A REVIEW OF THE STATUS OF THE USE AND POTENTIAL TO USE MICRO AND MACROALGAE AS COMMERCIALLY VIABLE RAW MATERIAL SOURCES FOR AQUACULTURE DIETS

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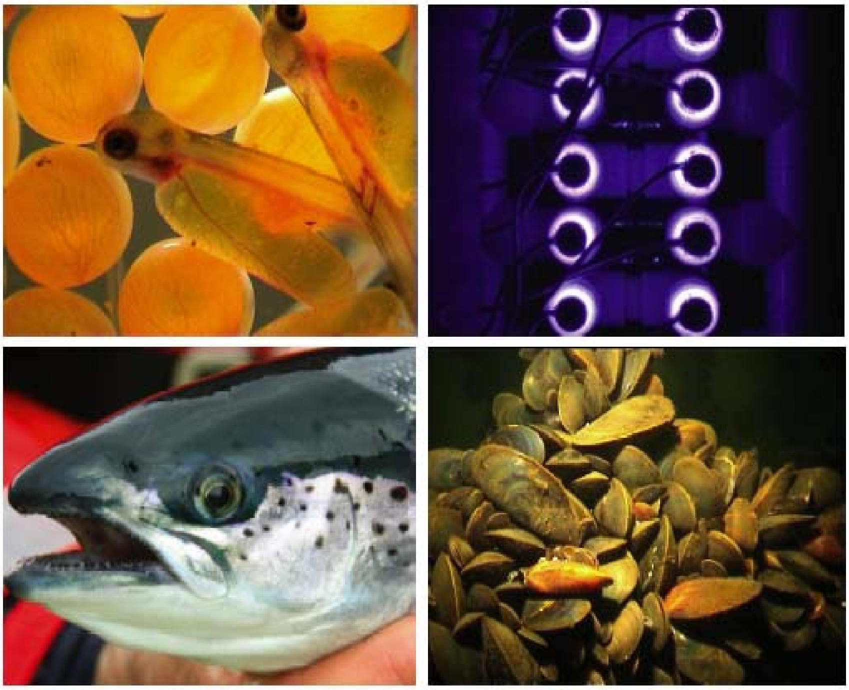

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A REVIEW OF THE STATUS OF THE USE AND POTENTIAL TO USE MICRO AND MACROALGAE AS COMMERCIALLY VIABLE RAW MATERIAL SOURCES FOR AQUACULTURE DIETS

FINAL REPORT

June 2011

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CONTENTS

EXECUTIVE SUMMARY

BACKGROUND

1 The Scottish Aquaculture Research Forum (SARF), in association with Marks and Spencer, has commissioned this research to look at the potential to use seaweed (macroalgae) and other microscopic algae (microalgae) as commercially viable sources of raw materials to feed fish. The objectives of the study were:

- A comprehensive review of the current and potential use of micro and macroalgae as sources of raw material for aquaculture diets
- An assessment of yields, the scale of available resources and their cost effectiveness
- Identify specific knowledge gaps, technical, commercial and marketing constraints and opportunities.
- A critical assessment of the future potential to develop commercially viable supplies of novel or currently niche feed raw materials from these sources.

These objectives were further refined on the advice of the Project Steering Group.

APPROACH

2 Primary research was undertaken in three ways:

- Desk-based literature research and analysis, taking into account both peer-reviewed and “grey” literature
- Direct structured contact with organisations involved in algae production or related activities
- Individual meetings, email and telephone interviews with organisations requiring aquaculture feed ingredients, or with organisations producing or interested in algal production.

MAIN FINDINGS

3 Lipids are the most limiting global commodity for aquaculture finfish feeds – especially n-3 HUFA rich lipids containing docosahexaenoic acid, 22:6n3 (DHA) and eicosapentaenoic acid, 20:5n3 (EPA). All the other nutritional ingredients in finfish diets are not so limiting, although they could come from algal sources if the specifications and cost are appropriate.

4 Salmonid finfish diets are high energy, designed to produce optimum fish growth whilst minimising environmental impacts. Potential new feed components should deliver high nutritional advantages in relation to the percentage volume of inclusion in the diet.

5 The Scottish industry’s main current requirement is for up to **10,000 tonnes** per annum of EPA and DHA lipids. The industry could justify paying something in the region of **£2,200 per tonne** for a lipid containing only EPA and DHA at prevailing market prices, although this price is indicative, since raw material prices fluctuate considerably.

6 There are currently available algal products that could be used in the salmonid finfish aquaculture feeds sector, primarily those containing micro nutrients such pigments. Other products based on macroalgae are also available, recommended for inclusion at a level of 15% of the diet, although these have not so far been taken up by UK feed manufacturers. Other aquatic plant-based products are considered, and whilst their use should not be anticipated in salmon diets, they may have some applications in animal feeds in the future.

7 There is a very large variation in both the proximal makeup (the main nutritional components such as protein, lipid, ash and water) and the fatty acid makeup of algae, whether macro or micro. On that basis, it is impossible to rule out the future use of algae of either type as a source of components for aquaculture finfish feeds.

8 The composition of algae varies considerably within a single species, depending upon environmental conditions – often culture conditions in the case of microalgae. The implication is that culture conditions, for the best species, could be enhanced for the purposes of producing a nutritional component for future use in aquaculture finfish feeds, particularly considering that:

- Whilst algal proteins might need some blending with other sources, or amino-balancing in some other way, some of them could be used in animal feed formulations
- Fatty acids are basic nutritional building blocks, and for specific fatty acids that are required in finfish diets, whether they are sourced from marine animals or from algae is relatively unimportant – as long as the cost is competitive.

9 The average protein level in all macroalgal species is around 18-25% of dry matter, although only 8-15% in those species which are commonly cultured and therefore available. This compares with 41% for all the microalgal species considered. The average lipid level in macroalgae is only 1 or 2% of dry matter in the red and green algae, and 10% in the brown algae. For commonly cultured species, lipid levels are around 2%.The average lipid level across all the microalgae is 20%.

10 There are 18:3 n-3 (ALA); 20:4 n-6 (AA) and 20:5 n-3 (EPA) fatty acids in both macro and microalgae – although the relative amounts is species dependent. There is little evidence of much 22:6 n-3 (DHA) fatty acid in most macroalgae, whereas some microalgae contain very high amounts. Although there are examples of both micro and macroalgal species with much higher levels of protein or lipid it is likely that microalgae would provide the high yielding candidates most suitable for use in finfish diets.

11 Red and brown macroalgae are currently farmed in large quantities in Asia for both food and as raw material for hydrocolloid manufacture. Those species currently produced are considered unsuitable as ingredients for aquaculture finfish feeds. In their raw form, their protein content is low compared to other plant sources of roughly equivalent cost and similarly the lipid content is too low to make them interesting. The majority of production is used in various processes to extract hydrocolloids and these are too harsh to produce by-product of any significant nutritional value.

12 The production of microalgae is much more limited in terms of volume than macroalgae: estimated at a few thousand dry tonnes a year of *Spirulina*, mainly in Asia, and some 5,000 – 10,000 dry tonnes a year of other species intended for use in the nutracueticals and related markets. The sale price of all current microalgae products renders them too expensive for use in aquaculture. *Spirulina* sells at a minimum of **£5,000 per tonne** (dry matter), whilst other microalgal products equate to **£150,000 per tonne,** with much higher prices for specialised DHA-rich products.

13 There is a long tradition of culturing and using phototrophic microalgae for marine finfish and shellfish hatcheries, and even with the most realistic estimates and a microalga with a lipid content of 50%, the cost of the lipid might be between **£6,150** and **£152,000 per tonne,** before taking into account processing costs. This may be affordable for hatcheries, but does not meet the cost requirements of the finfish ongrowing sector.

14 Heterotrophic microalgal species are also produced, but the cost of end products is very high at the present time. As sources of lipids, these products are entering the direct human consumption markets as 'nutraceuticals' for incorporation into 'functional foods' and other products such as capsules, and these markets can pay considerably more than the finfish feed producers can.

15 The expectation that algal-oils could be produced for the human market, and somehow take the pressure off prices for n-3 HUFA rich oils from traditional sources, would seem to be optimistic. An abundance of n-3 HUFA rich oils coming onto the market from new sources would seem to be the solution.

