CODEX PLANETARIUS

Key Impacts, Metrics, and Minimum Performance Standards for Aquaculture Production

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About *Codex Planetarius*

Codex Planetarius is a proposed system of minimum environmental performance standards for producing globally traded food. It is modeled on the *Codex Alimentarius*, a set of minimum mandatory health and safety standards for globally traded food. The goal of *Codex Planetarius* is to measure and manage the key environmental impacts of food production, acknowledging that while some resources may be renewable, they may be consumed at a faster rate than the planet can renew them.

The global production of food has had the largest impact of any human activity on the planet. Continuing increases in population and per capita income, accompanied by dietary shifts, are putting even more pressure on the planet and its ability to regenerate renewable resources. We need to reduce food production's key impacts.

The impacts of food production are not spread evenly among producers. Data across commodities suggest that the bottom 10-20% of producers account for 60-80% of the impacts associated globally with producing any commodity, even though they produce only 5-10% of the product. We need to focus on the bottom.

Once approved, *Codex Planetarius* will provide governments and trade authorities with a baseline for environmental performance in the global trade of food and soft commodities. It won't replace what governments already do. Rather, it will help build consensus about key impacts, how to measure them, and what minimum acceptable performance should be for global trade. We need a common escalator of continuous improvement.

These papers are part of a multiyear proof of concept to answer questions and explore issues, launch an informed discussion, and help create a pathway to assess the overall viability of *Codex Planetarius*. We believe *Codex Planetarius* would improve food production and reduce its environmental impact on the planet.

This proof-of-concept research and analysis is funded by the Gordon and Betty Moore Foundation and led by World Wildlife Fund in collaboration with a number of global organizations and experts. For more information, visit www.codexplanetarius.org

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Abstract

Aquaculture has several types of negative environmental impacts, but water pollution is arguably the major negative impact of several types of aquaculture. Water pollution results mainly from the use of feed in which the waste from feeding (uneaten feed, feces, and metabolic excretions) enters the culture system and the waterbody into which the culture system discharges.

The major water pollutants of concern in effluents from feed-based aquaculture facilities are: total suspended solids (TSS), 5-day biochemical oxygen demand (BOD_5), water clarity (measured as turbidity or Secchi disk visibility), and dissolved oxygen (DO). The primary means of lessening the pollution potential of an aquaculture facility is improvement in feed management leading to a lower feed conversion ratio (FCR). The FCR is the amount of feed required for a unit of production, e.g., if 1,600 kg feed (air dry weight) is used to produce 1,000 kg fish or shrimp (live weight), the FCR is 1.6.

This is the practical FCR, but from a water pollution standpoint dry matter FCR is the more important issue. The feed is about 10% moisture while live aquaculture biomass is about 75% water. The waste load is not associated with the water and is greater than suggested by the practical farm FCR. Nevertheless, reducing the practical FCR by 0.1 unit will lessen the feed necessary to produce 1,000 kg of aquaculture biomass by 100 kg. This will lessen the waste loads per tonne of live biomass production by the amounts of carbon, nitrogen, and phosphorus contained in 100 kg feed.

Maximum FCR limits were suggested for 13 different species/species groups of common aquaculture animals in international trade. One water quality standard was selected for each of the four major types of production systems (ponds, flow-through systems, cages and net pens, and water recirculating systems). Because it is doubtful that one standard would be adequately rigorous, an additional standard was recommended for pond and flow-through systems.

Pond culture affects the quality of water in ponds, and a pond bottom soil health standard was recommended. Some species, sites, production methods, and chemical uses that might be disallowed by the *Codex Planetarius* are discussed.

Introduction

Global food and fiber production includes plant and animal crops farmed either on land or in water and at different levels of production intensity. There is a general consensus that the key negative impacts of food production are biodiversity loss, habitat conversion (land use), soil health (soil quality), water intake quantity (water use), water effluent quality (water pollution), greenhouse gas (GHG) emissions that are closely related to energy use, and agrochemical toxicity (largely pesticide use). The *Codex Planetarius* has the goal of developing minimum environmental and resource use standards for these impacts that can be imposed at the farm level on primary products destined for international trade.

This report offers suggestions that may be of application in the development of standards for the major impacts for farming of aquatic animals and plants (aquaculture). By comparison to terrestrial farming (traditional agriculture), aquaculture is a relative newcomer of global significance in food production. Many of those who will be engaged in developing the *Codex Planetarius* will not have been involved with the aquaculture sector. The present report gives basic information on aquaculture methodologies, the relationships of aquatic farming to global resource use, negative environmental impacts of aquaculture, and suggests standards for consideration in aquaculture.

Aquaculture has become a significant factor as a source of animal protein for human consumption and in the food security of many developing countries (Boyd et al. 2022). Aquaculture also has elicited concerns related to efficient use of natural resources, and it is the cause of diverse environmental perturbations (Naylor et al. 2021). Some background information related to aquaculture should be helpful.

Background

Aquaculture traditionally has been considered separately from terrestrial agriculture. The Food and Agriculture Organization (FAO) of the United Nations maintains two separate databases on global food production. One is for traditional agricultural production, and the other is for global fisheries and aquaculture production maintained by the FAO Fisheries and Aquaculture Department. Much effort over many years was required in the United States to transfer the federal oversight of aquaculture production from the US Fish and Wildlife Service to the US Department of Agriculture where is now resides. In many countries, the governmental oversight of aquaculture remains separate from that of agriculture.

Basic facts

Both traditional agriculture and fish and shrimp aquaculture require land, water, nutrients contained in fertilizers and feeds, liming materials, energy inputs to power farm machinery and other equipment, and a variety of pesticides, disinfectants, and antibiotics or other drugs. Most of the inputs used in fish and shrimp aquaculture are the same ones used in traditional agriculture. Seaweed and molluscan culture are conducted primarily in the ocean and thereby do not require land and water in the usual sense and feeds, fertilizers, liming materials, and other inputs are not used. Of course, energy often is necessary for establishing and harvesting crops. They are often referred to as extractive aquaculture because they remove organic matter and nutrients from the water where they grow.

Aquaculture is primarily animal production, but there is much production of farmed seaweed and lesser production of ornamental aquatic plants. Traditional agriculture also includes some aquatic plant production, with rice being the major example. The plant production component of traditional agriculture is a much larger sector in terms of biomass production than is animal agriculture, while the opposite is true of aquaculture. Farming of aquatic animals is important in food security as a source of animal protein in the diets of millions of low-income families in many developing nations. Moreover, several salmonid fish species, penaeid shrimp, and various other fish, crustacean, and molluscan species are farmed largely for the export market because of their popularity with consumers in more wealthy nations.

A crucial point is that the unique feature of aquaculture, especially crustacean and fish culture, relates to the availability of molecular oxygen for respiration during their production. Aquatic animals must extract molecular oxygen for respiration from the water in which they live. Water holds very little of this vital gas. Freshwater contains 9.08 m/L of molecular (dissolved) oxygen at 20°C and standard atmospheric pressure. This means that by weight, freshwater contains 0.00098% dissolved oxygen. Terrestrial animals have the luxury of breathing air that contains 20.95% molecular oxygen by volume. Feed-based aquaculture makes up about 70% of total aquaculture production. Feeds increase production, but they also generate organic waste loads in culture systems to impose a large oxygen demand. Much of feed-based production is dependent upon mechanical aeration for sufficient dissolved oxygen.

Seaweed and molluscan species usually are planted (attached) to artificial substrates suspended in marine waters. Seaweeds rely on nutrients from the surrounding water and molluscan species filter suspended organic matter from the water. Neither fertilizer nor feed is normally used, and the natural availability of dissolved oxygen is seldom a factor.

Fish and shrimp are cultured by several techniques, but nearly three-fourths of production is by feed-based culture. In addition, nearly three-fourths of the total production of fish and shrimp likely is from pond culture (Naylor et al. 2021). These ponds vary greatly in size from less than 0.1 ha to more than 50 ha, but the normal pond water surface area would be less than 10 ha in the western hemisphere and less than 2 ha in the eastern hemisphere. Ponds typically are earthen lined and have average depths of 1–2 m. A water supply must be available to fill and maintain water levels in ponds.

