HEALTH IMPLICATIONS OF FARMED FISH

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Summary

The NHMRC have recommended that the Australian diet should contain an increased level of the n-3 polyunsaturated fatty acids (PUFA). Fish are one of the best sources of these PUFA. Since 1984, there has been a doubling in the production of farmed or cultured fish and in 1991 they comprised 13% of total world seafood production. In Australia, the main species under culture are edible oysters and salmonids. While the evidence suggests that the fatty acid composition of cultured species is variable in terms of its n-3 PUFA content, due to diet, the consumption of cultured (and wild) species can make a substantial contribution to the n-3 PUFA content of the Australian diet. At the present time fish and fish oils are the main sources of long chain n-3 PUFA in the western diet, however recent developments suggest that these PUFA may become increasingly available from traditional species such as pigs and poultry which have been fed on diets enriched in n-3 PUFA. In order to meet the demand for seafood products, intensive forms of farming fish will become increasingly important together with all the disadvantages of such intensification, namely use of chemicals and increased nutrient pollution in our waterways. It is likely, though, that careful regulation and monitoring can prevent such a scenario. Carefully managed, the use of aquaculture to provide seafood can improve the overall consistency and quality of our diet.

I. INTRODUCTION

In 1992, the NHMRC published a report on the role of PUFA in the Australian diet (NHMRC 1992). The committee recognised the importance of n-3 PUFA in maintenance of health and prevention of disease and recommended that the Australian diet should contain an increased level of the n-3 PUFA. There are two main types of n-3 PUFA, the short chain n-3 PUFA (18 carbon PUFA, alpha-linolenic acid, ALA) found in vegetable oils such as linseed oil, soyabean oil, canola oil, walnut oil and the long chain n-3 PUFA (20 and 22 carbon PUFA, such as eicosapentaenoic acid, EPA, and docosahexaenoic acid, DHA) which are found in fish and other marine foods (Nettleton 1991; Sinclair 1993).

The purpose of this paper is to discuss the importance of farmed fish as a source of n-3 PUFA for the Australian diet. We will consider the benefits of fish consumption, the potential of farmed fish to supply n-3 long chain polyunsaturates (LCP) , the composition of farmed versus wild fish, the potential benefits and disadvantages of farmed versus wild species and the possibility of using linseed oil, fish or algal oils in the diet of presently farmed species such as pigs and poultry.

The pioneering work on Greenland Eskimos in the mid-1970s (Bang and Dyerberg 1981) has resulted in extensive research programs in laboratories worldwide on the beneficial effects on health of diets rich in marine oil fatty acids and fish. In most western countries the level of n-3 PUFA in the diet is low relative to the n-6 PUFA and this is reflected in the balance of these fatty acids in plasma and tissues of individuals consuming western diets. For example, this is particularly obvious when the platelet membrane fatty acids of Danes are compared with Eskimos. In Danes the ratio of arachidonic acid (AA, an n-6 PUFA) relative to EPA (an n-3

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PUFA) is 44:1 whereas in Eskimos it is only 1:1 (Dyerberg 1986). Analysis of plasma phospholipid PUFA of Australians indicates a low dietary intake of n-3 PUFA (Sinclair et al. 1994).

Since the 1970s, there has been widespread recognition that the long-chain n-3 PUFA may play an important role in reducing the severity of occlusive vascular disease by modifying processes involved in the regulation of atherosclerosis, platelet function, fibrinolysis, blood pressure, plasma lipid levels and cardiac arrhythmia (Leaf 1992; Malle and Kostner 1993; Morris et al. 1993; Sanders 1993). There is experimental evidence which suggests that the long chain n-3 PUFA can influence eicosanoid and cytokine production (Kinsella et al. 1990; Endres 1993), are substrates for their own series of eicosanoids (Raz et al. 1977), are important components in structural membranes of the retina and brain (Connor et al. 1992), and are powerful hypotriglyceridaemic substances (Nestel 1990). There is epidemiological evidence to support the notion of the beneficial effects of fish consumption in protecting from occlusive vascular disease (Kromhout et al. 1985; Shekelle et al. 1985; Norell et al. 1986), and an intervention trial in a study of over 2000 men who had experienced a myocardial infarction showed that consumption of 2-3 meals per week of fatty fish significantly reduced their risk of a second infarction (Burr et al. 1989). The MRFIT study showed that reduced coronary heart disease mortality was positively associated with the dietary intake of long chain n-3 PUFA (Dolecek 1992).

Since the biologically active components of the n-3 PUFA are the n-3 LCP themselves or derivatives of the n-3 LCP (e.g. eicosanoids), the preferred dietary source of n-3 PUFA is fish. There is also a strong argument for providing the n-3 LCP in the diet rather than relying on ALA as a source of the LCP, since the rate of conversion of the ALA to the LCP in humans is slow (Sanders and Younger 1981; Emken et al. 1993).

