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REVIEW OF THE ENVIRONMENTAL EFFECTS OF FIN-FISH FARMING.

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AUTHOR: ~~MR~~ DR. JASPER TRENDALL

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I. EXECUTIVE SUMMARY

Aquaculture is undergoing extremely rapid development worldwide. As part of this trend it is likely that fish farming in tropical Australia will increase substantially over the next ten years and the sheltered waters of the Great Barrier Reef appear attractive for the cage-farming of fish.

Fish farms produce substantial quantities of waste in the form of sediment and soluble nutrients. The sediment associated with farms is generally localised, although the effects on bottom-dwelling fauna within 30 metres of the cages are severe. The soluble nutrients are mainly nitrogen in the form of ammonia and carbon as carbon dioxide. The environmental impact of the major nutrients (phosphorus, nitrogen, carbon) and the minor components (i.e, minerals, vitamins) depends upon the sensitivity of the surrounding habitat.

Apart from discharging nutrients, fish farms are also associated with a range of chemical, physical, biological and aesthetic modifications to the environment.

Fish farming in tropical areas is relatively new in Australia and there are very few situations comparable to the Great Barrier Reef overseas. A substantial amount of information is required to adequately assess the full environmental impact of any particular operation and collecting accurate field data can be very costly. A management and monitoring program for fish farming should provide for flexibility within a basic set of environmental guidelines.

II. CURRENT STATUS OF FISH FARMING IN AUSTRALIA

Aquaculture is undergoing extremely rapid development world-wide. The current world average production of fish by aquaculture is 10% of consumption and FAO predicts that this will rise to 20% by the year 2000. This growth is at a time when the productivity of most capture fisheries is falling. In 1985 the value of production from aquaculture in Australia was approximately $49 million, around 9% of the value of the wild catch. This had risen in 1989-90 to a production value of more than $200 million dollars, which was almost 25% of the value of wild fisheries (O'Sullivan 1991, Treadwell et al. 1991). Aquaculture production in Australia is concentrated in a few areas (Table 1) and most projections indicate that there will be significant growth in aquaculture in Australia during the next decade.

Tropical areas have natural climatic advantages for fish farming because the warmer water temperatures enhance growth rates. Among the currently favoured technologies for commercial fish farming are cage-farming systems for which the relatively sheltered water in the Great Barrier Reef region are especially attractive

Aquaculture in Australia concentrates on the intensive production of high value species and the development of fish farming in tropical areas is likely to be along similar lines. As an indication of the extent to which the farming of tropical species is likely to grow, Table 2 compares the production of farmed trout in Europe and Australia, which is regarded as a stable industry, with the production of barramundi in Australia, which is regarded as a new industry. In the Great Barrier Reef region there are two broad types of fish farming which can be developed, sea-cage farms and

TABLE 1. Estimated value of Australian aquaculture production in 1988/89 and 1989/90 (from O'Sullivan, 1991).

Species	1988-89 ($ million)	1989-90 ($ million)
Salmonids	25.0	41.5
Freshwater fish	2	2.9
Barramundi	0.3	1.0
Aquarium fish	2	2
Marine fish	<0.1	<0.1
Eels	no data	1.6
Fwater crayfish	2.5	2.6
Penaeid prawns	2.7	8.5
Crabs	<0.1	<0.1
Brine shrimp	0.1	<0.1
Edible oysters	52.0	45.8
Pearl oysters	63.0	93.5
Giant clams	0	<0.1
Abalone	0	<0.1
Mussels	1.6	1.8
Scallops	0	<0.1
Micro-algae	3.0	3.5
Seaweeds	0	<0.1
Crocodiles	0.9	1.5
Total	$155.1	$206.2

land-based farms, and they have different management and monitoring requirements.

TABLE 2. Production of trout in Europe in 1989, together with the estimated production of trout and barramundi in Australia in 1989/90.

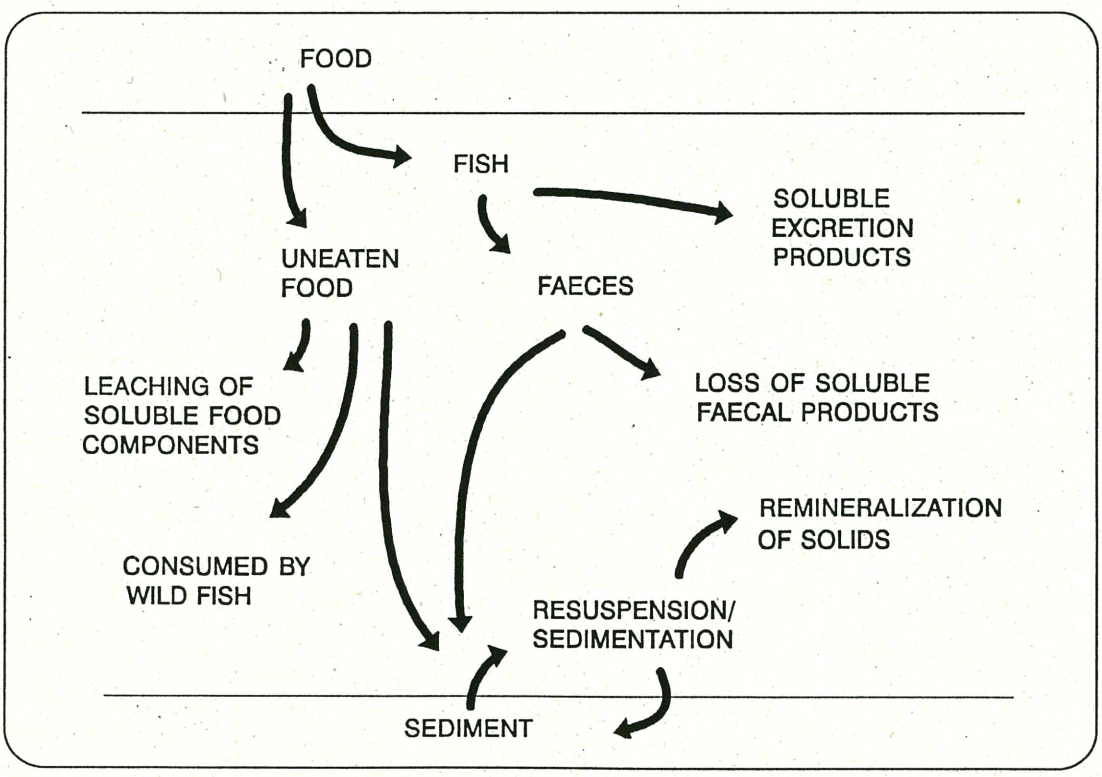
COUNTRY	TROUT (Tonnes)
Belgium/Lux.	800
Denmark	23,000
Spain	16,600
France	36,000
Greece	1,850
Ireland	645
Italy	30,000
Holland	100
Portugal	1,000
FRG	17,000
UK	16,600
TOTAL EUROPE - TROUT	143,595
AUSTRALIA - TROUT (est.)	1,500
AUSTRALIA - BARRAMUNDI	33