Some species such as tilapia and *Pangasius*, and particularly trout, are often reared in flow-through pond systems and concrete raceways through which water continuously flows at rates of 3–4 changes per day to 2–3 changes per hour. Water exchange also may be used in ponds and especially in marine shrimp culture where it is applied at rates of 2–20% pond volume per day. Earthen ponds for *Pangasius* culture may be flushed at greater rates and occasionally as much as 3–4 pond volume daily.

Tanks in which water is exchanged several times per hour can be used for shrimp and some fish species. Water also can be treated and reused in water recirculating aquaculture systems (RAS aquaculture).

In pen and cage production, fish are either confined by placing nets around an area of shallow water to form a pen in which to rear fish or they are confined in cages that float above the bottom of the water body. Water freely flows through nets and pens at rates dependent on the natural water currents. Much of the production of Atlantic salmon and of some species of marine fish is achieved in cages.

The natural supply of dissolved oxygen is sufficient for molluscan farming, and seaweeds conduct photosynthesis releasing dissolved oxygen in the process. Extensive fish and crustacean farming does not require the intervention of mechanical aeration, because productivity, even when stimulated with fertilizer nutrients, is quite low and natural sources of dissolved oxygen usually are sufficient.

Extensive aquaculture (including mollusks and seaweeds) is conceptually similar to livestock production in pastures or on rangelands. What is known as semi-intensive aquaculture uses feed but not mechanical aeration to supplement natural sources of molecular oxygen. Conceptually, it is similar to supplemental feeding of livestock in pastures or on rangeland. Intensive aquaculture that requires both feed and mechanical aeration is like unto feed lots for beef cattle or to chicken and pig production in housing. Typical production intensities for different methods of aquaculture are given in Table 1 (pg 12).

Studies have verified that intensification of fish and shrimp farming through use of feeds and mechanical aeration diminishes land and water use greatly even when land and water requirements for plant-based ingredients in fish and shrimp feeds are included. Because of the need for mechanical interventions to supply dissolved oxygen, the energy requirements per unit weight of production increases when feeding and mechanical aeration are applied. Nevertheless, the increment of production increase possible both per unit weight of feed and per horsepower of mechanical aeration are relatively constant, and the amount of energy needed per unit weight of production does not increase appreciably with respect to greater intensification in feed-based culture.

The expected amounts of land, freshwater, and energy use were estimated for culture of a pond fish species (Table 2, pg 12). The amounts of total land and total freshwater use per tonne of production decreased with greater crop yield, but aeration energy use remained constant as production increased in aerated ponds. In the feed-based example, cropland for feed exceeded aquaculture farmland for ponds at production above an estimated 4.0 t/ha.

As a rule, fish and shrimp production is comparable to chicken and pig production with regard to land and water use per unit weight of production, but higher in energy use (Boyd et al. 2021). Feed-based fish and shrimp production requires less freshwater per unit of biomass than does beef cattle production, but as much or more energy use as required for beef cattle is necessary per equal unit of shrimp biomass. Of course, greater energy use carries with it a larger contribution of greenhouse gas (GHG) emissions.

Aquaculture leads to negative environmental impacts of land use modification and to the discharge of nutrients, inorganic and organic suspended matter, and potential toxins into natural water bodies. Greenhouse gas emissions result from energy use in aquaculture. In pond aquaculture, sediments in pond bottoms sequester more carbon in organic matter than is emitted in microbial respiration during decomposition of organic matter that settles to pond bottoms (Boyd et al. 2020). This benefit is largely negated by emissions of two more potent GHG gases, methane and nitrous oxide (Boyd and McNevin 2023).

The global negative impacts of aquaculture add to similar ones from traditional agriculture. The combined influences of farming to produce food and fiber are habitat conversion and degradation, pollution of water, air and land, erosion, and sedimentation. These impacts lead to biodiversity loss, eutrophication, and climate change. Aquaculture also requires the largest portions of the global fishmeal and fish oil supply for feed ingredients (Naylor et al. 2021). This has a major impact on marine food webs.

Aquaculture Production

Aquatic animals yielded an estimated 13,950 kilotonne (Kt) of edible animal source crude protein in 2018 (Boyd et al. 2022). This represented 15.3% of edible crude protein from all meats, eggs and animal milks for human consumption. Aquaculture provided roughly one-half of total aquatic animal source protein in 2018. The capture of aquatic animals from the ocean and other water bodies has exceeded its sustainable limit for the majority of species, and capture fisheries are struggling to merely supply a constant level of production from year to year. The demand for aquatic animal-source protein continues to increase, and future increases in demand can only be provided by aquaculture.

Putting aside crude protein and looking at live weight of aquatic animal production alone, the production of aquatic animals by aquaculture (the farm-gate product) must increase from an estimated 82,087 Kt in 2018 to 129,000 Kt by 2050 (Boyd et al. 2022). This was a straight-line projection using current population growth and aquatic animal consumption per capita annually. The calculated increase was 57% of the 2018 production and using the 2020 total aquaculture production of 87,500 Kt, the percentage increase over 2020 production necessary by 2050 remains 57%.

Some readers may be interested in some details about the amounts of different types of aquaculture production. A summary of the marine and inland production reported by FAO for 2020 (Table 3, pg 13) and the amounts of some selected species or species groupings have been provided (Table 4, pg 13). From the standpoint of quantity, inland aquaculture is mainly fish while the reduction fisheries (fish for fishmeal and oil production) was used in aquaculture feeds in 2017 (Naylor et al. 2021). Not only does the reduction fishery remove forage fish necessary for larger carnivorous species in marine food webs, but it also can compete with artisanal fisheries, supplying fish important in the food security of many developing, coastal countries. Of course, whole fish used for fishmeal production could have been used for human food. There is a limit in the capacity of the reduction fishery to provide fishmeal and fish oil and this could threaten the growth of aquaculture in the future, and the sustainability of the food web for marine carnivores.

Fishmeal and Fish Oil

The fish in-fish out (FIFO) ratio has become a popular way of assessing wild fish use in aquaculture. The average FIFO for some popular species for which feed usually contains fishmeal and fish oil derived from whole, pelagic, marine fish are: whiteleg shrimp, 0.85; Atlantic salmon, 1.80; and rainbow trout, 1.84 (Boyd and McNevin 2023). These FIFO values mean that to produce 1 t of whiteleg shrimp requires 0.85 t of wild fish, while 1.84 t of wild fish are required for 1 t of Atlantic salmon. It is significant to note that when the FIFO for a species is above 1.0, the production of those fish or shrimp actually decreased global fisheries and aquaculture production, because the capture of the reduction fishery (fish for making fishmeal and fish oil) is part of global, capture fisheries production. It should be noted again, contrary to popular belief, much of the catch of the reduction fisheries is suitable for human consumption (Boyd et al. 2022).

The Scale of Aquaculture in Resource Use and Negative Impacts

Aquaculture is actually a rather small contributor to land use, 0.17% of global land area as compared to 38% for traditional agriculture. When estimated as the reduction in downstream flow, freshwater use in aquaculture was estimated at 0.82% of the annual, renewable and available freshwater (Boyd and McNevin 2015). When calculated as the amounts of water that entered ponds naturally and by human interventions (green water plus blue water in water footprints), the portion used increased to about 3% (Verdegem and Bosma 2009). By comparison, traditional agriculture uses about 70% of the annually available and renewable freshwater (green water excluded).

The results of two recent and completely independent estimates of GHG emissions attributed roughly 0.50% of global GHG emissions to aquaculture (Boyd and McNevin 2023). The estimate for traditional agriculture is 30–35%. The amount of aeration in aquaculture has increased greatly in recent years, and the estimate for aquaculture may be as much as 0.75 to 1% of global emissions as a result of energy use in aeration. It has been estimated that about 2% of anthropogenic nitrogen pollution and 3% of anthropogenic phosphorus pollution results from aquaculture effluents (Boyd and McNevin 2015). The amount of the global biological oxygen demand caused by aquaculture is likely similar to its contribution to nitrogen and phosphorus loads. It is fair to say that global aquaculture is neither a major consumer of land, freshwater, and energy nor is it a major source of nutrient pollution or GHG emissions.

If one is satisfied with such an assessment, then it would seem reasonable to consider aquaculture a relatively insignificant source of negative environmental impacts. There are some realities that make such a decision unwise as are itemized below:

- Aquaculture usually is done in lower portions of catchments or in coastal areas, both of which tend to be above average with respect to biodiversity. Superimposing aquaculture farms into such settings potentially does more harm to biodiversity per unit area of land conversion than does traditional agriculture conducted on higher terrain. A good example is conversion of mangrove habitat in coastal areas to farms for shrimp, other crustaceans, and fish.