16 The algal bio-fuels sector is of interest to this study, because *if* it can deliver product at the prices its market can afford, there is a chance that it can also deliver algal feed components to the aquaculture finfish feeds sector at the right price. The economics of algal bio-fuels is still a matter of considerable conjecture, and will be influenced by production costs and the cascade of products that can be economically extracted.

17 Some of the fundamental 'processing' steps that are required to transform a raw algal material into a useable product are reviewed. Whilst it does not seem likely that useable by-products or waste products can be obtained from industrial processes that are or could be applied to macroalgae,

unless a high-lipid strain is being cultured for the bio-fuel sector, this is not necessarily the case for bio-fuel production from microalgae, and further research is warranted.

18 Regulation and trade are not currently considered to be barriers to using algal materials for aquaculture feeds.

19 Genetic engineering is briefly considered, and its hypothetical use would be most appropriate in terrestrial plants, where the infrastructure to extract lipids cost-effectively is already in place.

CONCLUSIONS

20 Algae contain the basic nutritional building blocks for carnivorous finfish species such as salmon, and the sector is already well advanced with the use of non-marine and non-traditional ingredients in diet formulation. If algal-originated products are developed and come on to the market at the right price, there is no doubt the aquaculture finfish feeds sector would use them.

21 However, this study has found no obvious **current** opportunities to use algal materials in aquaculture finfish diets for species such as salmon – or rather, none that are mainstream in terms of percentage inclusion or that have been somehow overlooked.

22 The study has identified areas where such products could potentially become available in the future, and some of these are covered in this report's final recommendations. In particular:

- Microalgae (or related organisms) grown primarily for a future commercially viable bio-fuels sector offer good prospects – although most experts agree that this is a challenging area, and success is likely to be some way in the future
- If microalgae *could* be cost-effectively grown to supply the bio-fuel sector, it is certain that they could be specifically grown cost-effectively to produce animal feeds, including feeds for finfish such as salmon
- If that were the case, judicious choices of species might offer the prospect of supplies of both n-3 HUFA rich lipids **and** high quality proteins.

RECOMMENDATIONS

23 One recommendation is made with respect to additional research:

- **An expert and critical review of the various bio-fuel production processes should be undertaken, with a focus on the potential of any of them to provide a side-stream capacity for extracting algal lipids that could be used in finfish diets.**

1 INTRODUCTION

1.1 Project Aims and Objectives

1.1 The vast majority of global aquaculture production (c. 88%[1]) is either marine plants, filter feeding shellfish, or omnivorous/freshwater finfish with a low requirement for marine protein and lipid derived feeds. However, the remaining small (but important to Scotland and other EU27 states) percentage are carnivorous finfish species, which require commercially formulated feeds that contain high levels of protein and lipid. The traditional source of the raw materials to manufacture these diets has been fishmeal and fish oils derived from the feed fish capture sector – largely to ensure that the amino acid and fatty acid components are nutritionally suitable for the finfish species being cultivated.

1.2 This issue was discussed at a recent Marine Conservation Society workshop - "Feeding the Fish of the Future – Alternative choices for aquafeeds"[2], which highlighted the increasing need for the aquaculture feeds of the future to rely on alternative, non-marine or non-traditional marine ingredients. The event also highlighted the growing interest and concern for the future formulation of aquaculture feeds by policy makers, environmental NGO's, feed companies, and retailers, including the extent to which algae, as a "marine" source, could potentially be a viable ingredient for aquafeeds.

1.3 The Scottish Aquaculture Research Forum (SARF), in association with Marks and Spencer, has commissioned this research to look at the potential to use seaweed (macroalgae) and other microscopic algae, microalgae, as commercially viable sources of raw materials to feed fish.

1.4 The study investigates, assesses, and provides conclusions/recommendations with respect to the following **initial** objectives, later refined by the input of the Steering Group (see Section 1.3):

1. A comprehensive review of the current and potential use of micro and Macroalgae as sources of raw material for aquaculture diets

2. An assessment of yields, the scale of available resources and their cost effectiveness:

3. Identify specific knowledge gaps, technical, commercial and marketing constraints and opportunities.

4. A critical assessment of the future potential to develop commercially viable supplies of novel or currently niche feed raw materials from these sources.

1.2 Approach and Methods

1.2.1 Research Plan

1.5 The primary research was undertaken in three ways:

- Desk-based literature research and analysis, taking into account both peer-reviewed and "grey" literature

[1] http://www.fao.org/fishery/statistics/en
[2] http://www.mcsuk.org/what_we_do/Fishing+for+our+future/Aquaculture+-+what+we+do/Feed+event.

- Direct structured contact with organisations involved in algae production or related activities
- Individual meetings, email and telephone interviews with organisations requiring aquaculture feed ingredients, or with organisations producing or interested in algal production.

1.2.2 Project Meetings

1.6 Where necessary this research has benefited from focused project meetings, and/or more in-depth bilateral consultations with identified experts. Specific attendees at any project meetings included individuals and organisations experienced in fish feed formulation and near-market delivery of algae-based products.

1.7 A SARF **Steering Group** was a vital part of this research, and its members have a significant amount of expertise in this field. Membership of the Steering Group is shown in Annex 1.

1.3 Refinements to Objectives and Methods

1.8 The initial Steering Group meeting was held in Edinburgh on 14th December 2010. The core original objectives and methods (Section 1.1 and 1.2) remain relevant, but it is important to note that the Steering Group recommended that efforts be focused on:

- **A review** to pull together relevant information on potential uses of algae with specific reference to the role that they might play in substituting current sources of marine oils and proteins

- A need to address the potential to utilise algae in the round, by assessing **synergies with other initiatives** such as bio-fuel production and integrated multi-trophic aquaculture (IMTA) etc.

- For algae to be utilised as a raw material it must be part of a **profitable enterprise** and therefore it is important to understand the nature and potential use of the various products that can be derived from algae – in particular, the higher value components of this cascade.

- Algae-specific attributes will need to be considered such as **micronutrients, immunostimulant properties** etc.

- The scale of production will be an important factor and the project will need to assess opportunities for other algae based processing and production regimes (e.g. **bio-fuels, alginates** etc) to provide the relevant raw materials for feeds.

- There are many ingredients in aqua feeds – and the **costs of these change** all the time, in real terms and in relation to one another. It is important this research is aware of cost sensitivities.

- **Health claims for farmed finfish** must be maintained and substantiated in actual terms, from a consumer perspective.

- **Direct human consumption of marine oils** in refined capsule form and, increasingly, as an (EPA/DHA) additive to a variety of "functional foods" is placing additional pressure on supply and raw material costs. This project may need to consider the potential for algae to service this high value market and thereby reduce pressure on marine supplies.

- There was general agreement that the most pressing issue in terms of feed sustainability was the need to find alternative, cost effective, sources of **marine oils and EPA and DHA in particular**.

- Whilst the project will review the potential for both macro and microalgae to provide alternative raw materials for aquaculture feeds, it was acknowledged that the **most likely sources of marine oil substitutes would be from microalgae** given available evidence.

- There was some discussion on the potential to grow microalgae in the "Scottish" climate. Whilst there was production and research relevant to the production of temperate microalgae this was recognised as a **potential limitation** that the project would need to explore.

- The potential for the production of these raw materials from **genetically modified (GM) algae** was discussed. The project will need to assess the regulatory implications, together with likely political and consumer sensitivities to the use of GM in this context.

- The review of available information will need to take into account the **quality of the available data**. Evidence will need to be carefully referenced to differentiate peer reviewed literature from uncorroborated claims made on the internet, commercial publicity and the popular press.

- There was an understanding that much of the information held by the feed companies may be commercially sensitive and that **direct bilateral communication** between the project team and feed manufacturer's representatives would be the best approach.

- The steering group acknowledged the potentially broad scope of the project and the need to remain focused on key areas. With respect to species this meant **UK finfish aquaculture species, with an emphasis on Atlantic salmon**.

2 PRIMARY RESEARCH AND CONSULTATION

2.1 Introduction

2.1 Commercial utilisation of wild-harvested or cultivated algae, marine and freshwater, is a rapidly growing area of research, development and investment. Traditional uses of algae also still continue to one degree or another, and include:

- Land dressing fertilisers[3]
- Animal forage[4]
- Food for human consumption[5]
- Extracted chemicals for use in the food industry – alginates, carrageenans, etc[6]

2.2 A new wave of interest in algae was initiated in the 1970s, as the US government became concerned about oil supplies and prices, and instigated research into bio-fuel production – including production from marine biomass resources[7]. This original phase of active research, broadly know as the Aquatic Species Program[8], faded as oil prices stabilised, but it has re-emerged in recent years as concerns about future oil supplies have intensified, and as other issues such as climate change and food security have gained prominence in scientific circles and governmental policies. Increasing thought has also been given to the further use of algae or algae products for animal feeds[9] or human foods[10].