This review describes the basic features of barramundi farming, two types of farming operation, sea-cage and land-based, and the potential environmental impacts from fish farms. Sea-cage farms are the most immediate concern, partly because this type of operation is already established in the area and is therefore a potential model for future developments, and partly because the environmental impacts from sea-cages have not been clearly defined and are difficult and expensive to monitor. In examining the environmental impacts of fish farming this report will focus on sea-cages. This does not mean that land-based farming is environmentally innocuous, but land-based fish farms are not yet common in Australia and the environmental management problems they present are more clearly defined.

III. DESCRIPTION OF BARRAMUNDI FARMING IN AUSTRALIA

The dynamics of a fish farm are outlined in Figure 1. The primary input is food. A proportion of the food is not eaten and contributes to sediment, soluble waste and wild fish populations. Of the food that is eaten by the farmed fish, some is converted into fish tissue, some is metabolised and excreted as soluble waste and some is converted to faeces. Each of these pathways can be measured, either directly or indirectly, and used to calculate the input component of the mass balance of the production cycle. The outputs from a farm are the fish that are harvested, the fish that die and the fish that escape.

FIGURE 1. Outline of the principal nutrient pathways in a sea-cage farm.



Although barramundi (*Lates calcarifer*) has been farmed in south-east Asia for many years it is only recently that it has been commercially cultured in Australia. The industry has grown rapidly, from no commercial production in 1986, to a harvest of more than 100 tonnes with a farm gate value of more than 1.4 million dollars (Trendall and Fielder, 1991).

There are a number of operationally separate stages in barramundi farming and this report briefly outlines some of the main features of each stage.

Broodstock and egg production.

Captive broodstock are now the principal source of fertilised eggs for the industry. Government supported facilities operated by the Fisheries Departments of Queensland and the Northern Territory routinely produce fertilised eggs over a six month interval between October and March. These eggs are sold to commercial operators who use a variety of hatchery methods to produce fingerlings.

Hatchery production

There are two main methods for the hatchery production of fingerlings. Extensive pond-rearing, where newly hatched larvae are released into salt-water ponds in which a zooplankton bloom has been cultivated. The plankton bloom is maintained for approximately three weeks, after which time the pond is drained and any surviving fingerlings harvested. This method of production is relatively cheap and simple and is capable of producing large quantities of low-cost fingerlings. It has some disadvantages - production is subject to the environmental conditions being suitable at the time, and the fingerlings that are harvested cannot be guaranteed to be free of diseases or parasites.

The other form of hatchery operation is the enclosed, intensive production of fish using cultured live foods such as rotifers and brine shrimp. This is a labour-intensive process and the fingerlings that are produced have a higher cost. However, production is independent of the environment and can be managed in a way which minimises the opportunity for disease to infect or be transferred by the fingerlings.

Grow-out production

At present, cage culture is the main farming method for barramundi, with a mixture of pond and sea-cage farms in Queensland and the Northern Territory. There are some new land-based, enclosed farms in New South Wales and South Australia.

The cage farms use small floating cages (2m by 2m up to 5m by 10m) in creeks or ponds to hold fish from sizes of 30-40 mm total length up to a market size of 300-400 gms. The fish are fed manufactured pellet diets and the growth rates can be rapid, with the fastest fish growing from fingerling to market size in six months.

Associated with these rapid growth rates is a strong tendency to cannibalism, because the bigger fish rapidly reach a size where they are capable of eating the smaller fish. The management of cannibalism requires regular grading of the fish into different size classes. This is particularly important when the fish are smaller than 100 gms and is a labour intensive procedure which adds considerably to the operating costs of grow-out farms. Many aspects of commercial grow-out, such as disease control and food conversion efficiency, are not well documented or researched and there is still scope for improvements in the efficiency of operation of commercial barramundi farms.

Processing and marketing

Farmed barramundi are generally sold as a fresh, whole fish. They are scaled, gilled and gutted and packed on ice for shipping to markets in the capital cities. The product from Australian farms competes in the market place against other fresh fish, such as farmed salmon, and against frozen imported barramundi from Thailand and Vietnam. Wholesale prices for fresh Australian farmed barramundi are currently in the region of $10 - 14 per Kg (O'Sullivan 1991, Trendall and Fielder 1991).

IV. CHARACTERISTICS OF SEA-CAGE FARMS

The primary reason why sea-cage farms are widely used for fish farming is economic. The costs associated with maintaining a supply of clean water are much lower if the fish are held in cages in open water, than if an equivalent amount of water is pumped through land-based tanks or ponds.