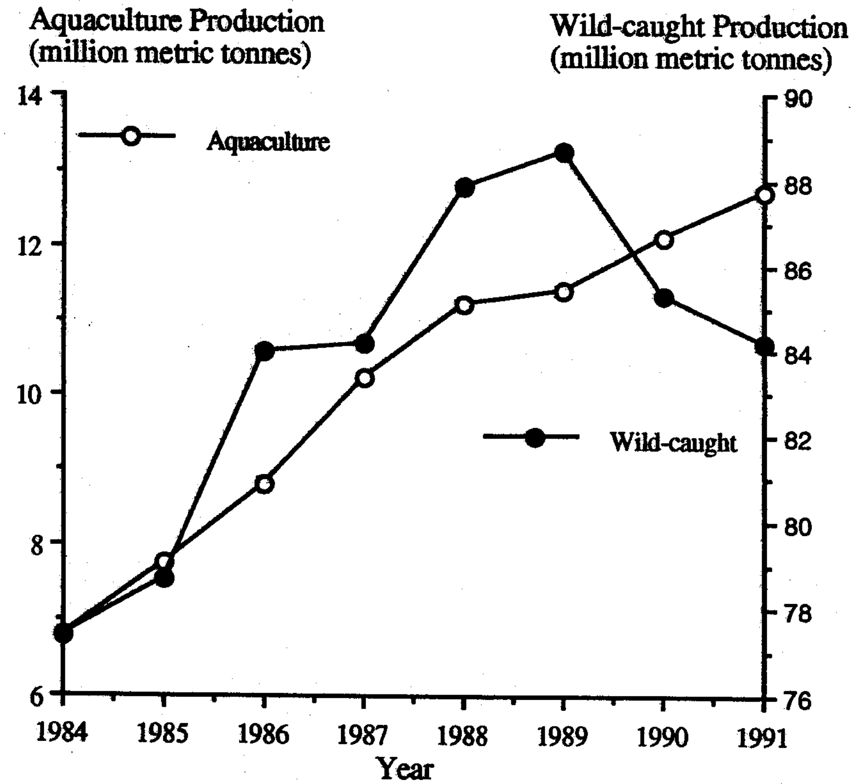
II. VARIATIONS IN THE FATTY ACID COMPOSITION OF FISH AND FISH OILS

Much of the research on long chain n-3 PUFA has been conducted using EPA-rich oils (van de Kamp 1993), however there are some fish oils which contain more DHA than EPA (Moffat and McGill 1993). There is increasing evidence that EPA and DHA, while sharing some biological properties, cannot be considered to be equally physiologically active in all biological systems (Bonna et al. 1992; Lagarde et al. 1993; Willumsen et al. 1993). This is an important point when considering fish as a source of long chain n-3 PUFA since there are large variations in both the amounts and types of n-3 PUFA in different species. In general terms, the flesh of fish which contains less than 1% fat is usually rich in phospholipids which are rich in DHA (eg. flathead, Sinclair et al. 1992) whereas fatty fish contain a high proportion of triacylglycerols which are often rich in EPA (eg. Atlantic salmon, Sinclair et al. 1992). In addition, while the flesh of most fish is extremely rich in n-3 PUFA relative to n-6 PUFA, there are a number of important exceptions to this rule, including barramundi (Sinclair et al. 1983). In Australian waters and other regions of the world, it has been reported that arachidonic acid and other long chain n-6 PUFA are present in the flesh of certain coastal species at levels equal to or greater than that of EPA (O'Dea and Sinclair 1982; Gibson 1983; Gibson et al. 1984; Fogerty et al. 1986; Ktob et al. 1991). It is thought that the origin of the arachidonic is from the brown algae which occur in shallow waters (Dunstan et al. 1988).

III. WHAT IS THE SOURCE OF OUR SEAFOOD?

In 1991, the world aquaculture production of approximately 12.7 million metric tonnes (mmt) comprised 13.08% of total world seafood production not including aquatic plants (FAO 1993). This represented growth over the previous eight years since 1984 of 6 mmt, almost doubling production (Fig 1). During the same period, wild seafood production grew by 7 mmt from 77.25 mmt to 84.25 mmt (Fig 1). It is notable that wild production peaked in 1989 at 88.78 mmt and has since declined by more than 5% while aquaculture production grew at an average of almost 10% per year between 1984 and 1991 (FAO 1993). These data support the contention by many fisheries biologists that wild production is at, or at least very near, the maximum production and that any further production of seafood will require expansion of aquaculture activities.