- Aquaculture farms require specific sites that are suitable for their installation and operation. Level or slightly sloping, accessible terrain near a water source and with good drainage is usually essential. Ponds also require sites where soils are not rocky, have a sufficient mixture of sand, silt, and clay particles for compaction to prevent excessive seepage, and soils free of iron pyrite that is highly acidic. Organic soils also are undesirable sites for aquaculture ponds because organic matter decomposition results in enough loss of the soil mass to render dikes unstable.

  Where areas of suitable terrain are afforded by nature, many aquaculture farms often are installed. Some examples are the Mekong Delta in Vietnam, the lower Guayas River basin in Ecuador, the Nile Delta in Egypt, and the Mississippi River flood plain in Mississippi (USA), and others.

- The tendency is to concentrate farms into relatively small areas. Aquaculture effluents are quite small in global perspective, but they can become and are sources of major environmental perturbations and particularly water pollution in some localized areas.

- Feeds are the input necessary to make fish and shrimp farming yields great enough to justify the practice beyond low-input production by small-holder farmers. Feeds also are the main source of nutrients in aquaculture effluents leading to eutrophication, and they are a source of GHG emissions that contribute to climate change. Feeds also are the reason that most of the world's annual production of fishmeal and fish oil is consumed by aquaculture. From the standpoint of excessive use of fishmeal and fish oil and the resulting impacts on small pelagic, oceanic fish and marine food webs, aquaculture is far more harmful than the total of traditional agriculture in which the use of fishmeal and fish oil in chicken and swine feeds has been declining in recent years.

- Aquaculture has been responsible for nonnative species introduction in many places, but this has already happened. It may be of local concern even now, but it does not seem necessary to emphasize either nonnative species or genetically modified organisms (GMOs) in the *Codex Planetarius*.

The several major concerns about aquaculture seem to be in the following increasing order of importance: water use < water pollution = GHG emissions < land use < wild fish use for feed ingredients = ratio of feed used to biomass produced. The greatest concern in feed-based aquaculture operations should be placed on feed quality, feed management, and the feed conversion ratio (FCR). The FCR can be defined as the amount of feed necessary to result in a 1.0 weight unit of biomass production. For example, if 1,700 kg feed results in 1,000 kg increase in biomass, the FCR will be 1.7 (1,700 kg feed ÷ 1,000 kg biomass).

The less feed required per unit of biomass produced, the smaller will become several of the other effects such as organic waste, nitrogen and phosphorus in effluent and direct carbon dioxide emissions. The feeds for Atlantic salmon, rainbow trout, certain mostly carnivorous marine fish, and marine shrimp contain considerable fishmeal and fish oil made from whole fish. Reducing the FCR also will improve the FIFO ratio. Much of the fishmeal from whole fish in aquaculture feeds also can be replaced with animal byproduct meals and high-protein-content plant meals such as soybean meal or with plant protein concentrate. Of course, cost of ingredients play a key role in the possibilities of fishmeal and fish oil replacements in aquaculture feeds.

Aquaculture Production Systems, Waste, and FCR

Wastes from feeds are greater than they may appear from the FCR definition. An FCR of 1.5 seems to suggest that 1.5 kg feed results in 1.0 kg of harvest biomass and 0.5 kg waste. This is not an accurate assessment in terms of solid waste. Most feeds contain about 10% water and 90% dry matter. Whole fish and shrimp typically contain around 75% water and 25% dry matter. At a practical (farm level) FCR of 1.5 calculated on the amount of feed divided by the amount of harvest biomass (both on and "as is" basis), the FCR based on dry matter would be 5.4 [(1,500 kg feed x 0.9) ÷ (1,000 kg biomass x 0.25)]. In other words, to get 1 kg dry matter in harvest biomass requires 5.4 kg dry matter in feed and results in 4.4 kg dry matter in waste. The organic pollution potential of feeding waste resides in the dry matter fractions of carbohydrates, proteins, and fats. The water in waste is of no ecological consequence. These basic organic nutrients also contain nitrogen and phosphorus which are released during their decomposition in the form of plant available nutrients.

In ponds, waste that is not flushed from ponds into the environment via water exchange is partially assimilated within ponds before final discharge of pond water for harvesting. Most of the waste from feeding is carbon dioxide resulting from the respiration of the animals eating the feed. There also are feces and other metabolic waste, and some of the feed applied (about 2–5% by fish and 10–20% by shrimp) is not eaten. The typical amounts of nitrogen and phosphorus applied to culture systems in feeds that are not recovered in harvested biomass for seven common aquaculture species are given (Table 5, pg 13). The amounts of nitrogen and phosphorus entering culture systems from feeding waste are not drastically different among these species if ictalurid catfish is excluded. The high FCR for ictalurid catfish can be explained by the methodology used in rearing ictalurid catfish, which results in an elevated FCR. Fish are harvested with seines and ponds are seldom drained. Some fish escape harvest and become larger and able to out-compete smaller fish for feed. These larger fish do not convert feed efficiently leading to more waste. Also, feed is applied with mechanical devises that result in overfeeding. The FCR could be reduced by changes in the production methodology of this species.

Ponds have large capacities to assimilate waste, and only about 10–20% of the carbon and phosphorus and 20–40% of the nitrogen contained in feed typically are discharged from ponds into natural water bodies. Organic and commercial fertilizers used in extensive aquaculture are also sources of nitrogen and phosphorus pollution. The efficiency with which fertilizer nitrogen and phosphorus are converted to biomass is similar to that mentioned for feeds.

Water continually passes through flow-through aquaculture systems at different rates from 1 or 2 exchanges of system volume per day to 2 or 3 exchanges per hour.

Raceways and tanks are the production units of common flow-through systems. Some of the waste, possibly up to 25% can be removed by sedimentation, but most is flushed into the environment.

Water recirculating aquaculture systems (RAS) are becoming more common. This technology may be applied to ponds, but it is used more often in indoor intensive culture systems. The water is treated by sedimentation, screening, biofiltration, and other methods to remove waste, and of course, mechanical aeration is applied. Much of the waste load can be removed, but the water becomes high in dissolved inorganic and organic solids and ultimately, a portion must be discharged and replaced.

Cage and net pen culture also are popular methods of fish production. The animals are confined in mesh enclosures in a large body of water (the sea, a lake or reservoir, or a stream) and feed is applied daily. The portion of the feed that is not converted to biomass of the farmed animals passes through the mesh of cages and pens with larger particles settling on the bottom or the remainder of the waste being suspended or dissolved in the water that passes through the cages via natural water movement. This means that in cage or net pen culture of tilapia or Atlantic salmon, the amount of waste entering natural water bodies would usually be similar to those reported in Table 5 (pg 13).

The production system waste loads in Table 5 were calculated for typical FCRs achieved on farms. The typical FCRs, and FCRs for these and some other groups of aquaculture species follows: ictalurid catfish, 2.5; freshwater crustaceans, 1.8; carp, tilapia, milkfish, and other marine fish, 1.7; marine shrimp, 1.6; eel, 1.5; Atlantic salmon and rainbow trout, 1.3. It is clear from research that all of these groups can be produced at somewhat or much lower FCRs with high quality feeds and good feed management. For example, ictalurid catfish can be cultured at FCR 1.5–1.7 by merely applying more conservative feeding practices. Many marine shrimp farmers have achieved FCRs of 1.0–1.2 and some Atlantic salmon farmers achieve FCRs of 1.0 or even less. [Note: as already mentioned, the feed has a higher dry matter content than fish or shrimp, practical FCRs less than 1.0 are possible even where feed is the only source of food, i.e., no natural food production occurs in the culture system]. It also is possible to use feeds with especially high protein content to achieve an FCR of 1.0 or less, but this usually is a wasteful practice.

The FCR is the key factor in determining the proportion of the feed applied that becomes waste in an aquaculture system. It also is apparent that aquaculture production using fertilizer will have a waste load. The waste load can be separated into two fractions. The waste that enters the culture system or the "production system waste load" and the waste that is ultimately discharged into the receiving water body or the "environmental waste load." With respect to organic solids, nitrogen and phosphorus, the environmental waste load is less than the system waste load in all but net pens and cages. The carbon waste load in form of carbon dioxide released by respiration of the culture animals and decomposition of organic matter in the system by bacteria mostly enters the atmosphere as carbon dioxide. Average system waste loads for carbon dioxide emissions from feed for production of some common species also were given in Table 5. The environmental waste loads vary by system type and within systems of the same type and require individual measurements.