There is wide variety of cage designs which share the common features of a floating collar, a suspended net bag and a mooring system. Modern cage designs are usually floating pontoons which are moored to fixed anchors or pylons. There is often a walkway for feeding and servicing the nets. The provision of food, fingerlings and other operating requirements, as well as the removal of harvested product requires boat access. Depending upon the size of the operation this can be at regular intervals to on-site storage in a barge or pontoon, or it may be daily, with all staff and equipment commuting to the farm site.

The large-scale production of fish in sea cages is relatively recent and was initiated in Japan for growing yellowtail in the late 1950's and then in Norway in the late 1960's as a means of growing Atlantic salmon. All of the commercial barramundi production in tropical Australia currently comes from cage farms, although there have been some very recent trials using both open pond and fully enclosed land-based systems.

The size of the farm, the size of the cages and the precise details of operation are highly variable and are determined primarily by the finances and inclination of the farmer. Typical cage farm systems currently in use in Queensland comprise of cages approximately 8 m^2 that are connected by a common pontoon. There has been a move towards larger cages, of up to $100m^2$, with appropriate walkways for access. However, the requirement for frequent handling and grading means that smaller cages will always have a role.

Cage farming can be very important means of production where the availability of land is limited, or if there is an existing infrastructure that can be utilised e.g. there is wild fishery in decline with under utilised resources, such as boats and people. However, the mode of operation can have an important influence on the environmental impact of the farm and management of the environmental effects requires management of the farm. Cages must be located in sites in which there is enough water flow to provide clean oxygenated water to the fish and to remove all waste material. The risk of equipment damage and stock losses from the weather and predators must be minimised and the site must be close enough to a shore base to be efficiently serviced. The current farming methods for tropical fish species in Australia are primarily manual - feeding, net-cleaning, maintenance and harvesting. The efficiency with which these operations can be carried out is a direct function of the degree to which the site is protected from wind and weather.

Recent developments in salmon farming in Europe and Japan have involved the establishment of off-shore sea-cages, in which routine functions, such as feeding, are automated. This reduces the need for day-to-day access and allows the farms to be sited in open water where environmental problems are less immediate. In comparison with salmon farming, barramundi farming in Australia is recent and it lacks the depth of technological support that is available for salmon farming.

V. CHARACTERISTICS OF LAND-BASED FARMS

Land-based fish farms have advantages over open sea or estuary farms in five areas:

Protection from the climate: Land-based systems are less vulnerable to the effects of climate. There is less risk of damage or stock loss from storms, there is less difficulty in servicing the farm when the weather is inclement and there is also less likelihood that variations in the weather will affect production. For example, barramundi in cages feed less readily on bright sunny days.

Reduced conflict with other user groups: Land-based farms have relatively little impact on the community. There is no direct user conflict with recreational or fishing user groups and there is much less opportunity for aesthetic problems.

Improved security: Land-based farms are easier to secure against theft or vandalism and they also avoid potential problems with natural predators such as sharks and birds.

More efficient environmental management: A land-based farm allows direct control over all the operationally important environmental factors. For example, with sea cages it is almost impossible to isolate cages from each other and prevent disease spreading. In a land-based farm with tanks the fish can be kept separated and infections contained. Similarly, the treatment of disease is more easily and effectively managed in land-based systems. There can be control over all aspects of the environment, including temperature, oxygenation and photoperiod. Most importantly, the waste that is produced by land-based farms can be managed and treated to meet specific requirements.

Improved biological performance: The increased control over the environment extends to the management of food, stocking densities and harvesting and in many instances land-based farms have better survival, better growth rates and improved food conversion ratios (Anderson 1988).

The principal disadvantage of land-based farming is that costs are generally higher. The operating costs for both sea-cage and land-based farms depend upon the species being farmed, the size of the fish at harvest and the type of water treatment system that is being used. For example, the cost of holding salmon for three years to a size of 3-5 Kg in a land-based farm which uses a flow-through water supply is substantially higher than the cost of producing equivalent fish in sea-cages.

However, as in most forms of primary industry, there is generally little or no accounting of future costs, in particular, environmental costs. In direct comparisons between land and sea-cage farms the future costs of environmental degradation are hidden and often conveniently overlooked.

VI. OVERVIEW OF ENVIRONMENTAL EFFECTS OF FISH FARMING

It is generally accepted that cage farming of fish is a significant source of nutrients, solids and other waste products (Seymour and Bergheim 1991). A typical salmon farm with an annual production of 200 tonnes of fish produces an annual loading of 2 tonnes of phosphorus, 18 tonnes of nitrogen and 100 tonnes of oxygen consumed through the BOD. The quantities of waste produced reflect the levels of production. In Norway, which is the worlds largest producer of cage-farmed Atlantic salmon, there are substantial quantities of wastes produced by salmon farms (Table 3) and it has been estimated that the waste from salmon farms contributes 840 tonnes of total-P and 7250 tonnes of total-N, which was 14% and 8% respectively of the total P and N in coastal discharge from all sources (Seymour and Bergheim 1991).

TABLE 3. Salmonid harvest, quantity of food used and estimated production of waste in Norway from 1979 to 1989. (from Seymour and Bergheim, 1991).

	Production (x 10^3 t)		Source of waste (x10^3 t)			
Year	Harvest	Food used	Feed	Faeces	Processing	Mortalities
	wet wt	dry wt	dry wt [a]	dry wt [b]	wet wt [c]	wet wt [d]
1979	6.8	22.1	6.6	3.1	0.8	0.7
1981	12.9	35.2	10.6	4.9	1.6	1.2
1983	22.1	48.3	14.5	6.8	2.8	2.1
1985	33.8	88.2	26.5	12.3	4.2	3.6
1987	56.2	145.7	43.7	20.4	7	6.4
1989	115	302	90.6	42.3	14.4	?

a Estimated as one-third of used feed

b Estimated as 20% of consumed feed (less wastage)

c Estimated as 12.5% of weight of harvested fish

d Estimated as 8% of total fish production

In order to establish some sort of reference for quantifying discharge the waste from fish farms has been compared to municipal sewage and direct comparisons made using PE values or Person Equivalents. For example, it has been estimated that the pollution from 1 kilo of trout is equivalent to the untreated sewage from 0.2 - 0.5 persons (Bergheim et al. 1982) or that a medium-sized fish farm that produces 100 tonnes of fish will generate wastes equivalent to several thousand people (Bergheim and Selmer-Olsen 1978). Such comparisons should be treated with caution because, even if reference is made to an individual component, such as BOD[5] , the wastes from a fish farm are quite different from untreated sewage, in both the C,P and N ratios and in the proportion of settlable and solid wastes (Rosenthal et al. 1988).