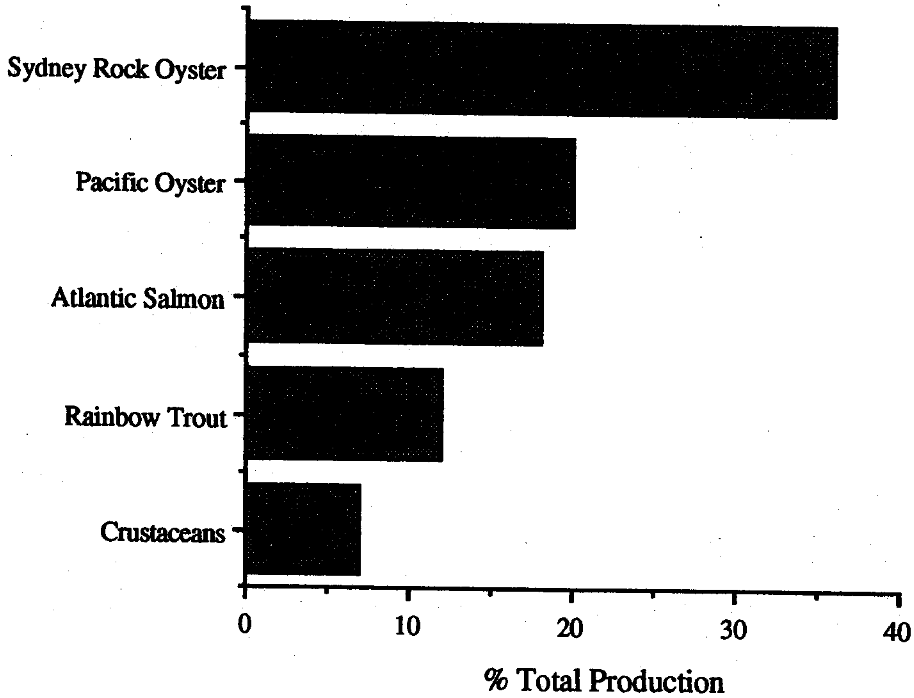
Figure 1. Production of aquatic organisms, not including seaweeds, by either aquaculture or wild-caught fisheries for the years 1984 to 1991. (Data from FAO 1993)



Analysis of the environment of aquaculture also provides an interesting perspective. Production of fish from freshwaters comprises approximately 60% of the total production from aquaculture, while marine and estuarine environments produce about 30% and 10%, respectively. There was some small change in the relative proportions of production from each environment with a growth of 2% in estuarine production occurring at the expense of marine production. By far the greatest component of aquacultured fish production was provided by the freshwater carps at 74% of the total. This breakdown of aquaculture production reflects the relatively high proportion of world aquaculture that takes place in Asia where extensive culture of carps predominates.

The Australian aquaculture industry shows a different pattern. Apart from pearl oysters, the largest components of local production are edible oysters and salmonids. These species contribute 55% and 30% of total Australian production, respectively. Approximately two thirds of the salmonid production in Australia is from the marine cage culture of Atlantic salmon which is also the greatest area of growth of salmonid production (Fig. 2). As well as these, the most prominent species targetted for development by Australian authorities are barramundi, silver perch, eels and freshwater crayfish. These species currently support small, but growing, industries which produced 94, 10, 200 and 135 tonnes, respectively, in 1991 (FAO, 1993). With the exception of eels, these developing industries have probably doubled production since 1991. Culture of snapper and jewfish or mulloway, both marine species, is also being investigated. The thrust of development involves intensive culture, although some freshwater crayfish producers are proving low density, low technology extensive culture techniques to be economically viable.

Figure 2. Percentage of total production of selected aquaculture products in 1991. (Data from FAO 1993)



IV. DOES FISH FARMING ALTER THE COMPOSITION OF FISH

Intensive farming of cattle, sheep, pigs and poultry through selective breeding programs and management practices has led to the development of animals with a high proportion of subcutaneous and intra-muscular fat, much of which is saturated fat. In the last 10-15 years, there has been a sustained effort in the pork, poultry and red meat industries to reduce the amount of visible fat at the point of sale in an effort to increase the appeal of the product to consumers and health professionals (National Research Council 1988; Watson 1994). There is concern that intensive fish farming may result in a similar deposition of unwanted and excess fat in the products.

Since the n-6 and n-3 PUFA content of fish flesh reflects the dietary input of these PUFA (Pigott 1989; Greene and Selivonchick 1990; Bimbo and Crowther 1992), it is clear that there can be some manipulation of the n-3 content of the flesh of farmed species. For example, if fish oil is the main dietary lipid in a farmed species, the fatty acid composition of the flesh of the farmed species will reflect the dietary fatty acids. Use of different fish oils would be likely to have a major influence on the flesh fatty acids since fish oils vary in their n-3 PUFA composition (eg, some oils such as salmon oil or cod liver oil are EPA rich, others such as tuna oil are DHA rich) and in their proportion of triacylglycerol to wax esters (eg orange ruffy oil, high in wax ester and low in n-3 PUFA, Elliott et al. 1990). In freshwater species, the use of a combination of linoleic acid-rich vegetable oils together with fish oil (to provide the essential fatty acids for the fish) will presumably result in higher proportions of linoleic acid in the flesh (van Vliet and Katan 1990).

