarias gariepinus*) | Fed raceway Ponds | 93 000 | 6 | 4.0 |
| | Fed raceways | 3 600 | 18 400 | 400 |
| Channel Catfish (*Ictalurus punctatus*) | Fed ponds | 2 882 | 37 | 0.42 |
| | Fed aerated ponds | 4 032 | 53 | 0.6 |
| | Fed ponds with water reuse | 3 350 | 37 | 0.42 |
| | Fed biofilters | 908 | 2 800 | 26 |
| Rainbow Trout (*Oncorhynchus mykkis*) | Fed raceways | 252 000 | 6 700 | 35 |
| | Fed raceways with water reuse | 63 000 | 6 700 | 35 |
| Carp Polyculture (*Hypothalmichthys molitrix, Aristichthys nobilis, Ctenopharyngodon idella*) | Fertilized pond | 12 000 | 56 | 0.3 |
| | Fed pond | 5 000 | 168 | 0.9 |
| | Fed, aerated pond | 2 250 | 200 | 2.0 |

TABLE 4
**Efficiency of various fish production systems as measured by edible output, crude protein production, and digestible energy**

| Culture species | Production system | Edible output (kg dry matter) | | Crude protein (kg) | | Digestible energy* (kcal) | |
|---|---|---|---|---|---|---|---|
| | | per $m^3$ water | per kg N | per l water | per kg N | per $m^3$ water | per kg N |
| Tilapia (*Oreochromis* spp.) | Fertilized ponds | 0.1200 | 0.0048 | 0.0224 | 0.90 | 360.0 | 14 400 |
| | Sewage-fed ponds | 0.1371 | 0.0082 | 0.0256 | 1.53 | 411.4 | 24 480 |
| | Fed ponds | 0.0857 | 0.0050 | 0.0160 | 0.94 | 257.1 | 15 000 |
| | Fed aerated ponds | 0.0114 | 0.0049 | 0.0021 | 0.91 | 34.3 | 14 570 |
| | Fed cages | 0.3158 | 0.0035 | 0.0591 | 0.66 | 947.4 | 10 590 |
| | Fed biofilters | 0.2649 | 0.0030 | 0.0495 | 0.56 | 794.7 | 9 000 |
| Common Carp (*Cyprinus carpio*) | Fed ponds | 0.0595 | 0.0004 | 0.0111 | 0.07 | 178.6 | 1 200 |
| | Fed eaceways | 0.0003 | 0.0029 | 0.0001 | 0.55 | 1.0 | 8 770 |
| Sharptooth Catfish (*Clarias gariepinus*) | Fed raceway ponds | 0.0026 | 0.1600 | 0.0005 | 29.92 | 7.7 | 480 000 |
| | Fed raceways | 0.0667 | 0.0052 | 0.0125 | 0.98 | 200.0 | 15 650 |
| Channel Catfish (*Ictalurus punctatus*) | Fed ponds | 0.0833 | 0.0027 | 0.0156 | 0.51 | 249.8 | 8 170 |
| | Fed aerated ponds | 0.0595 | 0.0027 | 0.0111 | 0.51 | 178.6 | 8 150 |
| | Fed ponds; water reuse | 0.0716 | 0.0027 | 0.0134 | 0.51 | 214.9 | 8 170 |
| | Fed biofilters | 0.2643 | 0.0022 | 0.0494 | 0.42 | 793.0 | 6 690 |
| Rainbow Trout (*Oncorhynchus mykkis*) | Fed raceways | 0.0010 | 0.0013 | 0.0002 | 0.23 | 2.9 | 3 760 |
| | Fed raceways; water reuse | 0.0038 | 0.0013 | 0.0007 | 0.23 | 11.4 | 3 760 |
| Carp Polyculture (*Hypothalmichthys molitrix, Aristichthys nobilis, Ctenopharyngodon idella*) | Fertilized pond | 0.0200 | 0.0013 | 0.0037 | 0.24 | 60.0 | 3 860 |
| | Fed pond | 0.480 | 0.0013 | 0.0090 | 0.24 | 144.0 | 3 860 |
| | Fed, aerated pond | 0.1067 | 0.0024 | 0.0199 | 0.45 | 320.0 | 7 200 |

* These figures have been amended by the author after first printing and an errata is being provided for the printed version

in ponds ranks highest, followed by tilapia in cages and biofilter systems. In terms of nitrogen used, sharptooth catfish in fed raceway ponds did the best, followed by tilapia in sewage-fed ponds and sharptooth catfish in fed raceways. In terms of crude protein production per $m^3$ of water, tilapia in fed cages were the best, followed by tilapia in fed biofilter systems and channel catfish in fed biofilter systems, while in terms of nitrogen inputs, fed sharptooth catfish in raceway ponds were the most efficient, followed by sewage-fed tilapia ponds and sharptooth catfish in fed raceways. For digestible energy produced per $m^3$ of water, tilapia in fed cages and biofilter systems were the most efficient, followed by channel catfish in fed biofilter systems; in terms of nitrogen inputs, sharptooth catfish in fed raceway ponds was number one, followed by sewage-fed tilapia ponds and fed sharptooth catfish raceways.

Using the evaluation system described above for crop systems , tilapia in sewage-fed ponds, cages and fed biofilter systems and sharptooth catfish in fed raceway ponds and fed raceways were each most efficient in three of the six categories. Overall, sharptooth catfish produced in fed raceway-ponds are most efficient with nine points. Tilapia in fed cages were second best with eight points, while tilapia in sewage-fed ponds came third with six points.

Except for the generally low-intensity production of carp polycultures, herbivorous (tilapia) and omnivorous (sharptooth catfish) species were more efficient to produce than were carnivores (channel catfish, rainbow trout).

## COMPARING EFFICIENCY OF CROP PRODUCTION AND AQUACULTURE

Aquaculture is of comparable efficiency to crop production only in terms of edible dry matter output per cubic meter of water and crude protein production per kg of nitrogen. Only sharptooth catfish in fed raceway ponds exceeded crop production in any of the efficiency criteria. From these data, aquaculture in arid areas will be more efficient than agriculture only when it is highly intensive and/or strongly integrated with other farm enterprises so that the costs of nutrients and water can be amortized over multiple production units.

Using the logic of Yong-Sulem and Brummett (2006), edible yield per unit area can be considered a fair estimator of farming system intensity. Regression of yield per unit area (leaving out the very high values of 34.6 kg/m$^2$ for greenhouse tomatoes and 400 kg/m$^3$ for raceway sharptooth catfish) against the six pooled efficiency criteria showed a strong positive correlation between intensity and efficiency. The relationship for crops (B = 0.669, adjusted $r^2$ = 0.42, $p < 0.002$) was stronger than for fish (B = 0.493, adjusted $r^2$ = 0.20, $p < 0.038$). Although difficult to quantify, aquaculture efficiency was also closely related to the level of integration with other enterprises, reflecting the ability of fish production systems to take advantage of nutrients recycled from agriculture (or from humans, in the case of sewage-fed tilapia ponds) and for water from fish facilities to be recycled to other uses.

The high degree of variability within and among farming systems renders a precise estimate of efficiency extremely difficult to achieve and probably of limited use, in light of the over-riding importance of economic profitability and diversity in the selection of species and farming systems. Nevertheless, observed trends towards water recirculation and intensified production systems in the aquaculture industry closely parallel their relative efficiency in terms of water and nitrogen transformation.

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