Quantifying the effect of discharge from a fish farm is difficult. Apart from localised increases in sediments and suspended solids there are often few short-term measurable effects from cage farms (Gowen and Bradbury 1987, Woodward et al. unpubl). The differentiation between soluble and particulate waste is important. The solid wastes are more easily observed, measured and monitored and are usually more localised. The soluble wastes are more difficult to monitor and track, with the result that their eventual fate and environmental effect is not well understood. The majority (approximately 90%) of the nitrogen released from a fish farm is in the soluble form of ammonia while the majority of the phosphorus (approx. 50%) is bound in particulate material.

The waste loadings of both nitrogen and phosphorus are likely to be available to algae (Gowen and Bradbury 1987) and, in general, large fish farms will tend to promote eutrophication.

The assessment of the environmental effects of cage farming has usually followed the development of the farms and has not integrated environmental assessment with farm management. For example, there are detailed studies on mass flux and nutrient balances in some farms but relatively little information on sedimentation rates or phytoplankton levels.

The management of the pollution created by cage farms has taken three broad approaches:

i) devising monitoring programs to measure the environmental impact of proposed or existing cages;

ii) positioning the cages at sites where strong currents or tides minimise the local build-up of wastes, and more recently;

iii) developing technology and farming practices which optimise the operation of the farms and reduce wastage.

The underlying assumption in all of these approaches is that a cage farm will create waste products and that the purpose of management is to limit the impact of the wastes to acceptable levels. This assumption has two prerequisites, an effective means of measuring the impact of the waste, and a realistic means of determining an acceptable level of impact.

With cage farms that are sited in areas with optimum water flow it is extremely difficult to measure the short-term effects of dissolved nutrients or model their long-term effects.

It can be similarly difficult to determine an acceptable level of impact, particularly if it involves balancing the economic value of the farm against the environmental costs of its operation.

For example, in the U.S. there has been significant opposition to the cage culture of salmon in the State of Washington, primarily because of fears that the aesthetic impact of floating cages will reduce property values and adversely affect existing users of the waterways (Stickney 1988).

In countries such as Norway, where salmon farms are an important part of the economy, there is considerable effort being directed into the improved production methods, such as low pollution feeds which have improved digestibility and reduced wastage and the use of vaccines instead of chemicals to treat disease (Anon. 1988).

VII. TYPES OF ENVIRONMENTAL IMPACTS.

There has been a substantial amount of work documenting the levels of wastes produced by fish farms but relatively little work that details the effects of these wastes on the water column. This is partly because processes such as eutrophication or hypernutrification are often cumulative and measurable effects may take many years.

Sediment and solids

Uneaten feed and faeces accumulate underneath net cages and contribute to sedimentation which may alter the benthic environment and change the existing chemistry of the sediment. The rate of sedimentation depends upon the characteristics of the site, the water flow rate, the type of food and the method of feeding. It is estimated that 15-20% of the dry weight of the food is indigestible and contributes directly to particulate and sedimentary loadings. In Red Sea Bream cages in Japan it has been estimated that 37.2 gm per square metre per day are deposited under the cages (Rosenthal 1985)and Table 4 summarises sedimentation rates for a range of farms. The final effect is a function of both the rate and the magnitude of farming. For example, in Norway the dry weight of faeces produced by the salmon farming industry has been estimated at more than 42,000 tonnes per year (Seymour and Bergheim 1991).

TABLE 4. Waste sedimentation rates at various fish farms (from Beveridge, 1987)

Species	Country	Diet	Sedimentation rate (g dry wt/m2/day)
Rainbow trout	Sweden	dry/moist	range 17-26
	Scotland	dry	mean 87
	Scotland	dry	mean 16.43
Yellowtail and seabream	Japan	trash fish	range 4.1-5.9
	Japan	trash fish	range 17-21.6

The fate of the particulate wastes will depend upon the settling velocities and the current flow in the area but the effects are generally localised, with the area influenced by sediment between 5 and 40 metres around sea-cages (Brown et al. 1987, Gowen et al. 1985, Hall et al. 1990). Heavy sedimentation can lead to the creation of anaerobic conditions which prevent the breakdown of nitrogenous wastes (Kaspar et al. 1988). There are three main consequences to the change from aerobic to anaerobic conditions in the sediment: 1) The sediment and the seawater immediately above it become oxygen depleted; 2) Toxins such as hydrogen sulfide, ammonia and methane can be produced, and; 3) The concentrations of nutrients increases more rapidly (Caine, 1989). All of these effects contribute to an overall degradation of water quality in the vicinity of the farm.

An accumulation of sediments may have deleterious effects on both the fish in the cages and the existing benthic fauna. In Japan, Arizono and Suiza (1977) established a positive correlation between a simple Environmental Index (EI = {Conc. of sulphides in sediment/dissolved oxygen in water above sediment} x 100) and major disease outbreaks, in which more than 1% of stock was lost.