2.3 Many research organisations and commercial companies are involved in algal production or exploitation, and the literature, both peer-reviewed and 'grey'[11], is extensive and rapidly expanding. This study's review of historic and current literature is as wide-ranging as possible, but it must be considered only a 'snapshot' in this rapidly evolving subject area. The study has taken advantage of several thorough recent review papers within the field, but its focus has been unique: a review of all algal research and developments, but always with a focus on material that could be introduced cost-effectively into **aquaculture finfish diets**, specifically for salmonids. The authors have attempted to focus on known or projected economics of algal material production, as well as applicability in terms of nutritional composition.

2.4 In addition to an extensive literature review, the study team has been pro-active in seeking direct information about developments and trends from a large number of organisations. Such contacts have involved:

- Formal consultation meetings with key organisations or groups
- *Ad hoc* telephone and email dialogues with individuals and organisations
- Semi-structured (i.e. tailored to suit specific recipients) questionnaire-style approaches to a wide range of organisations. In some cases, such as the high-tech microalgae bio-fuel companies, all organisations for whom details could be found have been contacted

[3] See for example: http://193.62.154.38/celtica/manureb.htm
[4] See for example: http://eatscotland.visitscotland.com/food-drink/scottish-food/vegetables/seaweed.html
[5] See for example: http://www.oceanvegetables.com/edible-seaweed.html and http://www.spirulina-benefits-health.com/spirulina_algae_history.html
[6] See for example: http://www.cybercolloids.net/library/alghistory/history-alginate-chemistry-production and http://www.cargillpersonalcare.com/products/hydrocolloids/carrageenans/pc_prod_hyd_carrag.shtml
[7] http://www.nrel.gov/biomass/pdfs/jarvis.pdf
[8] http://www.nrel.gov/docs/legosti/fy98/24190.pdf
[9] See for example: http://www.algae4feed.org/brief/microalgae-in-feeds/57
[10] http://www.fcrn.org.uk/interviewSeries/interviews/archives/marinealgae/index.htm
[11] For the purpose of this study, we define 'grey' literature as any form of publication that is in the public domain, but specifically not one that has been published in a peer-reviewed scientific journal or similar.

2.5 Annex 2 provides full details of all the contacts initiated by the study team, divided into appropriate categories. Information provided by some of those contacted is contained within the main sections of the report, specifically referenced if the contact agreed to this, or non-attributably if they did not.

2.2 Finfish Feed Manufacturers

2.6 The essential starting point for this research, agreed with the Steering Group, was a dialogue with the three main aquaculture finfish feed manufacturers in the UK: Biomar, Skretting and Ewos. It was important to ascertain:

- What type of feed ingredients the sector required
- Where it sourced these from
- What the cost implications and trends were
- Whether there was any global constraint on availability
- Whether they were currently using any algal-sourced products
- Whether they were aware of any algal-sourced products available currently for inclusion into finfish diets – and if they were not using them, why not
- What the formulation constraints were to introducing new products into a modern salmonid diet
- Whether they would be receptive to using future ingredients sourced from algal production, assuming the technical and economic attributes were favourable or at least acceptable.

2.3 Research Organisations

2.7 It was felt important to have a dialogue with various research organisations, mainly in the UK but also including some around the world. In a pure literature review, it would be the publications emerging from such organisations that would form the bulk of the 'evidence base' for a study, but in such a fast-developing sector the study team believed that additional information and possibly new contacts could be gained from having an informal dialogue with the relevant researchers. There are other research organisations around the world that were not directly approached in this way, but time and project constraints did not allow any further activity of this sort. This is not seen as a challenge to the study, since publications from these organisations, or material from their websites, have been covered and are reported in later sections.

2.4 Commercial Companies

2.8 There are many commercial companies now involved in algal production. Some are long-established companies involved in the production of traditional products such as sodium alginate. Others are harvesting wild algae and processing it in various ways for a variety of markets.

2.9 Many other companies are relatively new, and are focusing – in the main – on algal biomass production for the bio-fuels sector. It is clear from the literature that many of the newer bio-fuel focused companies, whilst well financed by governments and major energy corporations, are still in the very early start-up phase in terms of commercialising their production and activity. Nevertheless, it was felt important to offer them an opportunity to contribute to this very specific piece of research, since it was felt that some of them, perhaps most, would not have been considering animal feeds, and specifically aquaculture feeds, as possible additional market niches for their processes. A ‘guide questionnaire’ used for contact with these companies is shown in Annex 3. It should be noted that Annex 3 is just a broad guide: the exact form of words was varied from contact to contact, depending upon the study team’s understanding of their exact niche within the general field of algal production.

2.5 Additional Consultations, Key Literature Reviews and Databases

2.10 The research has taken account of a significant volume of published literature, all of which is referenced as footnotes where appropriate. In many cases the references are to specific papers or articles covering specific research topics. However, as in most broad-ranging reviews of this type, the study has also benefited from several key earlier review papers related to one or other aspect of this field[12]. None of these were as focused on aquaculture feeds as the current study, but all of them provided valuable information about algal production, nutrition, harvesting, processing and economics. Where appropriate, information from these reviews is presented within later sections of this report, and referenced accordingly.

2.11 There is a significant use of both wild-caught and cultured algae on a global basis, for a variety of purposes. Some international databases provide information about this production, with the primary one being that maintained by the Food and Agricultural Organisation of the United Nations (FAO)[13]. The FAO was specifically contacted as part of this study, as were other experts who responded and provided advice and information, including:

- **Infoyu**, a Chinese government/trade body involved with fisheries
- **Dennis McHugh**, in Australia, a former FAO macroalgae expert.

2.6 Reliability of Data

2.12 The public domain databases accessible for this study, and for any other researchers pursuing similar studies, are important. However, they are only as reliable as the quality of the raw data they gather and report. In this regard, it should be noted that the FAO has expressed some concerns about some of the raw material it includes in its FISHSTAT database. Whether quantities and values are being recorded as wet weight or dry weight is a common concern – and an important one as far as algal production is concerned.

12

Bruton et al (2009)	A Review of the Potential of Marine Algae as a Source of Bio-fuel in Ireland	http://www.seambiotic.com/uploads/algae%20report%2004%202009.pdf
Carlsson et al (2007)	Micro- And Macro-Algae: Utility For Industrial Applications	http://www.epobio.net/pdfs/0709AquaticReport.pdf
McHugh (2003)	A Guide to the Seaweed Industry	http://www.fao.org/docrep/006/y4765e/y4765e00.htm#Contents
Olsen (2011)	AEI Feed Resources in Mariculture	http://www.int-res.com/articles/aei2011/1/q001p187.pdf
Benemann (2008)	Introduction to Bio-fuels from Algae	http://advancedbio-fuelsusa.info/wp-content/uploads/2009/03/microalgae-bio-fuels-an-introduction-july23-2009-benemann.pdf

13 http://www.fao.org/fishery/statistics/en

2.7 Summary

2.13 The field of algal production and commercial utilisation is large and varied, and there is the potential for many diverse parts of it to contribute in one way or another to aquaculture finfish feeds – in the future, if not currently. This study has accessed a wide a range of literature and individual contacts to provide a reasoned assessment of the potential to use **algae as commercially viable raw material for aquaculture finfish diets.**

3 FINFISH NUTRITION AND FEED FORMULATION

3.1 Introduction

3.1 The production of formulated diets for feeding to aquaculture species – mainly finfish and crustaceans – has been taking place around the world for many decades. The progression from feeding wet 'trash' fish, to semi-moist pellets, to 'dry' pellets has been well documented[14]. The nutritional composition of the diets, and therefore the exact mix of raw materials required to make them, vary from species to species – and often vary quite markedly for one farmed species, depending upon life cycle stage or other specialised considerations. The focus for this study is on finfish feeds required for the Scottish industry, and in large part that therefore means feeds for Atlantic salmon (*Salmo salar* – referred to as 'salmon' hereafter). Where appropriate, issues that might concern feeds for other finfish species are mentioned in this report, but the primary focus is on **salmon**[15], and on possible future inclusion of **algal components** in their diets.