Most aquacultured animals require n-3 PUFA at about 1% to 2% of their diet and in nearly all cases this can be provided by ALA, since the short-chain PUFA can be readily desaturated and elongated by fish (Cowey and Cho, 1993). The exceptions to this are the juveniles of some species such as turbot (Sargent et al. 1989). A requirement for n-6 PUFA by fish has neither been demonstrated nor discounted. Other lipid requirements (a total of 5-25% of the diet depending upon species) can be met by any other form including saturated lipids (Stickney and Andrews, 1972).

The evidence from compositional studies on wild versus farmed fish is not extensive, but it does suggest that the latter contains a higher fat level (Nettleton 1990, Abrami et al. 1992; Sinclair et al. 1992). Depending upon the species, excess fat may be deposited in the liver or visceral fat bodies which are removed when the animal is dressed (e.g. golden perch, Collins and Anderson 1994) or within the muscle which is retained in the final product (e.g. salmonids, Lie et al. 1986). The level of long chain n-3 PUFA in farmed species by comparison to wild species has been reported to be lower in some species and higher in others (Pigott 1989; Nettleton 1990; van Vliet and Katan 1990; Abrami et al. 1992; Bimbo and Crowther 1992; Sinclair et al. 1992). The saturated fat content of the flesh of farmed species can be influenced by the type of fat included in the feed (Boggio et al. 1985). While it is apparent that the diet of farmed species can influence the fat and fatty acid content of the flesh, it should be recognised that in the wild there can be considerable variation in the fatty acid composition within a species of marine fish, even when all environmental and physiological effects are minimised (Olsen and Skjervold 1991; Lytle and Lytle 1993).

Despite the variations in fatty acid composition of the flesh of wild or cultured fish, it is important to recognise that one meal of 100g of cultured or wild fish will significantly increase the intake of n-3 PUFA of our current diet which has been estimated to contain between 100-250mg of n-3 LCP/day (NHMRC 1992; Sinclair et al. 1994). For example, if we consider the following two extremes as examples of the likely impact of 100g of fish on the n-3 PUFA intake. Consumption of a cultured fish (rainbow trout, Sinclair et al. 1992) with a relatively low n-3/n-6 ratio of 1.0 will provide 500mg n-3 LCP/meal (2.8% lipid, n-3 LCP 19%). This contrasts with the consumption of 100g of cultured Atlantic salmon, with a higher fat content and higher n-3/n-6 ratio of 3.7, which will provide 2000mg n-3 LCP/meal (7.1% lipid, n-3 LCP 30%, Sinclair et al. 1992).

With extensive culture, the feed for the fish is provided by natural production in the ponds which may be stimulated by the introduction of chemical or biological fertilisers (Edwards 1980; Diana et al. 1991). Although fish stocked into ponds fertilised with human or animal excrement have been consumed in some Asian countries for many hundreds of years, there is no evidence for the transmission of disease through the food chain as has occurred in intensive culture of other animals such as cattle and sheep (Taylor 1993). Neither has there been evidence that the use of chemical fertilisers has resulted in heavy metal contamination of aquacultured products. In this regard, Australian aquaculture products compare well with the wild-caught fisheries in which heavy metal contamination is of concern (Currey et al. 1992). In the case of shark, heavy metal contamination is likely to be a result of their longevity since other wild-caught species do not show such contamination.

With increasing intensification of culture, it is necessary to provide supplemental feed that is intended for direct consumption by the cultured species. The essential amino acids have been provided by the use of fishmeal as the major protein source, and fish oils as the major essential fatty acid sources (Bimbo and Crowther 1992). Fish meal has the added benefit of satisfying some or all of the nutritional requirements for PUFA (de Silva and Anderson 1994). Replacement of fish oils with terrestrial plant oils has been discussed above. Use of fishmeal has drawn criticism for being a wasteful process which replaces large amounts of trash fish with small amounts of species acceptable to affluent consumers in developed countries. It is also an expensive form of protein and there is considerable effort being made to replace fishmeal with other protein sources - usually oilseed meals. The most successful of these has been solvent-extracted soymeal (Jie et al. 1991) although a variety of other oil-seed by-products have been used with varying success (Hasan et al. 1991). Even when care is paid to essential amino acid requirements, it appears that fishmeal is superior to other sources of protein for use in aquaculture feeds. Another area of investigation has been attempting to reduce the protein content of aquaculture feeds from the 35%-50% considered to be necessary for optimal growth. These experiments have involved the use of grain starches as energy sources (Walton 1986; Degani and Viola 1987). The result of both of these areas of investigation is an increasing amount of terrestrial crop products, generally grown under very intensive conditions with the aid of fertilisers, herbicides and pesticides, being included in the diet of aquacultured species. Although there is no evidence of a carry-through of any residues to aquacultured products, it is necessary that producers and consumers are aware of the possibility of such an occurrence.