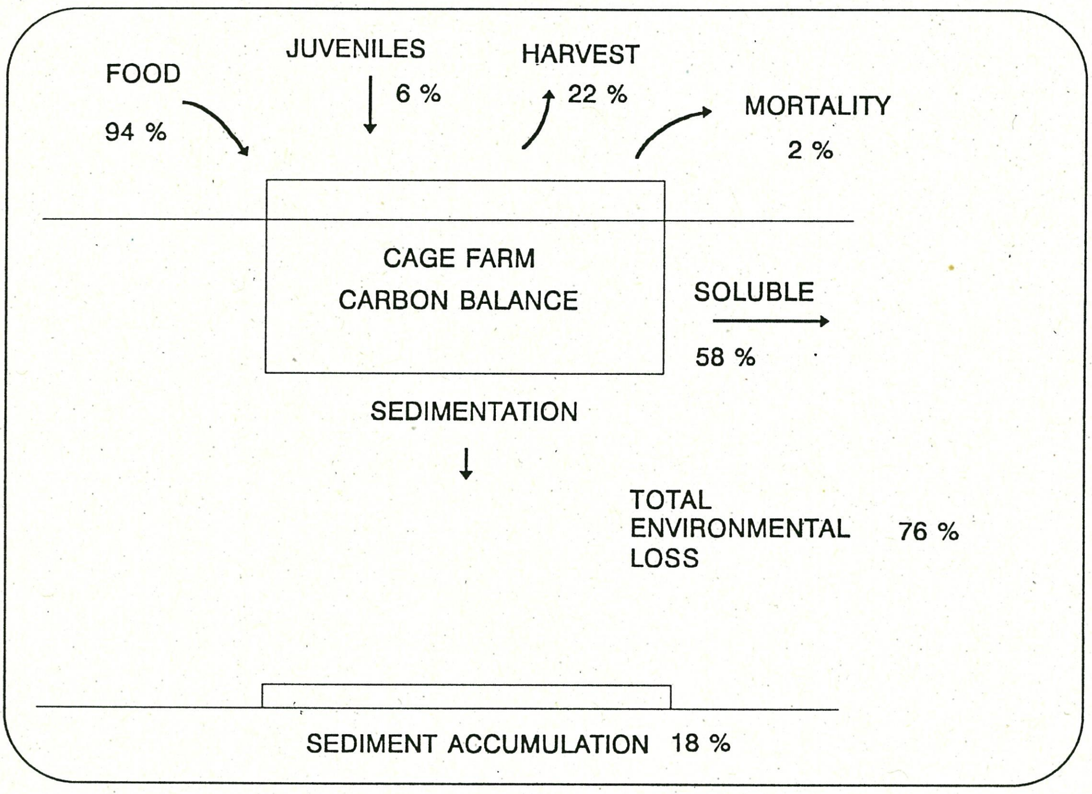
Directly below cages the substrate may become azoic but at a greater distance a proliferation of opportunistic species has been suggested (Weston 1986), together with the loss of species intolerant of the physical or chemical changes. The biomass and species diversity at affected sites can change markedly, depending upon the population size of opportunistic species at the time of sampling (Tsutsumi et al. 1991). In general the spatial and temporal effects of the waste from mariculture are similar to the effects of other sources of organic waste (Caine 1989, Roper 1990, Sandulli and Nicola 1991).

Nutrients

- CARBON

Carbon is a primary constituent of the food in fish farming and a major input to the environment. In a detailed study on the carbon balance of a marine trout cage farm in Sweden, Hall et al. (1990) found that approximately 76% of the carbon input into a fish farm is lost to the environment (Figure 2). This was about 900 Kg of carbon per tonne of trout produced. More than half of the carbon input is lost as dissolved carbon in the water column, primarily as CO_2 from respiration, a further 18% accumulates in the sediments (Hall et al. 1990). Gowen and Bradbury (1987) have estimated that the carbon content of the food and faeces is 44% and 30% respectively. If decomposition is only occurring slowly in the sediment the carbon load will increase to the point where it lowers the redox potential of the sediment and creates anoxic conditions (Caine 1989). It has been suggested that a

FIGURE 2. Basic outline of the carbon balance for a typical sea-cage fish farm (from Hall et al. 1990).



carbon loading as low as 2 kg/m2/yr is sufficient to initiate anoxic conditions in the sediment below salmon sea-cages in Scotland (Gowen et al. 1988).

- **NITROGEN**

Chemical and metabolic processes change the forms in which elements occur in all living systems. In aquatic systems nitrogen exists as dissolved inorganic ions (nitrate and nitrite) and in organic forms (such as proteins) in solutions, suspensions or as part of small organisms. The ions are measured as dissolved inorganic nitrogen (NOx), the organic nitrogen is measured as total