3.2 There has already been a significant amount of development with respect to the degree to which salmon diets can already incorporate non-traditional sources of protein and lipid[16].

3.2 Trends in Finfish Diets

3.3 Expanding on the point above in connection with developments in feeding species such as salmon, the review of Olsen 2010 covers in some detail the changes that have already taken place, and the need for further changes. The AQUAMAX[17] project which ran from 2006 to 2010 was set up to research the possibilities of reducing both fish meal and fish oil (lipid) in the diets of farmed finfish species, including salmon. Unfortunately algal materials were not generally considered amongst the sources of alternative feed ingredients[18].

3.4 The search for alternative sources of lipid for finfish diets is typified by the RAFOA[19] research project, an EU Fifth Framework Programme. Its main objectives were to:

- Replace as much as possible of the fish oil used in aquaculture feeds with vegetable oils, without compromising the health, welfare and growth performance of the fish.
- Maintain health benefits, taste and other quality characteristics important to processor and consumers preferences.
- Advance basic scientific knowledge of fish lipid nutrition.

3.5 Olsen's key themes were:

- The future need to conserve as much terrestrial plant material as possible for direct human nutrition, and to rely increasingly on mariculture for the provision of animal proteins for human food

[14] For a good overview, see: http://www.fao.org/DOCREP/003/AB412E/ab412e10.htm
[15] http://www.westcoastaquatic.ca/Aquaculture_feed_environment.pdf
[16] http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2095.2010.00780.x/abstract
[17] http://www.aquamaxip.eu/content/view/9/14/
[18] http://www.aquamaxip.eu/files/03_Development%20of%20feeds%20based%20on%20sustainable%20alternatives%20to%20FM%20and%20FO.pdf
[19] http://www.rafoa.stir.ac.uk/

- The need to constantly drive aquaculture species to operate at lower trophic levels of nutrition than their wild ecological niche would suggest
- That much has already been done in this area – but more work is required.

3.6 Duarte et al (2009)[20] make similar observations, and state: "*Constraints on the availability of freshwater and land plants and animals to feed the 9.2 billion humans projected to inhabit Earth by 2050 can be overcome by enhancing the contribution the ocean makes to food production. Catches from ocean fisheries are unlikely to recover without adequate conservation measures, so the greater contribution of the oceans to feeding humanity must be derived largely from mariculture. For the effort to be successful, mariculture must close the production cycle to abandon its current dependence on fisheries catches; enhance the production of edible macroalgae and filter-feeder organisms; minimize environmental impacts; and increase integration with food production on land, transferring water-intensive components of the human diet (i.e., production of animal protein) to the ocean. Accommodating these changes will enable the oceans to become a major source of food, which we believe will constitute the next food revolution in human history.*"

3.7 Olsen suggests that macroalgae could provide the 'bulk' aspects of ingredients to feed other culture species, and that the role of microalgae might be in the provision of the essential n-3 highly unsaturated fatty acids (HUFA)[21] lipids that are needed.

3.3 The Scottish Aquaculture Sector

3.8 Following sections discuss specific components of salmon diets, but it is important to highlight one key feature of salmon diets used within the Scottish industry. They are designed to feed and produce salmon flesh to a nutritional standard required by the main retailers of farmed fish in the UK. The emphasis is on using diets that are based on raw materials that are as 'natural' as possible. This issue is touched upon in more detail later in this report, but it is also one that has been the subject of another SARF project (SARF025[22]). In a very simplistic sense, this means that the focus on marine-origin lipids, and particularly n-3 HUFA, is more significant for salmon diets manufactured for the Scottish industry than it would be for salmon farmed in other countries. However, if there were suitable algal components for incorporation into salmonid diets at the correct price, there is little doubt that the global feed producing sector would be interested.

3.9 A modern salmon diet is a high-energy, carefully formulated feedstuff[23]. Sections 3.4 to 3.6 discuss the main components of the diets in more detail.

3.10 When the three main feed manufacturers were interviewed for this project, they were asked the initial question: "*Do you currently use any ingredients sourced from algal materials in your diets?*" The responses were consistent, and highlighted the following points:

- No algal materials were being used in salmon feeds, by any of the companies, at the time the research was being conducted (early 2011)

[20] http://www.bioone.org/doi/abs/10.1525/bio.2009.59.11.8
[21] Terms such as 'n-3 HUFA' and PUFA (polyunsaturated fatty acids) are also commonly used, but this report will hereafter use the term **n-3 HUFA** to mean long chain fatty acids with multiple double bonds, of the 'n-3 HUFA' series
[22] http://www.sarf.org.uk/Project%20Final%20Reports/SARF%20025_%20Final%20Report_11%20Feb%2008.pdf
[23] See for example: http://books.google.co.uk/books?id=8xwVaWUiC5wC&pg=PA133&lpg=PA133&dq=high+energy+salmon+pellet&source=bl&ots=4XiA92HuKY&sig=1aAViDZugNPJ017lq0W_9HPQy8A&hl=en&ei=VTu4TfnpIcKl8QP1jIlO&sa=X&oi=book_result&ct=result&resnum=5&ved=0CEgQ6AEwBA#v=onepage&q=high%20energy%20salmon%20pellet&f=false

- One manufacturer was including a small percentage of milled algae (unspecified) for incorporation into a low-volume market for freshwater ornamental fish diets – but only because the customers asked for it, not because of any nutritional requirement
- All three companies noted that they could purchase and use carotenoid pigments based on algal production, but did not choose to do so at the present time.

3.11 It is important to stress the different **nature** of the types of ingredients used in formulating and manufacturing a salmon diet. This is discussed further in section 3.7, but in essence:

- Some raw materials are incorporated into diets in their '**natural**' state – albeit dried, milled, etc. A good example would be fish meal. This is necessary because the 'key' nutritional ingredient that the raw material brings to the formulation cannot be easily or cost-effectively refined or extracted from the original raw material: digestible protein, in the case of fish meal. Fish protein concentrate can be made, but it is expensive in commercial formulations[24]
- Some key nutritional ingredients for salmon diets can be incorporated into formulation in almost '**pure**' form because they can be extracted or refined from a raw material easily and cost-effectively. Lipid is a good example.

3.4 Lipid

3.12 Lipid (also sometimes described as 'oil' or 'fat') is one of the key ingredients in a salmon diet. It provides two main nutritional functions:

- Metabolisable energy for the fish, so that it can perform its normal activities and functions. Protein is also a source of metabolisable energy (although not as energetic as lipid[25]), but there is an emphasis on sparing as much of the dietary protein as possible for incorporation into new fish flesh, i.e. growth. Salmon diets are generally very high in lipid for this reason[26]
- Building block elements for the salmon and in particular the n-3 HUFA fatty acids that the fish require as raw materials for cell structure and as precursors for biosynthesis of many regulatory biochemicals. Some elongation and desaturation of shorter-chain fatty acids can occur in salmon, but at a slower rate than is considered appropriate for modern farmed salmon, bearing in mind the required final product standards for n-3 HUFA lipids[27],[28] in the retail multiple sector.