Toxins also pose a potential threat to product quality. Although all manufacturers recommend dry, refrigerated storage of feeds, many farmers can only afford rudimentary facilities - often open sheds for feed storage. Use of unrefrigerated or moist storage areas increases the chance of lipids in the feeds becoming rancid or of the feeds growing fungi (New 1987). Significant amounts of rancid oils or aflatoxins can affect the palatability of the feed for the fish and in severe cases will impair their health (New 1987). If present in the feed in small amounts, however, there is some chance of undesirable compounds building up in the cultured species during its growout. This problem is not restricted to aquaculture. An example in wild-caught fish is the periodic episodes of poisoning by ciguatera and related toxins found in certain species of reef fish (Endean et al. 1993). The production of fish by aquaculture allows the opportunity to ensure the product is free from such toxins.

The use of chemicals such as antibiotics and malachite green (a general treatment for a variety of pathogens) is wide-spread in aquaculture. Increased use of these compounds is associated with increasing intensity of culture and has been largely unregulated, until recently. The National Registration Authority of the Federal government is in the process of developing regulations which restrict the residues permitted in aquaculture products. Although this will cause initial difficulties for the industry, it will provide necessary protection for the consumer against the presence of a wide range of chemicals in their supply of sea-food.

V. FISH VERSUS FISH OIL

While there has been relatively little research on the benefits of the consumption of fish compared with fish oil, it should be borne in mind that epidemiological and intervention studies support fish consumption (Kromhout et al. 1985; Burr et al. 1989). Studies have been conducted on the effects of fish consumption on lipoprotein lipid and fatty acid levels, platelet aggregation, thromboxane production, bleeding time and blood pressure (Atkinson et al. 1987; Gibson 1988; Sinclair et al. 1987; Agren et al. 1988; Brown et al. 1990; Butcher et al. 1990; van Houwelingen et al. 1990; Singer 1990; Cobiac et al. 1991; Gerhard et al. 1991; Wander and Patton 1991; Mori et al. 1994). The studies used fresh or canned fish to provide between 0.5 to 5g long chain n-3 PUFA/day from 2 weeks to 8 months. Most studies used marine species, however results have been reported from studies using freshwater (Atkinson et al. 1987) and brackish water fish (Agren et al. 1988). Some studies compared the effect of fish with fish oil (Brown et al. 1990; Cobiac et al. 1991). In general terms, the effects observed for fish consumption parallel those reported following fish oil supplementation and include an increase in bleeding time, a decrease in thromboxane production and platelet aggregation, a decrease in plasma triglyceride levels and in blood pressure. Not all these apparently beneficial effects have been observed in all studies. In some studies, adverse effects on LDL cholesterol levels have been reported (Gerhard et al. 1991), however consumption of fish associated with a reduction in the total fat content of the diet was reported to be associated with a beneficial effect on LDL cholesterol (Sinclair et al. 1987; Mori et al. 1994). Many of the studies involved intakes of fish of 200g or more each day of fish (fresh, canned or fish paste) for relatively short periods, however beneficial results were also reported in two studies which used lower daily intakes for prolonged periods (180g freshwater or brackish water fish 3.7 times per week for 15 weeks supplying approximately 0.25g of EPA and 0.55g DHA, respectively, per day, Agren et al. 1988; 300g of canned mackerel per week for 8 months supplying approx 0.5g of EPA and 0.7g DHA, respectively, per day, Singer 1990). In the studies which involved consumption of the lowest amounts of long chain n-3 PUFA from fish (0.5 - 1g/day), there were significant increases in the levels of these PUFA in the plasma and erythrocyte lipids within 2 weeks of commencing the diets (Sinclair et al. 1987; Brown et al. 1990).

VI. POTENTIAL ADVERSE EFFECTS OF FISH AND FISH OIL CONSUMPTION

There is concern about over-consumption of fish and fish oil for several reasons, including increased peroxidation resulting from the high intake of n-3 PUFA, and the presence of organochlorine pesticides, polychlorinated biphenyls and the heavy metal content in certain marine species (Kinsella 1987; Shukla and Perkins 1991). Several studies have reported decreases in plasma vitamin E concentrations following the consumption of fish oil (Bjornboe et al. 1988; Sanders and Hinds 1992). The estimated level of vitamin E required to prevent oxidation of linoleic acid is 0.4mg vitamin E/g linoleic acid and preliminary evidence suggests that approximately 10 times this level is necessary to protect the n-3 PUFA (Wahle and Brown 1990; Sanders 1993).