In the discussion of production systems above, the concept of FCR was defined and its vital connection to waste loads was discussed. The main way of reducing nutrient and organic loads is to use fertilizers only as necessary and to use proper feed management to maintain a low FCR. This also will lower carbon dioxide emissions from feed use. Using feeds from the local market, farmers are constrained by the types of feed available. Only large producers can demand custom-made feeds. The use of wild fish can be reduced by two methods. The feed manufacturers can offer feeds with lower inclusion rates of pelagic-fish derived fishmeal and fish oil. Fishmeal and fish oil derived from fish processing waste is not considered to negatively impact marine fisheries directly. The farmer also can strive to lower the FCR using whichever feeds are available. Both ways are important, and there has been considerable success in lessening fishmeal and fish oil inclusion rates (Naylor et al. 2021). Aquaculture feed use is increasing rapidly and despite lower inclusion rates in feeds, the total use of fishmeal and fish oil for aquaculture feed is not declining. Research clearly reveals that it is possible to reduce the dependency of aquaculture on marine fishmeal and fish oil made from whole fish. These research findings should be more widely adopted. Of course, while it is possible nutritionally, economic factors about feed ingredients may limit the options.

Major Resource Use

Aquaculture production by 2050 might increase by about 57% of 2020 production according to the *status quo* projection mentioned earlier. This would suggest the need for 57% more land conversion to aquaculture farms. It would be possible to obtain the apparent necessary increase in production by relying more on flow-through, cage and net pen, and RAS culture instead of constructing more farms with ponds or expanding farms with ponds that require more land than the other production methods. The more logical way of achieving this increase in production without major alterations in production methodology would be to intensify pond production (see Table 2).

Water use also can be reduced by intensification (Table 2). It should be noted that brackish water and marine aquaculture do not consume freshwater directly. Freshwater use in coastal and marine aquaculture is incurred mainly as embodied freshwater in inputs and primarily in feed.

The sparing of land and water by intensification of aquaculture requires more energy use. This tradeoff is necessary in intensification because feed and aeration are energy intensive. There are those who may object to intensive aquaculture based to a large extent on its high energy use. Some have advocated for "blue" species such as low-trophic level species of fish, extensive crustacean production, and greater production of molluscan species and seaweed. The success of this proposal would necessitate a huge amount of additional production area to accomplish with low-trophic fish production in ponds and major changes in consumer preferences. Reduction in land use could be achieved with molluscs and seaweed. Currently, about 18,000 Kt of molluscan species are produced by aquaculture, but this supplies only 4.7% of the edible, crude protein from aquaculture. Less edible, crude protein results from seaweed than from molluscan species (Boyd et al. 2022). A shift to mollusc and seaweed is not a realistic way of saving energy. Much energy could be spared by a huge shift to the consumption of low-trophic level fish species, but if such were done, much additional land and freshwater use would be incurred. The dependence on low-trophic level species is much less attractive than many tend to believe.

A harmful ecological heresy promoted by some environmental advocates and researchers is that agricultural production can be done without incurring major resource uses and negative environmental impacts. This notion flies in the face of natural and physical principles by which the world of nature operates. In many respects, because of the growing world population and consumer demand, the most realistic way of reducing negative impacts of aquaculture would be to lessen consumption of food and the waste of food in more affluent markets.

Think about it though, if we eat only what we need while wasting less food, the demand for food in the United States and in many other wealthy countries would decline by 20–40%. This would cause such a reduction in demand that the size of the food production sector would shrink. Objections to such an approach by farmers and the rest of the world's food providers could be expected. Reducing portion size certainly would not be popular with many producers and consumers in the United States. Efforts to lead consumers towards foods with lesser environmental impacts and to lessen food waste and over-consumption should continue. More immediate environmental improvements can be achieved by lessening resource use and negative impacts at the farm level.

Improvements in Resource Use and Environmental Performance

The major natural resource and management inputs to the different types of aquaculture production systems are summarized (Table 6, pg 14), and the major direct environmental impacts of the different management inputs are listed in Table 7 (pg 14). There are embodied uses of major resources associated with all of the management inputs. The production of feed requires milling of feed ingredients. Raw materials for these ingredients must be produced by agriculture or captured from the ocean and processed into feed ingredients. The milled feed must be delivered to farms. All these steps require resource use and result in negative environmental impacts. The same reasoning applies to most other management inputs such as electricity and other fuels, liming materials, fertilizers, etc.

Possible prohibitions

Before considering metric standards for different systems and impacts, there is the question of whether certain areas for farm sites, production practices, and management inputs should be prohibited. Such exclusions would be favored by some and contested by others, but a few possible exclusions for consideration will be mentioned.

Species. A species may be in demand for various reasons: some cultures traditionally favor certain species over others; individual consumers in other cultures may be grouped according to their species preferences, e.g., some favor shrimp and seldom purchase fish, some prefer fish over shrimp, and usually have a preference for certain fish species, etc. As the result of cultural and individual preferences, a large number of species are produced in aquaculture. Nevertheless, consumer preference often changes with respect to price. I do not believe that the *Codex Planetarius* should become involved in trying to alter consumer preferences for food products. Exclusion of certain species or methods of production, because of inability to comply with *Codex Planetarius* standards, are in line with those that will be applied to other species.

Exotic species introductions should not be favored by the *Codex Planetarius*. Nevertheless, in some countries, much aquaculture is of a nonnative species. A very good example is whiteleg shrimp in the eastern hemisphere. The *Codex Planetarius* should simply forbid new introductions of exotic species, not forbid species such as whiteleg shrimp in Asian countries.

Sites. Selection of inadequate sites can be a major cause of negative environmental impacts. A farm might be constructed where effluent is released into water bodies of high ecological value that formerly did not receive wastewater or a wetland area might be converted into an aquaculture farm. While the *Codex Planetarius* probably should not prohibit existing farms that were previously sited in ecologically sensitive areas, consideration might be given to prohibiting new farms or expansions of existing farms in such areas after initiation of the program. These prohibitions might include: ecologically sensitive sites, interference with navigation, alteration of natural hydrological connections and patterns, salinization of water bodies or soils, and wetland deterioration.

Systems and practices. Production systems that are clearly ecologically damaging or use excessive amounts of resources should be prohibited. A prime example is cage culture of tuna. The production of carnivorous species such as salmon, trout and most marine fish, at farms using feeds with more marine fishmeal and fish oil than necessary and achieving a higher-than-average FCR achieve FIFO ratios of 4 or 5. Farmed tuna are provided whole fish as a diet, and the typical FIFO is around 10–20 (Mrčelić et al. 2020). Until feeds are available that allow an FCR similar to that of salmonids, tuna farming should be prohibited by the *Codex Planetarius*.

Extensive culture of marine shrimp is done within the intertidal zone and often in mangrove areas. The production by such farms normally is around 250–500 kg/ha per year. Extensive shrimp farming not only damages coastal wetlands, it is not very productive of shrimp. Extensive shrimp farms make up about 50% of the shrimp farming area but produce only 10–15% of farmed shrimp (Boyd and McNevin 2018).

Extensive fish and crab culture in ponds can be more productive than extensive shrimp farming and a portion of extensive fish-crab culture is in upland areas of less ecological value than are intertidal wetlands.

The *Codex Planetarius* certainly should consider prohibiting participation of farms that are wasteful of land use and damaging to important ecological areas. Of course, for social reasons, it would not be possible to prohibit existing farms in such areas from participating.

Inland culture of marine and brackish water species in freshwater areas is sometimes possible by use of well water from saline aquifers or by applying salt or brines from coastal salt farms to freshwater ponds. The practice incurs a great risk of both surface water and groundwater contamination with saline water. Inland, saline water aquaculture in ponds is a candidate for exclusion from the *Codex Planetarius*.

Antibiotics and some pesticides are used in aquaculture production. The measurement of antibiotic and pesticide residues in effluents would be overly expensive. Rather than set standards that require expensive pesticide analyses for proof of compliance, the best approach might be to prohibit the use of certain potentially toxic and persistent compounds that are used in pest and disease control.