3.13 The latter bullet point is the most important one when thinking about lipid requirements for farmed salmon, and when considering the nutritional value of salmon to human beings. There is an extensive literature concerning n-3 long chain fatty acids and it is not appropriate for this study to rehearse all of these issues, except to note the main ones:

- Most vertebrate animals have rather limited metabolic capacity to chain-elongate and desaturate fatty acids – the received wisdom is that they need to ingest them directly in their diets[29]
- All vertebrates need to have some of these n-3 HUFA in their structure – they are particularly important in cell walls and membrane fluidity and as precursors for other metabolic processes. Critical here is docosahexaenoic acid: 22:6n3 (DHA). Its chemical

[24] http://www.fao.org/wairdocs/tan/x5917E/x5917e01.htm
[25] http://www.nutristrategy.com/nutrition/calories.htm
[26] See for example: http://www.google.co.uk/url?sa=t&source=web&cd=1&sqi=2&ved=0CBgQFjAA&url=https%3A%2F%2Fdspace.stir.ac.uk%2Fdspace%2Fbitstream%2F1893%2F1028%2F1%2FAqua%2520Nutr%2520-%2520Karalazos%2520et%2520al.%2520-%2520Effects%2520of%2520dietary%2520protein%2520and%2520fat%2520level%2520and%2520RO%2520on%2520Atlantic%2520Salmon1.doc&rct=j&q=Salmon%20feeds%20high%20in%20fat%20protein%20sparing&ei=uz24TZn8KIrF8QPY36hO&usg=AFQjCNGu1hX1cMF8KdGj4xCD8YSC8JWelw&cad=rja
[27] See for example: http://www.nrcresearchpress.com/doi/abs/10.1139/y93-102
[28] See particularly: http://www.mcsuk.org/downloads/fisheries/feedevent/Prof_Gordon_Bell_University_of_Stirling.pdf
[29] See for example: http://www.pnas.org/content/93/1/49.full.pdf

precursor, eicosapentaenoic acid: 20:5n3 (EPA) is seen as being almost as important in nutritional terms. Both of these fatty acids derive from (alpha) linolenic acid: 18:3n3 (ALA), another of the essential fatty acids (EFA)

- There appears to be some importance attached to arachidonic acid: 20:4 n-6 (AA) in finfish diets[30,31]
- Terrestrially-sourced lipids are generally rich in the n-6 class of fatty acids, and short of the n-3 class of fatty acids (with the slight exception of some plants such as hemp seed, etc)
- Lipids of marine and freshwater origin are generally much richer in the n-3 class of fatty acids, although the mix of chain length and degree of unsaturation varies depending upon source
- In human nutrition, there is a growing awareness of the importance of a diet not only balanced in terms of different types of fatty acids (see Mediterranean diet, for example[32]), but also well supplied with marine-sourced n-3 HUFA – hence the importance of eating oily marine species such as salmon, herrings and mackerel, which are relatively rich natural sources of these fatty acids[33].

3.14 In dietary formulation and life cycle feeding strategy terms, as discussed above, there have been some interesting developments in terms of substituting different types of lipids within salmonid diets during their lifetime, and these are discussed further in section 3.7. The main point for the purpose of this study is that at the moment, Scottish finfish feed manufacturers need to incorporate marine-originated lipids into their diets, at rather high levels, and a significant proportion of the overall lipids need to be those rich in EPA and DHA. Anecdotally this is seen as 20% of the total lipid in a salmon diet being long chain n-3 HUFA – where the total amount of lipid in a salmon diet can be in the region of 25% or more.

3.15 The feed manufacturers ensure sufficient quantities and types of marine-origin lipids in their salmon diet formulations by:

- Purchasing and blending in fish oils from various sources
- Taking into account the amount and nature of the small amounts of lipid that is contained within the fish meals or terrestrial plant meals they use – which are mainly in the formulations as sources of digestible protein
- Possibly using other specialised oils, if these provide metabolisable energy at reasonable cost.

3.16 Later sections of the report discuss availability and cost trends for all algal feed components, but it is important to stress at this point that this research has been strongly steered towards the potential for **algal derived lipids**, rather than the other macro or micro ingredients that might be hypothetically sourced from algae.

3.5 Protein

3.17 Protein is the other main component in salmonid finfish diets. Animal source proteins are considered good-quality proteins since they contain a good balance of essential amino acids. Plant proteins are thought to be poor-quality proteins because they lack some amino acids. These differences between the exact nature of nitrogenous compounds in 'protein' containing feed ingredients leads to the concept of **digestibility** of the protein – and this is

[30] http://www.bashanfoundation.org/zvi/publications/zvifeeding.pdf
[31] http://www.sarf.org.uk/Project%20Final%20Reports/SARF014%20Final%20report.pdf
[32] http://www.americanheart.org/presenter.jhtml?identifier=4644
[33] See for example: http://www.hsph.harvard.edu/nutritionsource/what-should-you-eat/n-3 HUFA-fats/

an area that animal feed formulators (including finfish) must take into account when balancing different raw material sources in their diets[34].

3.18 Considerable advances have been made in utilisation of protein sources in modern salmonid diets, to the extent that:

- Formulators are able to make use of plant-sourced high-protein meals (mainly soya), as well as the more traditional protein-rich fish meals
- Amino acid balancing is very well understood, and relatively easy to achieve in salmon diets
- Feed ingredients are regulated in many countries and raw materials permissible in some are not permissible in others e.g. Land Animal Products (LAPS). Specific markets may demand the complete absence of LAPS from diets even though some may be permissible in law. Specific customers may demand the complete absence of LAPS from diets even though some may be permissible in law and are used by their competitors in the same country[35].

3.19 All raw materials for feed ingredients are going up in price (Figure 1), but the salmon feed manufacturers are consistent in their advice to this study[36]: protein is not as potentially limiting a feed ingredient as lipid on a global scale. If a source of protein-rich material with high digestibility arising from algal production came onto the market at the right price, the companies would certainly consider using it. However, they believe that currently they have alternative options.

3.20 The final key point to note about protein is that it does not generally come onto the animal feeds market in a pure (refined, extracted) form. Unlike pressing lipid out of a raw material (possibly with the assistance of solvents) such as fish waste or some vegetables, extracting a purified protein from a raw material is more complex and therefore costly. For various reasons extraction of proteins from plant material is particularly difficult. Phenolic compounds and polyanionic cell-wall mucilages render conventional procedures of extraction and purification much more difficult[37]. The references in the footnotes are important sources, but the point to stress is that:

- An extracted lipid is a bottle of 100% lipid, and carries no indigestible or unwanted 'waste' – although there is always a question about how useful or otherwise some of the individual fatty acids in its composition are to the diet formulator
- A protein 'meal' is not 100% protein: a soya bean meal is 44-50% protein, and even a soya protein 'concentrate' is only 70% protein. The question for a diet formulator is what is the value of the non-protein component, if any? Section 3.7 discusses this in more detail.

3.6 Other Ingredients

3.21 A finfish diet, and specifically a salmon diet, is principally composed of lipid, protein and a small amount of water. Table 1 illustrates one example of a proximal analysis of a salmon

[34] See for example: http://www.pvj.com.pk/pdf-files/27_3/page%20121-125.pdf
[35]http://www.skretting.com/Internet/SkrettingItaly/English/webinternet.nsf/wprid/747C62369C594E8AC12575E0002D4CAF/$file/IngleseSostenibile.pdf
[36] Personal communications
[37] See: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6T1W-48951P1-16&_user=10&_coverDate=01%2F23%2F1991&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1630023856&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=c85a612657c3a30245d415df33a3b5ee&searchtype=a and also http://www.scipub.org/fulltext/ajas/ajas73331-342.pdf, http://www.fas.org/ota/reports/8315.pdf, http://www.princeton.edu/~ota/disk3/1983/8315/831508.PDF, and particularly http://www.fao.org/docrep/t0532e/t0532e03.htm#2.3

diet. Note that NFE is the nitrogen-free extract: the fraction that contains the sugars and starches plus small amounts of other materials.

Table 1. Salmon diet proximal analysis[38]

	Proximate composition (%[2])	Digestibility[3] (%)
Protein (min)	39	90
Fat (min)	33	95
NFE[5] (max)	10	60
Fibre (max)	1.5	10
Phosphorus (approx.[6])	1.2	50
Minerals[7] (max)	6.8	50
Moisture (max)	8.5	
Total	100	

3.22 What Table 1 does not illustrate very clearly is the importance of a range of ‘micro’ components in a salmon diet (with the exception of the minerals). These typically include nutritional components essential to the health of the farmed salmon, or essential in helping to ensure the final product quality of the farmed salmon. The main types of such components include:

- Vitamins
- Minerals
- Pigments (for flesh colour)
- Immunostimulants (if required)

3.23 It is not appropriate at this point in this project to go into any more detail about the different types of micro ingredients. They are generally well-understood by the finfish feed formulator, and they have assured this research that, as with proteins, they do not see a significant global shortage or supply problem.

3.24 However, later sections of this report discuss ranges of ‘micro’ ingredients that could or do already come from algal sources. In some cases (e.g. pigments) these are well-defined and available on the commercial market. It is a matter for the feed manufacturers to decide whether or not to purchase them. In other cases, claims are made about the nutritional advantages of incorporating some algal material in finfish diets, advantages that are likely to relate to ‘micro’ ingredients of one sort or another[39]. Finfish feed manufacturers have perhaps yet to be persuaded of the possible advantages of these materials in relation to their concerns about indigestible bulk, but all of the relevant issues are reviewed and discussed in the relevant sections of the report.