Since approximately one third of the fatty acids of fatty fish and fish oils are saturated fatty acids, concern has been expressed about the possibility of increasing plasma cholesterol levels following high intakes of these products/foods. Some studies do report evidence of hypercholesterolaemia following increased consumption of fish/fish oils, however beneficial effects on plasma cholesterol have been reported in those studies which also reduced the intake of saturated fats from other dietary sources (see above).

VII. LONG CHAIN N-3 PUFA FROM SOURCES OTHER THAN FISH

While fish and fish oils are the main sources of long chain n-3 PUFA in the western diet at the present time, recent developments suggest that these PUFA may become increasingly available from other sources. Purified fish oils in a microencapsulated form have been introduced into baking products (Nielson 1992). The n-3 PUFA, as linseed (flaxseed) oil or fish oils, have been incorporated into the diets of chickens and pigs leading to an increased content of long chain n-3 PUFA in chicken meat, eggs and pork (Olomu and Baracos 1991; Bimbo and Crowther 1992; Irie and Sakimoto 1992; Sim et al. 1992). Studies have already been initiated into the health benefits of these products (Oh et al. 1991). The advantages of using linseed oil are its availability and its potentially greater stability than fish oils. The use of the monogastric animal to synthesise long chain n-3 PUFA from the ALA in linseed oil also reduces our reliance on the marine environment for n-3 PUFA. Furthermore, the inclusion of these fatty acids in poultry and pork products may overcome the barriers which some consumers have for fish. Another development is the use of micro-algae for the production of designer oils rich in specific PUFA, such as DHA or AA. These products are already being investigated for use in infant formulas.

VIII. CONCLUSIONS

Increasing the consumption of fish will increase the demand for seafood products. These are already in short supply and so the demand can only be met by increased production through aquaculture. In order to meet the demand, intensive forms of farming fish will become more abundant together with all the disadvantages of such intensification, namely use of chemicals and increased nutrient pollution in our waterways. These can be catastrophic for an industry, and environment and a society as was observed in the rise and fall of the Taiwanese shrimp production industry and as is currently occurring in the Phillipines. It is likely, though, that careful regulation and monitoring can prevent such scenarios. Despite the disadvantages, imposition of monitoring is to the benefit of all from producers to consumers. Carefully managed, the use of aquaculture to provide seafood can improve the overall consistency and quality of our diet.

REFERENCES

ABRAMI, G., NATIELLO, F., BRONZI, P., McKENZIE, D., BOLIS, L. and AGRADI, E. (1992). Comp. Biochem. Physiol. 101B: 79.

AGREN, J.J., HANNINEN, O., LAITINEN, M., SEPPANEN, K., BERNHARDT, I., FOGELHOLM, L., HERRANEN, J. and PENTTILA, I. (1988). Lipids 23: 924.

ATKINSON, P.M., WHEELER, M.C., MENDELSOHN, D., PIENAAR, N. and CHETTY, N. (1987). Am. J. Hematol. 24: 143.

BANG, H.O. and DYERBERG, J. (1981). J. Meddr. Gronland Man. Soc. 2: 1.

BIMBO, A.P. and CROWTHER, J.B. (1992). J. Am. Oil Chem. Soc. 69: 221.

BJORNEBOE, A., SMITH A.K., BJORNEBOE, G.A., THUNE, P.O. and DREVON, C.A. (1988). Brit. J. Dermatol. 118: 77.

BOGGIO, S.M., HARDY, R.W., BABBITT, J.K. and BRANNON, E.L. (1985). Aquaculture 51: 13.

BONAA, K.H., BJERVE, K.S. and NORDOY, A. (1992). Arter. Thrombosis 12: 675.

BROWN, A.J., ROBERTS, D.C.K., PRITCHARD, J.E. and TRUSWELL, A.S. (1990). Am. J. Clin. Nutr. 52: 825.

BURR, M.L., FEHILY, A.M., GILBERT, J.F., ROGERS, S., HOLLIDAY, R.M., SWEETNAM, P.M., ELWOOD, P.C. and DEADMAN, N.M. (1989). Lancet ii: 757.

BUTCHER, L.A., O'DEA, K., SINCLAIR, A.J., PARKIN, J.D., SMITH, I.L. and BLOMBERY, P. (1990). Prost. Leuk. and EFA 39: 221.

COBIAC, L., CLIFTON, P.M., ABBEY, M., BELLING, G.B. and NESTEL, P.J. (1991). Am. J. Clin. Nutr. 53: 1210.