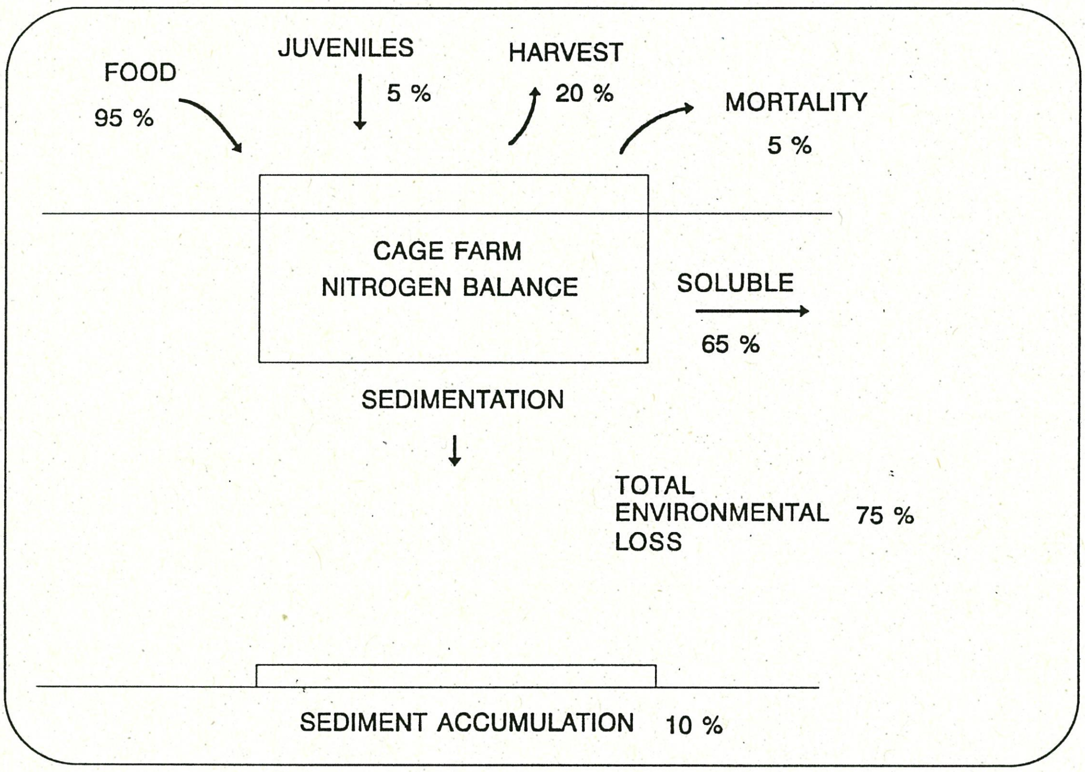
Kjeldahl nitrogen, which includes dissolved ammonia and suspended organic material.

A generalised nitrogen budget for a fish farm is illustrated in Figure 3 and is as follows. The food required to produce 1 tonne of fish contains 110-130 Kg of nitrogen. Of this 22% is converted into fish. The remainder is uneaten food or waste products. The majority (approximately 55-65%) of this nitrogen is excreted as ammonia with approximately 35-45% of the nitrogen contained in solids as uneaten food or faeces. The nitrogen in the sediment breaks down and is slowly released into the water, so that eventually more than 90% of the waste nitrogen (i.e. 90-100 kg of nitrogen per tonne of fish) is dissolved in the water with less than 10% bound in the sediment.

The data on the production of wastes varies with the species being farmed, the type of food and the local environment. However, the studies on trout and salmon sea-cages are reasonably consistent and indicate that salmon and trout farms produce approximately 80 kg of dissolved nitrogen per tonne of fish per year (Anon. 1988, Foy and Rosell 1991, Kaspar et al. 1988, Penczak et al. 1982).

There is little direct evidence that the nitrogen loads from fish farms increase the abundance of phytoplankton in the vicinity of farms (Anon. 1988). In studies in Norway (Ervik et al. 1985), Scotland (Gowen and Bradbury 1987) and Canada (Weston 1986) there was no correlation between phytoplankton abundance and nutrient levels. This indicates that the effects of high nutrient loads are difficult to monitor and may be very site specific, reflecting a variety of factors, including temperature, light, turbulence and the local N:P:K balance.

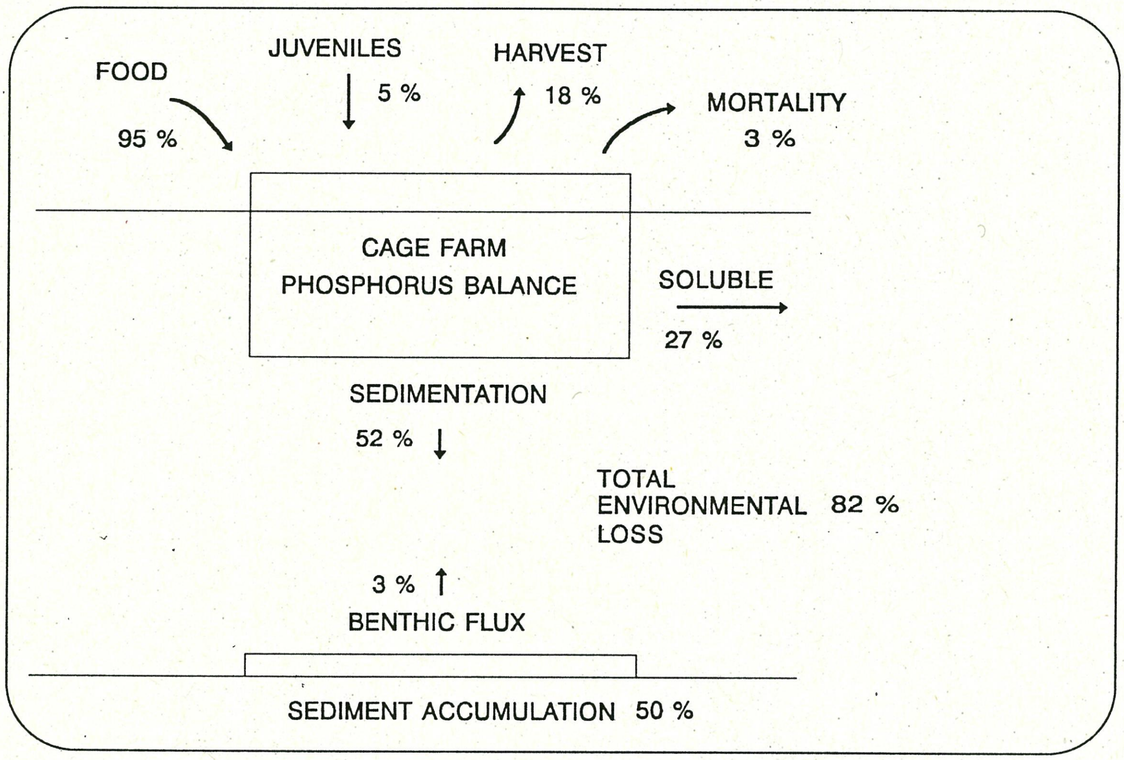
FIGURE 3. Basic outline of the nitrogen balance for a typical sea-cage fish farm (from Seymour and Bergheim 1991).