3.7 Feed Density, Bulk and Anti-Nutrients

3.25 Reference has been made to the high-energy nature of modern salmon diets, and to the issue of indigestible ‘bulk’ in formulation considerations. Reference has also been made to

[38] http://aquaculturegrowsns.com/wp-content/uploads/Reid-GK_Chapter-One-for-WWF-SAD-Nutrients-Stand-Alone-version.pdf
[39] See for example: http://www.springerlink.com/content/x2xj34726k636p58/fulltext.pdf

the fact that one cannot always obtain a nutritional component in a '100% pure' form. It is important to explore these concepts in more detail, in order to understand better some of the reasons for possible challenges to the use of algal materials in diets, or to the reluctance of feed manufacturers to consider the use of such materials.

3.26 Table 1 in Section 3.6 is helpful in exploring this concern about 'bulk'. It clearly shows that a salmon diet, energy-packed though it is, already contains:
- 8.5% moisture – with little nutritional value to salmon
- 10% carbohydrate (NFE) – which has a digestibility factor, but probably little core nutritional value to a salmon
- 1.5% fibre – which may have a mechanical role in the digestive tract of the fish, but which supplies no nutritional building-block advantage
- 8% phosphorous and minerals – some of which may have a nutritional value to the salmon, but some of which may not
- 3.9% indigestible protein.

3.27 From a feed formulator's perspective, a salmon diet needs to:
- Provide as much highly digestible protein as possible to enhance fish growth
- Provide as much lipid (of the correct types) as possible, to provide metabolisable energy and n-3 HUFA body reserves
- Provide the correct amount of micro-nutrients of one type or another (usually as fractions of a % of the total diet)
- Have a minimum amount of non-digestible material so that solid excreted waste is kept to a minimum, and so that the maximum amount of the desired elements above are contained in a single 'unit' of food.

3.28 If a new product (algal-derived or from any other source) comes onto the market, and claims to offer a biological advantage to salmon performance, perhaps because it contains a new micro-nutrient or mix of micro-nutrients or special biologically active chemicals, the issues for the feed formulator to consider are:
- If it is a 'pure' or almost pure product, which can be incorporated at range of say 1-2% of total formulation level, and if its activity is well-documented and its price correct, then there would be little concern about using it in diets
- If the beneficial ingredient is present as just a small percentage of a larger-bulk raw material (because it cannot be extracted and purified), then the formulator has to think very carefully about the potential benefit of the new ingredient in relation to the additional indigestible 'bulk' that acts as its carrier, and the other ingredients that would therefore have to be left out in order to accommodate that bulk.

3.29 This issue is important, and currently topical in the light of products that are being promoted for use in aquaculture feeds (see section 5). Ultimately it should be capable of being resolved by way of good independent science backed up by careful cost-benefit analysis: if the product works and confers an advantage to salmon diet formulation, it will ultimately be used.

3.30 The final point to consider about formulation, which is not exclusively an issue of 'bulk' and new raw materials, is anti-nutritional components that might be contained in different types of feed raw materials[40]. These are compounds that inhibit the normal uptake or utilization of nutrients. It is not appropriate for this report to consider all aspects of this topic at this stage, and good reviews are available[41]. Different algal raw materials may or may not contain such

[40] http://www.fao.org/DOCREP/004/Y2775E/y2775e07.htm
[41] See: http://www.nap.edu/openbook.php?isbn=0309048915 and http://ejeafche.uvigo.es/component/option,com_docman/task,doc_view/gid,775/, for example.

anti-nutrients, and this must be a topic for careful consideration when any new feed sources are developed and promoted.

3.8 Cost and Availability of Raw Materials

3.31 The principal raw materials required by salmon feed formulators are globally traded commodities, and their price and availability can be tracked and assessed by way of a number of publicly-available databases, including the FAO[42], Index Mundi[43], Globefish[44], and The International Monetary Fund[45]. Figure 1 provides a graphical illustration of price trends for some key commodities over recent years – drawing upon various data sources.

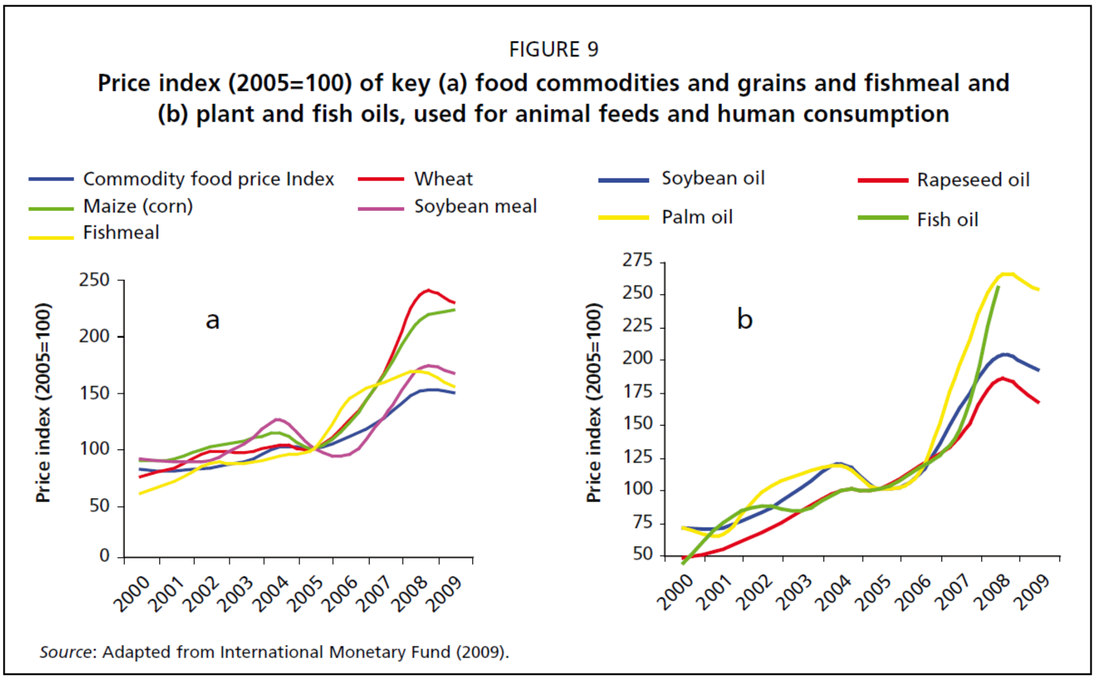

Figure 1. Price index trends in key feed ingredient commodities.

3.32 The price index trends presented in Figure 1 illustrate how raw material prices are changing with time, and generally becoming more expensive.

3.33 Table 2 provides a snapshot of recent actual prices for key aquaculture finfish feed raw materials.

Table 2. Raw material prices (generally FOB).

MATERIAL	DATE	PRICE ($/t)	PRICE (£/t)[46]	SOURCE
Fish Meal	April 2011	1,760	1,076	Index Mundi[47]
Soyabean Meal	April 2011	388	237	Index Mundi
Palm Oil	April 2011	1,123	686	Index Mundi
Rapeseed Oil	April 2011	1,446	884	Index Mundi
Peruvian Aqua Fish Oil	Wk 6 2011	1,900	1,161	IFFO[48]
Peruvian Omega-3 Oil	Wk 6 2011	2,400	1,467	IFFO

[42] http://www.fao.org/docrep/012/i1143e/i1143e02.pdf
[43] http://www.indexmundi.com/commodities/?commodity=fish-meal&months=60
[44] http://www.globefish.org/fish-oil-february-2010.html
[45] http://www.imf.org/external/data.htm#data
[46] http://www.x-rates.com/calculator.html
[47] http://www.indexmundi.com/commodities/?commodity=fish-meal
[48] http://www.iffo.net/downloads/WR%20Producer/WR9-2011.pdf

Chile Feed Oil	Wk 6 2011	2,000	1,222	IFFO

3.34 Table 2 serves as useful background to ascertaining how much the aquaculture feed manufacturing sector is willing to pay for key nutritional components such as lipid or protein-rich meals. Prices clearly fluctuate in line with global changes, but it is impossible to undertake an investigation of what might be available from algal sources around the world without having some sort of realistic target price with which to approach potential suppliers. The feed companies did not express any urgency with respect to a protein 'meal' of any sort, but value/cost estimates could be made from the data presented in Table 2.