COLLINS, A.L. and ANDERSON, T.A. (1994). J. Fish Biol. submitted.

CONNOR, W.E., NEURINGER, M. and REISBICK, S. (1992). Nutr. Rev. 50: 21.

COWEY, C.B. and CHO, C.Y. (1993). Proc. Nutr. Soc. 52: 417.

CURREY, N.A., BENKO, W.I., YARU, B.T. and KABI, R. (1992). Science of the Total Environment 125: 305.

de SILVA, S.S. and ANDERSON, T.A. (1994). "Fish Nutrition for Aquaculture" (Chapman and Hall: London).

DEGANI, G. and VIOLA, S. (1987). Aquaculture 64: 283.

DIANA, J.S., KWEI-LIN, C. and SCHNEEBERGER, P.J. (1991). Aquaculture 92: 323.

DOLECEK, T.A. (1992). Proc. Soc. Exp. Biol. Med. 200: 177.

DUNSTAN, G.A., SINCLAIR, A.J., O'DEA, K. and NAUGHTON, J.M. (1988). Comp. Biochem. Physiol. 91B: 165.

DYERBERG, J. (1986). Nutr. Rev. 44: 125.

EDWARDS, P. (1980). Aquaculture 21: 261.

ELLIOTT, N., SKERRATT, J. and NICHOLS, P. (1990). Aust. Fish. 48: 32.
EMKEN, E.A., ADLOF, R.O., ROHWEDDER, W.K. and GULLEY, R.M. (1993). 'Essential Fatty acids and Eicosanoids: Invited Papers from the Third International Congress', p. 23, eds A.J. Sinclair and R.A. Gibson (American Oil Chemist's Society: Champaign).
ENDEAN, R., GRIFFITH, J.K., ROBINS, L.E., LLEWELLYN, L.E. and MONKS, S.A. (1993). Toxicon 31: 723.
ENDRES, S. (1993). Am. J. Clin. Nutr. 57(suppl): 798S.
FAO (1993) Aquaculture production 1985-1991. FAO Fisheries Circular No 815 Revision 5. (FAO: Rome).
FOGERTY, A.C., EVANS, A.J., FORD, G.L. and KENNETT, B.H. (1986). Nutr. Rep. Int. 33: 777.
GERHARD, G.T., PATTON, B.D., LINDQUIST, S.A. and WANDER, R.C. (1991). Am. J. Clin. Nutr. 54: 334.
GIBSON, R.A. (1983). Lipids 18: 743.
GIBSON, R.A. (1988). Aust. N.Z. J. Med. 18: 713.
GIBSON, R.A., KNEEBONE, R. and KNEEBONE, G.M. (1984). Comp. Biochem. Physiol. 78C: 325.
GREENE, D.H.S. and SELIVONCHICK, D.P. (1990). Aquaculture 89: 165.
HASAN, M.R., AZAD, A.K., OMAR FAROOQUE, A.M., AKAND, A.M.and DAS, P.M. (1991). "Fish Nutrition Research in Asia", p. 107, ed S.S. de Silva (Asian Fisheries Society: Manilla).
IRIE, M. and SAKIMOTO, M. (1992). J. Anim. Sci. 70: 470.
JIA, L., HE, X. and YANG, Y. (1991). "Fish Nutrition Research in Asia", p. 119, ed S.S. de Silva (Asian Fisheries Society: Manilla).
KINSELLA, J.E. (1987). "Seafoods and Fish Oils in Human Health and Disease" (Marcel Dekker, Inc: New York).
KINSELLA, J.E., LOKESH, B. and STONE, R.A. (1990). Am. J. Clin. Nutr. 52: 1.
KROMHOUT, D., BOSSCHIETER, E.B. and COULANDER, C. (1985). New Eng. J. Med.312: 1205.
KTOB, A.H., ABU HADEED, A.F. and AL-BAKER, A.A. (1991). Food Chem. 40: 185.
LAGARDE, M., CROSET, M., BENISTANT, C., MARCELON, G. and Le BRETON, G.C. (1993). In 'Essential Fatty acids and Eicosanoids: Invited Papers from the Third International Congress', p. 139, eds A.J. Sinclair and R.A. Gibson (American Oil Chemist's Society: Champaign).
LEAF, A. (1992). Nutr. Rev. 50: 150.
LIE, O., LIED, O. and LAMBERTSON, G. (1986). Aquaculture 59: 187.
LYTLE, J.S. and LYTLE, T.F. (1994). Gulf Res. Rep. 9: 49.
MALLE, E. and KOSTNER, G.M. (1993). Prost. Leuk. and EFA. 49: 645.
MOFFAT, C.F. and McGILL, A.S. (1993). Proc. Nutr. Soc. 52: 441.
MORI, T.A., VANDONGEN, R., BEILIN, L.J., BURKE, V., MORRIS, J. and RITCHIE, J. (1994). Am. J. Clin. Nutr. 59: 1060.
MORRIS, M.C., SACKS, F. and ROSNER, B. (1993). Circulation 88: 523.
NATIONAL RESEARCH COUNCIL (1988). "Designing Foods: Animal Product Options in the Marketplace", (National Academy Press: Washington, DC).
NESTEL, P.J. (1990). Ann. Rev. Nutr. 10: 1.
NETTLETON, J.A. (1990). Aquaculture Mag. Jan/Feb.: 34.
NETTLETON, J.A. (1991). J. Amer. Dietet. Assoc. 91: 331.
NEW, M. (1987). "Feed and feeding of fish and shrimp" (FAO: Rome).
NHMRC: Report of Working Party. (1992). "The role of polyunsaturated fatty acids in the Australian diet", (Australian Government Publishing Service: Canberra).
NIELSON, H. (1992). J. Sci. Food Agric. 59: 559.
NORELL, S.E., AHLBOM, A., FEYCHTING, M. and PEDERSEN, N.L. (1986). Br. Med. J. 293: 426.
O'DEA, K. and SINCLAIR, A.J. (1982). Am. J. Clin. Nutr. 36: 868.