- **PHOSPHORUS**

Phosphorus exists in a range of forms in aquatic environments and appears to be able to change rapidly between these forms. By convention phosphorus is measured in two ways - as filterable reactive phosphorus (FRP or "Soluble P"; reactive forms of phosphorus which can pass through a 0.45 micron pore size and which include the important ionic species) and as total phosphorus (Total-P; all forms of phosphorus including biological material, phosphorus attached to suspended particles and filterable reactive phosphorus).

FIGURE 4. Basic outline of the phosphorus balance for a typical sea-cage fish farm (after Holby and Hall 1991).



There is some variability among different studies in the dissolved and particulate loadings of phosphorus, even within the same species (Foy and Rosell 1991a,b, Kasper et al. 1988, Ketola 1982). However, in a detailed study of the phosphorus balance of salmon farms Holby and Hall (1991) found that the method of calculation and allowances for losses through factors such as leakage and grazing accounted for the reported differences. At least 50 % of the phosphorus remains bound in the sediment (Figure 4) and only about 30% is lost in soluble forms. Seymour and Bergheim (1991) use a loading of 9 kg total-P per t of fish produced as typical for salmon cage farms. They point out that the production of all wastes is dependent upon the specific features at each farm. For example, if the Food Conversion Ratio (FCR) increases from 1.0 to 1.5 then the pollution loading increases by 86% for total-P and 70% for total-N.

- **OXYGEN**

There can be a substantial demand for oxygen from both the fish in the cages and from the biological oxygen demand (BOD) and chemical oxygen demand (COD) of suspended and sedimentary solids. In net cages in Japan as much as 0.5 mg/litre of oxygen was consumed by fish in cages with stocking densities of approximately 22 kg per cubic metre (Rosenthal 1985) and oxygen consumption by the fish has been estimated to be as high as 3mg/litre in some cases (Caine 1989). Reduced oxygen concentrations will not necessarily have any impact outside the immediate vicinity of the farm, although very large farms have the potential to compound lowered oxygen concentrations by also reducing water flow.

- **OTHER NUTRIENTS**

In addition to the primary components of carbon, nitrogen and phosphorus fish farms will also discharge a wide range of ions such as calcium and magnesium, as well as vitamins and trace elements released from the fish food. All of these components are capable of contributing to hypernutrification of the water column in the region of the cages. There is very little direct information on the quantities of these elements released, or their effects on water quality (Anon. 1988).

Chemicals

A range of chemicals are used for cleaning and sterilising equipment, anti-fouling cages and, most often, for the treatment of disease. At present, the use of chemicals in aquaculture in Australia is under review and it is likely that there will be restrictions on the indiscriminate use of chemicals.

- **ANTIBIOTICS**

Antibiotics (primarily oxytetracycline and oxolinic acid) are widely used for the treatment or prevention of diseases caused by gram-negative bacteria. The use of antibiotics has been declining in salmon farms in recent years with the advent of effective vaccines against some of the most common Vibrio bacteria. For example, in Norway the use of antibiotics has gone from 450g per fish in 1987 to 100-150 g per fish in 1990 (Seymour and Bergheim 1991).

The bioavailability of both oxolinic acid and oxytetracycline is relatively low and, because the antibiotics are usually administered in the food, there are likely to be quantities of the chemicals being released into the environment through both uneaten food and through faeces containing antibiotics which have not been absorbed.

The only studies which have examined the residual effects of these chemicals have been in salmon cages. Oxytetracycline is poorly absorbed by fish and forms very persistent residues in the sediments, with half lives of between 32 and 419 days reported for oxytetracycline in the sediments from fish farms (Bjorklund et al. 1991, Jacobsen and Berglind 1988, Samuelson 1989, Bjorklund et.

al. 1991). Oxytetracycline degrades much faster in water than in sediments (Samuelson 1989) with the half-life being dependent upon a range of factors, including temperature, pH and light intensity.

Oxolinic acid is more effectively absorbed by fish, with an apparent digestibility of 38%, compared with 7% for oxytetracycline (Bjorklund et al. 1991). Oxolinic acid does not appear to form persistent residues in the sediment below fish farms and shows a faster loss of antibacterial effect (Bjorklund et al. 1991).

The indiscriminate use of antibiotics, particularly as prophylactics, can create serious long-term problems for the fish farm because it increases the opportunities for the development of resistant strains of bacteria (Austin 1985, Rosenthal et al. 1988).

- **OTHER CHEMICAL TREATMENTS**

A wide range of chemicals have been used in cage farms for treating or preventing disease or parasites. Formalin and malachite green are the most common chemical treatments, but a range of fungicides and pesticides, such as Nuvan and Neguvon are routinely used (Rosenthal et al. 1988). Most of these chemical treatments are highly toxic to other marine life and represent a hazard to both the environment and to the stock in the farm (Anon. 1988)

- **ANTIFOULING**

Biofouling of marine net cages creates major maintenance problems for fish farms. The least intrusive management method is regular washing of cages. However, this is labour intensive and a variety of chemical antifoulants have been utilised. Some of these chemicals are biologically inert substances, such as waxes while others rely on toxicity to reduce fouling organisms.

Although toxic antifoulants, such as Tributyltin (TBT), have been used extensively in fish farming there is now more widespread awareness of the environmental effects and their use is being curtailed in Australia.

A study that monitored levels of TBT in a sea-cage farm for eight months reported concentrations of 0.1-0.2 mg/m near the cages shortly after application, reducing over time (Balls 1987). Levels of 0.08 mg/m were still recorded after 15 days. The effects of TBT are well studied and it has been shown to cause reproductive failure or growth abnormalities in molluscs and it is highly toxic to many forms of marine life (Cleary and Stebbing 1985, Paul and Davies 1986) .