Resource Use Standards

The four major natural resource uses in aquaculture, land, freshwater, energy, and wild fish for feed or feed ingredients, are critical issues (Table 8, pg 15). As already discussed, embodied land and freshwater use for feed ingredients are key considerations. In pond aquaculture, direct land use at farms and direct water use at freshwater farms are related to production intensity. By increasing the intensification of pond culture, a production level is reached where most land use per tonne of production is associated with feed (see Table 2). In freshwater pond culture, water use per tonne of production also is greatly reduced. In other types of feed-based aquaculture, production facilities require only a small amount of land, and most of that land use is embodied in feed.

The normal viewpoint is that by using feeds in aquaculture a great amount of additional land is required, and the benefits to intensification to land sparing are downplayed. There is a counter argument with which I agree. Aquaculture products are part of the available food supply. When people eat fish, crustaceans, and mollusks at a meal, they will forgo the consumption of some terrestrial-source meat. Like aquaculture-source meats, most terrestrial-source meats are produced using feeds. Feeds for chicken, pigs, and beef cattle have land use coefficients as great or greater than those for aquaculture feeds (Boyd and McNevin 2022). The FCRs for boiler chickens are similar to those of aquatic animals, but those for swine and beef cattle are greater. These observations suggest that global animal feed use likely does not increase because of aquaculture feeds; therefore, land use for feed would not increase either. Incidentally, only 4–5% of global, compounded feed use is incurred by aquaculture.

Feed and embodied land and freshwater use per unit production can be lessened mainly by improving the FCR. Using the average embodied resource use coefficients from Table 9 (pg 15), an improvement of FCR by 0.2 unit in the production of 1,000 t of tilapia by a cage culture farm would spare 200 t of feed equating to about 55 ha of cropland, 41,000 m^3 of freshwater, and 900 GJ of energy necessary for producing the feed from raw material. In addition, the pollutant waste loads from farms would be lessened by the amounts of nitrogen, phosphorus, and organic carbon contained in the 200 t of feed that were spared by improving FCR. This reduction also applies to direct and embodied emissions of carbon dioxide into the air.

The FCR is critical, and despite the likely resistance of aquaculture producers to merely the suggestion of limits on FCR, a minimum limit should be set in the *Codex Planetarius* for FCR by species. The FIFO is based on two factors, marine fishmeal and fish oil inclusion rates in feeds and the FCR, achieved at farms. The FIFO is rather difficult to calculate directly, and it often would be difficult or impossible to obtain the fishmeal and oil inclusion rates for some feeds. It would seem reasonable to put limits on FCER and avoid contending with the difficulties in calculating FIFOs.

Direct energy use is incurred mainly from aeration and pumping water for water exchange. Aerators fabricated on farms by farmers are extremely inefficient when compared with factory-made aerators. Farm-fabricated aerators should be excluded from use at farms to be brought under the *Codex Planetarius*. Maximum limits of water exchange should be imposed in pond aquaculture. An alternative would be to forbid water exchange in pond culture unless the ponds are operated as intensive, flow-through systems common in *Pangasius* farming and sometimes in tilapia production. In some arid coastal areas, water exchange in ponds is necessary to avoid excessive increase in salinity as a result of much greater evaporation than rainfall and an allowance for this should be provided.

Land use standard

The land use standard should not be concerned with land use for feed ingredients. As discussed above, land use for aquaculture feeds likely does not increase the total land area required for all compounded animal feeds. Most aquaculture feeds have land use coefficients between 0.220 and 0.292 ha/t feed with an average of 0.247 ha/t feed. The average land use for the major terrestrial, meat animal feeds reported by Boyd and McNevin (2022) were: broiler chickens, 0.201 ha/t; swine, 0.307 ha/t; beef cattle, 0.247 ha/t.

The land use coefficient for a feed for a given species made by a particular feed mill may vary from one lot of feed to another. This results from feed mill operations using least cost formulations that vary in ingredients (but of similar nutrient content) depending upon cost and availability of ingredients. This practice results in variation in resource use coefficients for feeds. There is no feasible way to establish a standard for feed land use coefficients.

In pond aquaculture, each 1-ha unit of water surface area required an average of about 1.4 ha of direct land use (Jescovitch et al. 2016), as the result of land necessary for dikes, farm buildings, roads, and staging areas. Land use per tonne of production will decline exponentially with greater production per hectare. Calculations summarized in Table 2 reveal that beyond a production of 6–8 t/ha/crop, sparing of land per tonne of production declines to a rather small amount of land per unit increase in biomass production. The implication is that production intensity above 6–8 t/ha/crop does not provide much benefit in lessening direct land use. The land use for a particular feed per tonne of production is fixed by FCR.

Without using feeds, production of more than 2–3 t/ha/crop is usually possible with filter-feeding species. With shrimp and other crustacean species, production beyond 0.5–1.0 t/ha/crop may not be achievable even in ponds receiving only fertilizer inputs.

It also is important to note that depending upon the species, production above 2–5 t/ha/crop seldom is possible in unaerated ponds to which feed is applied and only low rates (5–10%) of water exchange used as a water quality management technique. Higher production is possible only with mechanical aeration. The main exception to this situation is *Pangasius* farming. This fish is an air breather that can obtain oxygen at the water-air interface, and water exchange at rates of 25% pond volume up to three to four times pond volume daily allow annual production of 100 tonnes up to several hundred tonnes per hectare per crop.

The implication might seem that in order to spare land, all pond aquaculture should be feed based and maybe even conducted in ponds with feeding and aeration. This possibility should not be recommended. Land is one of the major resources available to humans. We live on it, it supplies most of our other resources, and on it and below its surface resides the sources of freshwater necessary for life. Because of its great value, access to land and its water has led to conflicts among people and nations throughout history. The poor have largely been excluded from owning land, especially the better land with access to water. A land use standard in the *Codex Planetarius* might exclude the poorest farmers from participating in production of internationally-traded aquaculture products. It is not morally acceptable to impose a land use standard that would exclude the poor from continuing to operate ponds constructed before initiation of the *Codex Planetarius*. In support of this statement, consider that there are no resource use limits on the excesses of the middle class and particularly on the wealthy elite.

Notwithstanding the comments above, a provision in the *Codex Planetarius* should prohibit further land use conversion to extensive aquaculture, and small-holder farmers should be required to comply with all other standards of the program if they desire to participate in production of internationally-traded, aquaculture products. Suggested land use standards for pond aquaculture are listed in Box 1 (pg 16).

Water use standard

Most freshwater use is incurred in freshwater aquaculture. In brackish water and marine aquaculture, direct freshwater use is mainly for drinking and sanitary purposes. Embodied freshwater use is incurred primarily in feeds, but all management inputs will contribute smaller quantities. The use of pumped water for water exchange as done in some types of pond aquaculture requires a large energy input. Reduction in water exchange is important to energy conservation in coastal and marine production ponds even though freshwater use is not incurred.

Information in Table 2 illustrated how direct land use in a culture system will decline with respect to greater production intensity, and direct water use will diminish in the same fashion. As a result, no standard is needed related to direct water use in ponds where water exchange is not used. By imposing a land use standard, water use will decline per tonne of biomass produced.

Embodied freshwater in aquaculture feeds ranged from 1,405 m3/t to 2,842 m3/t (Table 9, pg 15) with an average of 1,898. For comparison, average water use coefficients of feeds for broiler chickens, swine, and beef cattle were: 1,573 m3/t; 1,644 m3/t; 1,048 m3/t, respectively (Boyd and McNevin 2022). As concluded for embodied land use in feeds, it should be neither necessary nor feasible to impose an embodied freshwater use limit on feed.

There should be a standard on water exchange rate for three reasons: (1) the practice is inefficient for improving water quality in ponds (other than for avoiding excessive salinity in ponds in arid regions); (2) exchange reduces water retention time in ponds and lessens the amount of feeding waste that can be assimilated naturally within ponds resulting in greater environmental loads of pollutants in effluents; (3) water that must be pumped into ponds increases energy use and associated GHG emissions. Of course, tidal water exchange should be allowed in coastal ponds.

Flow-through systems usually do not pump water but rely on gravity flow to convey lake, stream, or spring flow through tanks and raceways. Water use in trout raceways typically ranges from 60,000 m3/t fish to 120,000 m3/t fish. Raceway and tank effluents typically pass downstream, and the waste imparted by aquaculture use does not appreciably degrade downstream flow. Nevertheless, a water quality standard will be suggested for discharge from flow-through systems to assure that downstream water quality is not seriously impaired. Water use standards are not needed for net pen and cage culture or for RAS facilities.