OH, S.Y., RYUE, J., HSIEH, C-H. and BELL, D.E. (1991). Am. J. Clin. Nutr. 54: 689.
OLOMU, J.M. and BARACOS, V.E. (1991). Poult. Sci. 70: 1403.
OLSEN, Y and SKJERVOLD,H. (1991). Omega 3 News VI: 2.
PIGOTT, G.M. (1989). Wld. Aquaculture 20: 63.
RAZ, A., MINKES, M.S. and NEEDLEMAN, P. (1977). Biochim. Biophys. Acta 488: 305.
SANDERS, T.A.B. (1993). Proc. Nutr. Soc. 52: 457.
SANDERS, T.A.B. and HINDS, A. (1992). Br. J. Nutr. 68: 163.
SANDERS, T.A.B. and YOUNGER, K.M. (1981). Br. J. Nutr. 45: 613.
SARGENT, J., HENDERSON, R.J. and TOCHER, D.R. (1989). "Fish Nutrition", 2nd edn, p. 154, ed J.E. Halver, (Academic Press: London).
SHEKELLE, R.B., MESSEL, L., PAUL, O, SHYROCK, A.M. and STAMLER, J. (1985). N. Eng. J. Med. 313: 820.
SHUKLA, V.K. and PERKINS, E.G. (1991). Lipids 26: 23.
SIM, J.S., CHERIAN, G. and JIANG, Z. (1992). Nutrition 8: 221.
SINCLAIR, A.J. (1993). Asean Food J. 8: 1.
SINCLAIR, A.J., DUNSTAN, G.D., NAUGHTON, J.M., SANIGORSKI, A.J. and O'DEA, K. (1992). Aust. J. Nutr. Dietet. 49: 77.
SINCLAIR, A.J., O'DEA, K. and JOHNSON, L. (1994). Aust. J. Nutr. Dietet. 51: 53.
SINCLAIR, A.J., O'DEA, K. and NAUGHTON, J.M. (1983). Lipids 18: 877.
SINCLAIR, A.J., O'DEA, K., DUNSTAN, G., IRELAND, P.D. and NIALL, M. (1987). Lipids 22: 523.
SINGER, P. (1990). Klin. Wochenschr. 68(supplXX): 40.
STICKNEY, R.R. and ANDREWS, J.W. (1972). J. Nutr. 102: 249.
TAYLOR, D.M. (1993). Developments in Biological Standardisation 80: 215.
van de KAMP, J. (1993). 'Effects of Fish Oils and Polyunsaturated Omega-3 Fatty Acids in Health and Disease' Special Bibliography 1993-A, US Department of Health and Human Services, (National Library of Medicine: Bethesda).
van HOUWELINGEN, A.C., ZEVENBERGEN, H., GROOT, P., KESTER, A. and HORNSTRA, G. (1990). Am. J. Clin. Nutr. 51: 393.
van VLIET, T. and KATAN, M.B. (1990). Am. J. Clin. Nutr. 51: 1.
WAHLE, K.W. and BROWN, J.E. (1990). Fett. Wiss. Technol. 92: 326.
WALTON, M. (1986). Fish Physiol. Biochem. 1: 7.
WANDER, R.C. and PATTON, B.D. (1991). Am. J. Clin. Nutr. 54: 326.
WATSON, M.J. (1994). Brit. Foods J. In press.
WILLUMSEN, N., HEXEBERG, S., SKORVE, J., LUNDQUIST, M. and BERGE, R.K. (1993). J.Lipid Res. 34: 13.