- **DEAD FISH AND PROCESSING WASTE**

Dead fish are not easily removed from cages and they decompose very quickly. There are no studies which have specifically measured this input but the mortality losses in salmon cages are in the order of 10-20% and are a significant contribution to both dissolved and particulate wastes (Seymour and Bergheim 1991). It is estimated that mortality rates in existing barramundi cage farms are in the order of 25% (Trendall and Fielder 1991). Processing wastes for scaled and gutted fish are approximately 12% of body weight (Seymour and Bergheim 1991) and, if disposed of at sea, can be a substantial contribution to organic waste.

Ecological Effects

These include mechanical effects that are a result of the cage providing a physical structure which can attract other fish and can also impede or disrupt water flow. There can be a range of biological effects associated with changes in the sediment as a result of increased sedimentation and the creation of anoxic conditions. In addition, a fish farm can directly affect existing fish communities by providing a regular source of food. Carss (1990) reported higher concentrations of both wild and escaped fishes close to fish farm cages in Scotland. In that study one wild species of fish (*Polachius virens*) was found to have eaten artificial food, with the interesting observation that individuals which had eaten farm food were found both close to the fish farms and at the control sites away from the fish farms.

- **MECHANICAL EFFECTS**

Any structure in the water column will alter existing water flow. The extent to which this is important depends upon the number and size of cages, as well as the type of net and stocking density of fish. There have been a number of studies which have examined the changes in water flow inside cages (Hisaoka et al. 1966, Inoue 1972) and they have observed reductions in water flow of more than 70%. However, there has been little work on the effects of cages on water flow outside the cages, although similar reductions can be expected (Weston 1986). A reduction in water flow will accentuate any potential problems with sedimentation, fouling and low oxygen concentrations.

- **AESTHETIC IMPACT**

  The aesthetic impact of cage farming is widely recognised but is very difficult to quantify. In general the location and layout of sea-cage farms should follow basic landscaping principles, with designated distances from the shore and maximum densities of cages, so as to minimise conflict with existing users of water bodies (Anon. 1987b, Boyce 1988).

- **PREDATOR CONTROL**

  The concentrations of fish in sea-cages attract natural predators, including seals, otters, sharks, crocodiles and birds (Ross 1988). Controlling predators involves either actively repelling potential predators (i.e. sonic scarers for seals, or shooting of birds) or attempting to exclude predators using separate nets or cages (Woodward 1989). In either case there can be significant effects on predator populations. For example, a study reported in Anon. (1988) found that considerably more birds are killed as a result of entanglement than as a result of shooting and that many hundreds of birds were reported killed.

  The effects of active predator control are likely to result in a local decrease in numbers of predators but it is likely to be difficult to obtain reliable information on the extent of this change, especially if the predator is a protected species (Anon. 1988). Passive predator control, through the use of devices such as exclusion cages would have little impact.

- **EXISTING FISH COMMUNITIES**

  Cage farming can have two main types of influence on existing fish communities: indirect effects, through alteration of the local habitat by adding a new food source or shelter, and; the direct effects of escaped fish on wild populations. There is a distinction between the introduction of exotic species, in which a fish is transferred to an area outside the normal geographic range of the species, and translocation, in which fish are moved between different populations of the same species, although still within the normal range of the species. The potential detrimental effects of introducing new fish species to an area are diverse and well-documented and it is generally accepted that, unless accidental escapement is impossible it is inadvisable to farm species which do not occur naturally in the area. For the purposes of this review it is convenient to limit consideration of the effects of escaped fish to translocation within a species.

Indirect effects - Excess food may attract wild fish and increase local populations (Phillips et al. 1985a). A range of environmental changes created by cages, including an increase in zooplankton and an increase in shelter, resulted in increased local populations of largemouth bass (Kilambi et al. 1978). However, there are also likely to be reductions in local diversity and abundance of the fish species that feed on benthic fauna (Anon. 1988).

Direct effects - There are two types of direct effects that are of particular importance.

i. Behavioural disturbance of wild fish. For example, behavioural interference with wild fish at spawning time or competition for food.

ii. Modification of the genetic characteristics of local populations by the introduction of domesticated or translocated fish. The genetic effects of farmed fish on wild populations are species-specific and depend upon the characteristics of both the wild population and the farmed fish.

iii. Introduction of diseases or parasites. There is good evidence that the uncontrolled transfer of invertebrates, such as mussels, has facilitated the transfer of a range of diseases and parasites (Anon. 1988). There are fewer good examples in fish, but there is no doubt that the indiscriminate or uncontrolled translocation of fish can carry disease and create serious problems. In Norway, the transfer of salmon from the Baltic coast to the Atlantic coast also resulted in the transfer of a monogenean parasite (*Gyrodactylus salaris*) (Hindar et al. 1991). The salmon on the Atlantic coast of Norway had no natural resistance to this parasite, with the result that many wild salmon stocks on the Atlantic coast of Norway have been severely reduced.

VIII. APPROACHES TO MONITORING AND CONTROL

The scope of this review was to summarise the available literature on the environmental effects of fish farming and did not include the identification of guidelines for a monitoring fish farms in the Great Barrier Reef Region.

The overall conclusion to be drawn from the literature is that sea-cage farming of fish has the potential to create a wide range of environmental problems. The environmental effects of a fish farm will be very specific and will depend upon the characteristics of the location, the type and scale of the farming operation, and the species being cultured. Although all potential problems should be addressed but it should also be possible to establish sea-cage farming operations which minimise environmental effects.

Management and monitoring programs for fish farms in the Graet Barrier Reef should allow operation-specific flexibility within a general set of guidelines that are established specifically for the Great Barrier Reef region. Effective monitoring, control and management of sea-cage fish farming operations, particularly if there is limited information on the hydrodynamics and background levels of nutrients, is likely to be difficult and costly.

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