Suggested water use standards are provided in Box 2 (pg 16).

Energy use standard

As concluded for land and freshwater use, a standard for embodied energy in feeds would not be necessary or practical. Aquaculture feeds vary greatly in embodied energy among warmwater fish (3.5–4.5 GJ/t), whiteleg shrimp (9.6 GJ/t) and salmonids (14.3 GJ/t) as shown in Table 9. Feed for freshwater fish compare favorably in embodied energy contents of 3.15 GJ/t for beef cattle feed, 3.83 GJ/t for swine feed, and 4.17 GJ/t for broiler chicken feed (Boyd and McNevin 2022).

The two main categories of direct energy use in aquaculture farm operations usually are pumping water and mechanical aeration. Limits placed on water exchange rates and on the production yield to aerator horsepower used per hectare would serve to avoid wasteful energy use.

GHG emissions

Although GHG emissions are a major concern, a standard for GHGs per unit of production would require data collection and calculations beyond those that could be considered reasonable to impose on farmers. There also are insufficient data at present to establish the typical GHG emissions per tonne of production of most aquaculture species.

At most aquaculture facilities, the two primary uses of direct energy in farm operations are pumping water and mechanical aeration. As already discussed, the standards suggested for water exchange and for yield per unit of aeration would be a control on the quantity of GHGs emitted from facilities per tonne of production. Methane and nitrous oxide are potent GHGs, and they are emitted from ponds. Again, not enough data on the amounts of these gases released and the factors that favor greater emissions to all generalization necessary in setting standards.

FCR standard

The FCR is the key standard for lessening the loads of potential pollutants from aquaculture production facilities. A list of typical FCR values for selected aquaculture species was given earlier. These estimates are somewhat greater than the FCRs that are achieved through use of good feeding practices and use of other proper pond management practices by the more efficient producers. The FCR values in Box 3 are this author's attempt at reasonable, minimum FCR limits that should be achievable with reasonable efforts by farmers. The FCR limits suggested here (Box 3, pg 16) should be given considerable scrutiny, because the author is not as familiar with some species as with others.

An important factor about FCR must not be overlooked. Some people like to calculate an overall FCR for aquaculture by dividing global feed use by aquaculture by global aquaculture production. There are three serious flaws in this procedure. The data on global aquaculture feed use are not highly reliable. The estimates of the total aquaculture production include seaweed and mollusk farming in which no feed is applied. Based on analysis of FAO production data, in 2018, there were 64.6 million tonnes of fish and shrimp, 17.8 million tonnes of molluscans and 31.5 million tonnes of seaweed for a total of 113.9 million tonnes. Of the 64.6 million tonnes of fish and shrimp, there are only estimates of what percentage of the production is feed based.

There is really no exact way to calculate an overall aquaculture FCR because there is no accurate way of estimating the tonnage of feed-based aquaculture. This limitation of FCR use does not affect the *Codex Planetarius*, because the FCR would be applied at the farm level.

Effluent water quality standards

The issues with effluent water quality standards have been thoroughly discussed in another report. These standards have major limitations, and a reduction in pollution at a given aquaculture facility may result in a reduction in pollution output but not lead to environmental improvement.

The use of FCR to limit pollutant concentrations in effluents is effective on a unit of production basis. The amount of waste resulting from feeding is a function of both FCR and the total amount of feed used (to which biomass production is directly proportional) at a farm. Therefore, while the FCR is indicative of the waste loads per tonne of biomass production (Table 5), the total waste load to the system is the waste loads per tonne of biomass multiplied by the annual farm biomass production in tonnes.

There is assimilation of pollutants by natural processes and especially in ponds. The proportions of the waste loads assimilated with the systems vary among different types of production systems and for different facilities operating by the same production methodology. Calculations of environmental pollutant loads require data on volumes of effluent and pollutant concentrations in effluent. The monitoring of effluent volume from facilities, and especially ponds, would require installation of flow volume-monitoring equipment that would be expensive and require considerable technical skill to use.

Some may not see the determination of the environmental loads as an unreasonable goal. Anyone of this opinion should be aware that knowing the loads of pollutants is one thing, but knowing the maximum acceptable loads above which gradual deterioration in water quality in the receiving water body may be expected is quite another topic. Determination of total maximum daily loads (TMDLs) or some other measure of the waste assimilation capacity of receiving water bodies is a task far beyond what is reasonable in the *Codex Planetarius*.

The application of FCR limits would minimize system loads of pollutants per tonne of production. Application of one or two concentration-based standards to effluents would restrict the environment loads for a particular discharge volume. The limits on water use suggested earlier also would avoid the possibility of diluting concentrations of potential in the effluent thereby allowing load increases. This approach seems the most reasonable way of handling the water pollution concern of aquaculture for purposes of the *Codex Planetarius*.

Cage and net pen culture are an exception because they do not produce an aqueous effluent. The entire system waste loads are discharged into the water body containing cages and net pens. The system waste loads calculated from feed use and FCR will be the same as the environmental waste loads. The water quality can be monitored in the water body where the cages or pens are located to determine if it is becoming more eutrophic or other negative impacts are occurring. Typically, a measure of the decline in water clarity would be a warning that the assimilation capacity of a water body has been exceeded. This could be done by frequent Secchi disk measurements.

The effluents from aquaculture facilities are much less concentrated in organic matter, suspended solids, and plant nutrients than most domestic and industrial wastewaters. Nevertheless, aquaculture effluents typically have higher concentrations of organic matter, inorganic solids, turbidity, nitrogen, and phosphorus than found in the water bodies into which they are discharged. Typical concentration ranges for water quality variables in aquaculture effluents follow: total suspended solids (TSS), 5–200 mg/L; turbidity, 5–150 nephelometer turbidity units (NTU); 5-day biochemical oxygen demand (BOD_5), 5–100 mg/L; total nitrogen, 0.05–10 mg/L; total phosphorus, 0.1–0.5 mg/L; salinity (freshwater culture, 100–1,000 mg/L, brackishwater culture, 1,000–25,000 mg/L; marine culture, 25,000–40,000 mg/L).

Dissolved oxygen concentration, pH, and water temperature usually are within acceptable ranges in aquaculture effluents with respect to receiving water bodies. Salinity is of concern in instances where a source of salinity allows estuarine or marine species to be produced in inland ponds that discharge into freshwater areas. Ponds supplied with brackish water or seawater in coastal areas also are sometimes discharged into freshwater areas.

Nearly all culture systems for fish and crustaceans use fertilizers and feeds, and aeration is common. The main water pollution concerns are nitrogen, phosphorus, and suspended solids in effluents. Most of the nitrogen and phosphorus is discharged in organic form as part of the organic solids. The organic solids decompose in receiving water bodies releasing plant available nitrogen and phosphorus that stimulate eutrophication. The decomposition process consumes dissolved oxygen in direct proportion to the amount of organic matter oxidized. The BOD_5 concentration is closely related to the amount of organic matter, and the amounts of nitrogen and phosphorus in effluents also are related to the quantity of organic matter. The BOD_5 concentration can be used as a surrogate indicator of the organic and nutrient pollution potential of effluents. The total suspended solids concentration consists of both mineral and organic particles. The BOD_5 concentration would be low despite a high concentration of suspended solids in situations where the total suspended solids are mainly mineral (soil) particles. The BOD_5 concentration would not be a good surrogate for nutrient concentrations or of the potential for sedimentation in such effluents.

Effluent standards for different types of aquaculture systems are recommended in Box 4 (pg 17). The water analyses should be made by a reliable laboratory having one or more international certifications. Water samples should be collected at least quarterly from the effluent discharge stream. In cases where water is not discharged other than at harvest, samples should be taken from the effluent stream at four equally spaced time intervals during draining, and equal portions of the samples combined into a composite sample for analysis.

Soil health

A large proportion of freshwater fish, essentially all penaeid shrimp, and most freshwater prawn, crayfish, and crabs are produced by pond culture. An estimate of the global aquaculture pond area based on 2020 satellite images placed the area at 5.53 million hectares (Wang et al. 2022). The author of the present report feels that the true pond aquaculture area is greater than 5.53 million hectares, because previous estimates based on national aquaculture production statistics suggest that the area is somewhere between 10 and 20 million hectares. Verdegem and Bosma (2009) gave an estimate of 11.6 million hectares in 2007.