3.35 The price the finfish feeds sector could pay for n-3 HUFA rich lipid at the present time has proved to be the most important indicator, and can be used to compare with prices currently paid for algal lipids entering the human nutrition or pharmaceutical markets, or the prices being projected for algal oil to provide raw material for bio-fuels. Based on feedback from the feed companies together and the Steering Group, this study is working on two algal lipid price assumptions:

- **£1,200** per tonne for general 'marine' algal oil, with some small amounts of EPA and DHA fatty acids, but with a generally good composition in terms of n3 rather than n6 fatty acids (see section 4)
- **£2,200** per tonne for an algal oil containing only EPA and DHA fatty acids, of the type produced by certain companies from microalgae bioreactors[49].

3.36 The basis for the higher price of a lipid containing EPA and DHA is that it could be blended with cheaper marine and/or terrestrial oils, providing an overall lipid combination that provided the optimum balance for the industry. It is important to stress that the prices shown above **are indicative only**: raw material prices rise and fall constantly.

3.9 Algal Product Tested on Salmon in Scotland

3.37 A recent trial on the use of an algal product from Ocean Harvest in salmon aquaculture in Scotland[50] indicated that there were several potential benefits to be ascribed to a blend of dried macroalgal materials, included in salmon diets at 15%, and compared with a 'standard' organic salmon diet. These benefits included improvements in: growth rate; FCR; mortalities; fish flesh flavour and texture; and reductions in levels of sea lice infection.

3.38 It is important to note that there is no peer-reviewed publication of this trial in the scientific literature. The science underpinning his particular product is based on a wide body of literature, albeit not particularly focused on salmonid feeds[51]. The company was contacted about their aims with respect to taking this product forward in the aquaculture sector, and the response was:

- An intention to carry this work forward into peer reviewed literature, but that it would take another 6 months due to patent protection
- The company saw no need to undertake any further demonstration trials, and felt that it had proved enough about the capabilities of the product – which is sold commercially in Canada, Holland and soon in Norway
- They are however completing trials with shrimps and pigs, with university input

[49] http://www.martek.com/
[50] http://www.oceanharvest.ie/download/articles/International_Aquafeed.pdf
[51] For a review, see: http://www.springerlink.com/content/x2xj34726k636p58/fulltext.pdf

- They felt that the lack of uptake of their product so far by the Scottish aquaculture feed manufacturers was largely driven by cost/profit considerations
- They stated that they were aware of what the key 'active' nutritional components were in their product, but were understandably reluctant to divulge this information
- They did not feel that further extraction efforts for the key components were warranted, at the level of 15% inclusion in salmon diets – i.e. the advantages of the components outweighed the 'bulk' disadvantages at such a modest level of the overall diet
- They will publish a more detailed analysis of the fatty acid and amino acid composition of their product in due course
- The product retails for 1,200 Euro per tonne – and in salmon diets, is an additive at 15%.

3.10 Healthy Properties of Farmed Finfish

3.39 Part of the project specification was to consider algal ingredients that could be used by the sector, whilst at the same time preserving the nutritional value of farmed Scottish salmon to its consumers[52]. There are two components to this:

- The level of n-3 HUFA rich lipids required or desired in the final harvested flesh of the farmed fish, with an emphasis on EPA and DHA[53]. This was defined as delivering a minimum of 1.2 g/100g of EPA+DHA in the flesh in the original Code of Good Practice for Scottish Finfish Aquaculture, but a more recent assessment was presented at the MCS workshop[54]
- The requirements of some UK retail multiples to have as far as possible a sustainable approach to feeding farmed salmon throughout their life cycle, not just at the end. This subject was considered by a previous SARF project[55].

3.40 There is some debate about the second of the two bullet points above, but this is not a matter of immediate relevance to the current research. The focus remains on whether there are any algal materials available that can be used in the manufacture of salmonid diets, and in the first instance the emphasis is on nutritional suitability and cost. Volume required is another question, and is addressed briefly in section 3.11. The study makes no assumption about decreased use of these materials, and therefore meets the original objective: *status quo* with respect to nutritional value of Scottish farmed salmon.

3.11 The Scale of Raw Material Requirements in Scotland

3.41 The ability to ascertain a **cost** level that might make an algal-sourced lipid economically interesting to aquaculture finfish feeds sector in Scotland (see Table 7 and section 3.8) has been an important step in allowing the research to progress in a realistic manner. The other useful early indicator is the **scale** of any requirement for raw materials or feed components in Scotland.

3.42 As with issues of cost, the finfish feed manufacturing sector was willing to discuss **n-3 HUFA rich lipid** requirements in most detail, since this was perceived to be the most pressing need for the sector. The following calculation illustrates how the sector considers this topic:

- Assume an industry producing 150,000 tonnes of salmon per annum (whole fish)
- Assume that economic food conversion ratio (eFCR) is 1.3:1[56]

[52] See for example: http://www.richinomega3.com and http://www.food.gov.uk
[53] See for example: http://www.youngsseafood.co.uk/web/policies/omega-salmon.pdf
[54] http://www.mcsuk.org/downloads/fisheries/feedevent/Ally%20Dingwall.pdf
[55] http://www.sarf.org.uk/SARF025.htm

- Leading to a requirement of some 195,000 tonnes of salmon feed required per annum
- Assume the lipid content of the average salmon grower diet is 25%
- Assume that EPA & DHA need to be 20% of the total lipid
- The annual requirement for an EPA/DHA lipid is some **9,750 tonnes**
- (Or 48,750 tonnes of lipid in total)

It should be noted that these calculations are for the Scottish salmon as it exists at the time of writing, and that there is a stated desire by the industry to increase its production in future years.

3.12 Summary

3.43 Section 3, which has focused on what the finfish aquaculture feeds sector needs in terms of raw materials, has highlighted some key points that serve to advise the remainder of the research:

- **Lipids are the most limiting global commodity for aquaculture finfish feeds – especially n-3 HUFA rich lipids containing EPA and DHA**
- **All other nutritional ingredients in finfish diets are not so limiting – they might come from algal sources if the specifications and cost are appropriate**
- **Compactness and the avoidance of indigestible bulk is an issue with finfish diet ingredients, and materials that only contain a small percentage of 'valuable' product will always be a difficult proposition for feed formulators**
- **One algal product intended for inclusion at 15% of salmon diets is available, but has not been taken up by the feed manufacturers, perhaps because of the current lack of peer-reviewed science relating to the product**
- **The Scottish industry's main requirement is for up to 10,000 tonnes per annum of EPA and DHA lipids**
- **The industry could currently justify paying something in the region of £2,200 per tonne for a lipid with EPA and DHA at prevailing market prices, although this price is only indicative.**

[56] Food conversion ratio (FCR) is expressed as tonnes of dry salmon pellet required to produce a tonne of whole Atlantic salmon. Economic FCR allows for wastage and mortalities as well as biological efficiency

4 NUTRITIONAL SUITABILITY OF MARINE ALGAE

4.1 Introduction

4.1 It is appropriate to introduce this section of the report with a fundamental observation: finfish species such as salmon are obligate carnivores, and algae are photosynthetic plants, grazed upon by a range of species that could best be described as herbivores[57].

4.2 However, advances in dietary formulations for feeding a whole range of 'farmed' animals have changed traditional perceptions about trophic levels quite significantly (Olsen 2010). Modern salmon diets, whilst they might still rely to a large extent upon animal-origin raw materials such as fish meal and fish oil, can utilise plant-derived proteins and lipids. The key features of this sort of advance appear to be:

- Understanding the roles of the basic components of proteins and lipids: amino acids and fatty acids
- Having the ability to blend/formulate diets that can use plant-originated amino acids and fatty acids
- Understanding the issues of protein digestibility
- Understanding the role of anti-nutritional components, and having good awareness of the role that indigestible bulk plays in terms of suitability of otherwise desirable raw materials.