Although the global aquaculture pond area is not known with certainty, the area is substantial, and most ponds have earthen bottoms. Soil organic matter increases considerably in pond bottoms because of the lack of molecular oxygen for aerobic decomposition in sediment more than a few millimeters below the sediment-water interface.[1] Anaerobic decomposition also results in methane and nitrous oxide formation, both of which are potent GHGs.

Sediment accumulates in pond bottoms at a rate of around 1 cm/yr (Boyd et al. 2010). Sediment may be removed periodically, but seldom at intervals of less than 5 years. Sediment has elevated concentrations of organic matter, nitrogen, and phosphorus, and a high salt burden is present in sediment for ponds supplied with saline water. Disposal of pond sediment should take into account its potential for causing nutrient pollution and salinization.

Pond bottom soils usually are net emitters of GHGs, because their ability to sequester carbon usually is exceeded by the carbon dioxide equivalence of methane and nitrous oxide that is released into the air (Boyd and McNevin 2023). Sediment removal should lessen methane and nitrous oxide emissions from ponds, assuming that the excavated sediments are disposed by spreading in a thin layer over agricultural land where the surface layer of soil does not become anaerobic as it does in waterlogged pond bottoms. As already mentioned, care must be exercised in sediment disposal from ponds filled with saline water to avoid salinization of nearby non-saline land and water.

Ponds should not be installed in areas where the bottoms and embankments are made of organic soil (greater than 10% organic carbon) or in areas with potential or active acid-sulfate soils (greater than 0.75% sulfur in form of iron pyrite). Pond bottoms of low pH non-acid-sulfate soils (pH above 4 but below 7) should be limed with agricultural limestone to increase soil pH to 7 or 8.

Soil quality standards for aquaculture pond bottoms and some practices for achieving compliance are given in Box 5 (pg 17).

Biodiversity loss

The determination of biodiversity loss is a complex analysis and the standards suggested for the *Codex Planetarius* would be a safeguard with respect to protection of biodiversity. A specific standard for biodiversity does not seem a reasonable expectation.

Conclusion

Standards used in aquaculture certification programs are much more detailed than those suggested here. There also are many other requirements in these certification programs that are not validated by compliance with metric-based standards. Aquaculture certifications are voluntary, and only a relatively small portion of aquaculture production is presently under one or more of these programs. The *Codex Planetarius* will extend the effort of achieving greater environmental responsibility to a much larger portion of global aquaculture production.

This report suggests standards for what are most commonly thought to be the major negative environmental impacts of aquaculture. The background information, assessments of impacts, and recommendations related to the standards of this report should be useful to those involved in development of the *Codex Planetarius*. ■

[1] Aquaculture bottom soils usually contain 2–4 times more organic matter than found in typical cropland soils of the same soil types. For example, fishponds in the southeastern United States usually reach an equilibrium organic carbon concentration of 2–3%, while in cultivated fields, the equilibrium organic carbon concentration is seldom above 0.5% (Boyd 1995). Note: Organic matter consists of 45–50% of organic carbon.

Literature Cited

Boyd, C. E. 1990. Water Quality in Ponds for Aquaculture. Alabama Agricultural Experiment Station, Auburn University, Alabama. Birmingham Publishing Company, Birmingham, Alabama.

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

Boyd, C. E. and A. A. McNevin. 2022. Overview of aquaculture feeds: global impacts of ingredient production, manufacturing, and use., pp. 3-30. In D. A. Davis (Ed.). Feed and Feeding Practices in Aquaculture, 2nd edition. Woodhead Publishing, Kidlington, Oxford.

Boyd, C. E. and A. A. McNevin. 2015. Aquaculture, Resource Use, and the Environment. Wiley-Blackwell, Hoboken, New Jersey.

Boyd, C. E. and A. A. McNevin. 2018. Land use in shrimp aquaculture. World Aquaculture 49 (March), 28–34.

Boyd, C. E. and A. A. McNevin. 2023. Resource use and pollution potential in feed-based aquaculture. Reviews in Fisheries & Aquaculture. https://doi.org/10.1080/23308249.2023.2258226.

Boyd, C. E., R. P. Davis, and A. A. McNevin. 2021. Comparison of resource use for farmed shrimp in Ecuador, India, Indonesia, Thailand, and Vietnam. Aquaculture, Fish and Fisheries. 1:3–15. https://onlinelibrary.wiley.com/doi/10.1002/aff2.23

Boyd, C. E, A. A. McNevin, and R. P. Davis. 2022. The contribution of fisheries and aquaculture to the global protein supply. Food Security 14:805–827. doi.org/10.1007/s12571-021-01246-9.

Boyd, C. E., C. W. Wood, P. L. Chaney, and J. F. Queiroz. 2010. Role of aquaculture pond sediments in sequestration of annual global carbon emissions. Environmental Pollution 158:2537–2540. https://doi.org/10.1016/j.enpol.2010.04.025.

Jescovitch, L. N., P. L. Chaney, and C. E. Boyd. 2016. A preliminary assessment of land-to-water surface area ratios (LWR) for sustainable land use in aquaculture. Papers in Applied Geography 2: 178–188. https://doi.org/10.1080/23754931.2015.1115367.

Mrčelić, G. J, I. Miletic, M. Piria, A. Grgičevic, and M. Slišković. 2020. The peculiarities and farming challenges of Atlantic bluefin tuna (*Thunnus thynnus*, L. 1758). Croatian Journal of Fisheries 78:33–44, http://doi.org/10.2478/cjf-2020-0004.

Naylor, R. L., R. W. Hardy, A. H. Buschman, S. R. Bush, L. Cao, D. H. Klinger, D. C. Little, J. Lubchenco, S. E. Shumway, and M. Troell. 2021. A 20-year retrospective review of global aquaculture. Nature 591:551–563, https://doi.org/10.1038/s41586-021-03308-6.

Verdegem, M. C. J. and R. H. Bosma. 2009. Water withdrawal for brackish and inland aquaculture and options to produce more fish in ponds with present water use. Water Policy 11:52–68. https://doi.org/10.2166/wp.2009.003.

Wang, Z., J. Zhong, X. Yong, C. Huang, F. Su, Y. Liu, and Y. Zhang. 2022. Global mapping of the landside clustering of aquaculture ponds from dense time-series 10 m Sentinel-2 images on Google Earth Engine. International Journal of Applied Earth Observation and Geoinformation 15, https://doi.org/10.1016/j.jag.2022.103100.

Tables / Boxes

Table 1. Typical ranges of production per crop in earthen ponds, lined ponds, and tanks for species groups of farmed fish and crustaceans.

Type culture	Production per crop (kg/ha equivalent)
Extensive:	
• Shrimp and other crustaceans	100 – 500
• Filter-feeding fish	1,000 – 2,000
• Other fish	250 – 1,000
Semi-intensive (feed only):	
• Shrimp and other crustaceans	1,000 – 2,000
• Tilapia	4,000 – 5,000
• *Pangasius*	5,000 – 10,000
Intensive (feed, water exchange, mechanical aeration)[1]:	
• Shrimp and other crustaceans	5,000 – 10,000
• Tilapia	15,000 – 20,000
• *Pangasius*	20,000 – 40,000
• Other fish	5,000 – 10,000
Hyper-intensive (feed, carbohydrate sources, water exchange, intensive mechanical aeration, small-lined ponds or tanks):	30,000 – 60,000

[1] In raceway culture or flow-through pond systems, aeration may not be used in intensive *Pangasius*, tilapia, and trout culture.

Table 2. Land, freshwater, and energy use for aeration per tonne of production at different production intensities in extensive and in intensive production of fish in ponds.[1]

Annual production (t/ha water surface area)	Land use (ha/t)			Land for feed (%)	Freshwater use (m^3/t)			Aeration energy (GJ/t)
	Farm	Feed	Total		Farm	Feed	Total	
1	1.40	None	1.40	0	30,000	None	30,000	None
2	0.70	None	0.70	0	15,000	None	15,000	None
3	0.48	0.4	0.88	45	10,000	2,880	12,900	None
4	0.35	0.4	0.75	53	7,500	2,880	10,400	8.6
5	0.28	0.4	0.68	59	6,000	2,880	8,900	8.6
6	0.23	0.4	0.63	63	5,000	2,880	7,900	8.6
7	0.20	0.4	0.60	67	4,290	2,880	7,200	8.6
8	0.18	0.4	0.58	69	3,750	2,880	6,600	8.6
9	0.16	0.4	0.56	71	3,330	2,880	6,200	8.6
10	0.14	0.4	0.54	74	3,000	2,880	5,900	8.6

[1] Notes: 1.0 ha water surface requires 1.4 ha land; feed requires 0.25 ha cropland/t; FCR is 1.6; farm water use of 30,000 m^3/ha water surface/yr; water for feed requires 1,800 m^3/t feed; aeration energy use is 8.6 GJ/t fish.

Table 3. Summary of 2022 global aquaculture production in kilotonnes in inland and marine and coastal areas. FAO database.

	Inland	Marine / Coastal	Total
Finfish	49,120	8,341	57,461
Crustaceans	4,477	6,760	11,237
Mollusks	193	17,848	17,741
Other animals	594	469	1,062
Algae	64	35,013	35,078

Table 4. Summary of 2022 global aquaculture production in kilotonnes of some species or group of aquaculture species often traded internationally. FAO database.

Species or group	Production
Tilapia	5,584
Striped catfish	2,520
Rainbow and other trout	960
Atlantic and other salmon	2,720
Marine fish	1,584
Whiteleg shrimp	6,200
Red swamp crayfish	2,469
Giant tiger shrimp	717
River prawns	522
Cupped oysters	6,670
Scallops	1,746
Crabs	1,184

Table 5. Typical waste loads of nitrogen and phosphorus (amounts in feed minus quantities harvested in biomass) for seven common aquaculture species.

Species	Waste load to culture system[1] (kg/t production)		Direct CO_2 emissions from feed (kg/t production)
	Nitrogen	Phosphorus	
Carp	68	15	2,020
Ictalurid catfish	104	27	3,380
Tilapia	65	14	2.050
Pangasius	44	16	1,600
Atlantic salmon	47	15	1,780
Rainbow trout	69	15	1,620
Whiteleg shrimp	61	10	1,880

[1] Production system waste load.

Table 6. Summary of major natural resource use in different production systems.

Production system	Major natural resource used	Major management inputs
Extensive ponds	Land and water	Fertilizers and liming materials
Feed-based ponds	Land, water, energy, and wild fish	Feeds, liming materials, fertilizers, carbohydrate sources, water exchange, and mechanical aeration
Flow-through units	Water and wild fish	Feeds
Water recirculating systems (RAS)	Energy and wild fish	Feeds, liming materials, mechanical aeration, and water treatment
Cage and net pens	Water surface area and wild fish	Feeds
Molluscan species	Bottoms or water columns in water bodies	Artificial structures
Seaweed species	Water columns in water bodies	Artificial structures

Table 7. Direct environmental impacts by major management inputs to aquaculture systems.

Input	Direct environmental impact
Organic fertilizers	Nitrogen, phosphorus, acidity, organic PM[1]
Phosphate fertilizers	Phosphorus, organic PM
Nitrogen fertilizers	Nitrogen, acidity, BOD, CO_2
Feeds	Nitrogen, phosphorus, BOD, CO_2, acidity, organic PM
Liming materials	CO_2
Carbohydrate sources	BOD, CO_2, organic PM
Natural water exchange	Flushing[2]
Mechanical (pumped) water exchange	CO_2, N_2O, and CH_4, flushing
Mechanical aeration	CO_2, N_2O, CO_2, organic (mineral) PM

[1] PM = particulate matter.
[2] Flushing shortens the retention time in production systems thereby reducing natural assimilation of waste.

Table 8. An overview of main resource use concerns and most likely negative impact for major group of farmed fish and crustaceans.

Farmed fish and crustaceans	Resource	Impact
Extensive culture (no feed used) of any species	Land	TSS
Feed-based culture:		
Carps	Land	BOD_5, TSS
Tilapia	Land	BOD_5
Penaeid shrimp	Energy[1]	BOD_5
Catfishes	Water[2]	BOD_5, TSS
Freshwater crustaceans	Land	BOD_5
Salmon	Energy, wild fish	N and P
Trout	Energy, wild fish	N and P
Eels	Wild fish	N and P, TSS
Milkfish	Land	TSS
Other marine fish	Energy, wild fish	N and P

[1] For purposes of the *Codex Planetarius*, it may be assumed that more energy use equates to proportionally more GHG emissions.
[2] Water exchange rates may be especially high in *Pangasius* culture, and less land use does not necessarily relate to less water use.

Table 9. Typical embodied land, freshwater, and energy coefficients per tonne of several types of aquaculture feeds.

Feed use	Land (ha/t)	Freshwater (m^3/t)	Energy (GJ/t)
Tilapia	0.273	2,061	4.50
Ictalurid catfish	0.233	1,405	4.11
Pangasius	0.259	1,793	4.35
Carp	0.220	1,803	3.54
Atlantic salmon	0.292	2,842	14.19
Rainbow trout	0.232	1,771	14.54
Whiteleg shrimp	0.221	1,612	9.59

Box 1. Land use standard.

Type of farming	Standard
Extensive pond production: • Natural productivity only • Fertilized	No standard recommended, but no new land conversion to extensive farming allowed.
Feed-based pond production: • No water exchange or aeration	• Shrimp and crabs, 1 t/ha/crop Fish, 2 t/ha/crop
• Water exchange (maximum of 10% pond volume daily)	• Shrimp and crabs, 1.2 t/ha/crop Fish, 3 t/ha/crop
• Aeration (with or without water exchange)	• Shrimp, 1 t/ha/crop + (0.4 t x hp aeration/ha) Fish, 2 t/ha/crop + (0.6 t x hp aeration/ha)

Box 2. Water use standard limits for water exchange.

Type of farming	Standard
Extensive ponds with tidal water exchange	None
Other ponds: • Coastal, brackish water • Freshwater (*Pangasius* and tilapia) • Other freshwater species	 • 10% or less of pond volume daily • 50% or less of pond volume daily • 10% or less of pond volume daily
Raceways	80,000 m^3/t biomass harvested or less
Net pens, cages, and RAS	None

Box 3. FCR standards.

Species or species group	FCR upper limit
Carps	1.6
Tilapia	1.6
Whiteleg shrimp	1.5
Black tiger shrimp	1.6
Ictalurid catfish	1.8
Pangasius	1.4
Other catfishes	1.3

Species or species group	FCR upper limit
Freshwater crustaceans	1.7
Trout	1.2
Salmon	1.2
Eel	1.4
Milkfish	1.6
Marine fish	1.5

Box 4. Suggested effluent water quality standards for different kinds of aquaculture.

Culture system	Standard[1]	Suggested additional standard
Ponds:		
• Unfertilized	None	None
• Fertilized	25 mg/L TSS	None
• Feed only	20 mg/L BOD_5	None
• Feed and aeration	30 mg/L BOD_5[2]	30 mg/L TSS[2]
Raceway and other flow-through culture units:		
• Cold or cool water	5 mg/L TSS increase	6 mg/L or more DO
• Warm water or tropical	10 mg/L TSS increase	5 mg/L or more DO
Cages and net pens:		
• Inland waters	No increase in average annual water clarity[3]	None
• Estuaries and ocean	None	
Recirculating aquaculture system (RAS)	30 mg/L BOD[4]	None

[1] Where saline water discharged into freshwater, salinity must not exceed 1,000 mg/L in the mixing zone.
[2] A more rigorous standard of 20 mg/L each for BOD5 and TSS might not be achievable in pond management for production over 8–10 t/ha/crop.
[3] Water clarity by Secchi disk visibility or nephelometry, and annual average of biweekly measurements.
[4] No limit if discharged into a municipal sewage.

Box 5. Aquaculture pond soil health standards and some precautions.

Pond bottom soils should contain less than 10% organic carbon and total sulfur concentrations above 0.75%.

Precautions:

- Sediment should be removed from ponds when its average depth exceeds 10 cm.
- Sediment from freshwater ponds should be disposed by spreading it over agricultural land (rice paddies excluded).
- Sediment from ponds with saline water must not be disposed in freshwater areas unless it has been stockpiled and leached free of salt by rainfall in areas where salinization is not an issue.
- Erosion of the insides of pond embankments by aerator-generated water currents that tend to resettle in ponds may be minimized by partial lining of insides of embankments with plastic liners.