4.3 Acknowledging this ability of modern animal feed formulators to potentially utilise a range of raw materials, it is appropriate to research the current state of knowledge about the possibility of identifying algal products containing materials that could be utilised in finfish diets. The presence of utilisable materials in algae (proteins, lipids or micro nutrients) is a primary consideration, but there are a range of subsidiary issues that must also be considered:

- How much of the 'interesting' ingredient is present in the relevant algal raw product?
- How much does it cost to harvest the algal raw product?
- How much does it cost to stabilise it such that it can be transported from point of origin to where it is required?
- How much does it cost, or how technically feasible is it, to extract the interesting ingredient from the raw product?
- Can the raw product itself (perhaps after stabilising and further processing such as drying, milling, etc) be incorporated into finfish diets?

4.4 Sections 4.2 and 4.3 consider these issues for different broad types of algae. The initial analysis is based on published information about the composition of algae, but it is essential to think about the 'downstream' costs of utilising whatever components are present in the algae. It is of little value to say "algae X has Y% lipid (dry weight)" if the cost of extracting that lipid and turning it into a useful product for aquaculture finfish feeds is an order of magnitude above what the sector can afford to pay for such a product. These issues are considered in much more detail in section 5, but it is important to remember them whilst undertaking the primary review in this section.

[57] See for example: http://www.racerocks.com/racerock/eco/taxalab/ensy02/aldoc.htm and http://www.ncmg.org.au/8%20FOOD%20WEB%20-%20WHAT%20EATS%20WHAT.pdf

4.5 This section of the report mainly focuses on the knowledge available on the chemical composition of different types of algae, with a particular emphasis on components that might be of interest in finfish diet formulation.

4.2 Macroalgae

4.2.1 Overview of Macroalgae

4.6 Macroalgae, as a term used for the purpose of this study, are the marine plants generally called 'seaweeds', i.e. multi-cellular aquatic plants. Globally there are over 9,000 species of seaweed divided into three major types (for which this report uses the term 'divisions'): green (*Chlorophyta*), brown (*Phaeophyta*) and red (*Rhodophyta*). Red is the most species-rich group (6,000) followed by brown (2,000) and green (1,200). Around 600 species are found on UK shores. Like terrestrial plants, all macroalgae depend on light for photosynthesis and growth, so they only occupy the intertidal area or relatively shallow photic (light penetrating) zone[58]. Figures 2 to 4[59] illustrate the appearance of some typical types of seaweed.

Figure 2. Brown seaweed: Long bladder kelp (*Macrocystis integrifolia*)

[58] http://www.fishonline.org/farmed/seaweed.php
[59] Source: http://nature.ca/explore/di-ef/isap_ts_e.cfm

Figure 3. Red seaweed: *Corallina officinalis*

Figure 4. Green seaweed: Dead man's fingers (*Codium fragile*)

4.7 In the Far East and Pacific, there has been a long tradition of consuming seaweeds as sea vegetables, while in Western countries the principal use of seaweeds has been as source of phycocolloids (alginate, carrageenan and agar), thickening and gelling agents for various industrial applications, including uses in foods[60].

4.8 To expand on this long tradition of using seaweeds for a variety of purposes in many different parts of the world[61]:

- Direct human consumption, principally in Asia, but also in countries such as Ireland, Wales and France
- Animal fodder – in its raw form or:
    - Seaweed meal, used an additive to animal feed, has been produced in Norway, where its production was pioneered in the 1960s. It is made from brown

[60] http://ejeafche.uvigo.es/component/option,com_docman/task,doc_view/gid,208/
[61] http://www.fao.org/docrep/006/y4765e/y4765e04.htm#bm04.3

seaweeds that are collected, dried and milled. Drying is usually by oil-fired furnaces, so costs are affected by crude oil prices. Approximately 50,000 tonnes of wet seaweed are harvested annually to yield 10,000 tonnes of seaweed meal, which is sold for $5 million[62]

- Fertiliser (surface dressing). The growth area in seaweed fertilizers is in the production of liquid seaweed extracts. These can be produced in concentrated form for dilution by the user
- Hydrocolloids: agar, alginate and carrageenan. Hydrocolloids are water-soluble carbohydrates that are used to: thicken (increase the viscosity of) aqueous solutions; to form gels of varying degrees of firmness; to form water-soluble films; and to stabilize some products such as ice cream
- Cosmetic products, such as creams and lotions.

4.2.2 Proximal Composition of Macroalgae

4.9 There are many references to the apparent health benefits of seaweed in human nutrition[63], but it is important to look in detail at what is known about the composition of different species of macroalgae from a finfish feed ingredient perspective. An overview slide presented at the recent MCS workshop makes a good introduction to this topic: Figure 5.

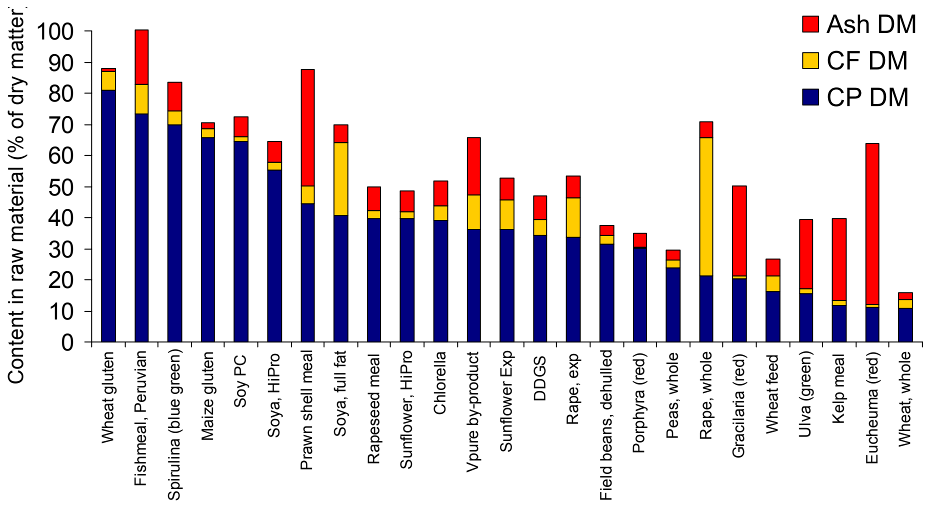

Figure 5. Different levels of core ingredients in different raw materials. Source: P.Morris[64]

4.10 The author of the chart presented in Figure 5 goes on to make the following observations about the issues surrounding the possible inclusion of macroalgae materials in finfish diets:

- *With exception of Spirulina, algal / seaweed meals generally have protein contents that only enable them to compete with low / medium level ("2nd division") protein sources such as sunflower and DDGS[65] and / or fillers like wheat / wheat feed → very limited monetary VALUE as feed materials alone*
- *Algal products would need to be price competitive with vegetable proteins if viewed as sources of protein and fat and high levels of ash consume excess "space" at the lower end of the scale*

[62] The symbol $ in this report denotes the United States Dollar.
[63] See for example: http://longevity.about.com/od/antiagingfoods/a/seaweed.htm, and particularly http://www.springerlink.com/content/x2xj34726k636p58/fulltext.pdf
[64] http://www.mcsuk.org/downloads/fisheries/feedevent/Paul_Morris_Skretting.pdf
[65] distiller's dried grains with solubles

- *Algal products have to have value as sources of micronutrients and / or value added "factors" in order to find a niche in salmonid feeds*
- *However, on weighted average basis, even with pigment included, the proportion of formula cost attributed to additives (vitamins, minerals and carotenoids) is < 10% of formula cost accounting for < 3% of formula space*
- *Basic algal products have to have a lot of "bonus" features / generate a lot of marketing value to justify the formulation space they consume.*

4.11 There are many species of macroalgae, and their proximal compositions vary from species to species, season to season and even by location. A good review of the nutritional value of macroalgae is provided by Burtin (2003)[66]:

- The protein content of brown macroalgae is generally low, with an average: **5-15 % of the dry weight**. Green and red macroalgae have higher levels of protein: on average 10-30 % of the dry weight. Some red macroalgae, such as *Palmaria palmata* (dulse) and *Porphyra tenera* (nori) have protein contents up to 35 and 47% of the dry matter, respectively. These levels are comparable to those found in high-protein vegetables such as soybeans (in which proteins represents 35 % of the dry mass). The digestibility of algal proteins *in vivo* is not well documented. The high phenolic content of macroalgae might limit protein availability *in vivo*.
- Lipids represent only **1-5 % of macroalgal dry matter**.

4.12 A comprehensive search of the published literature allowed the compilation of key macroalgal components illustrated in Table 3. The main components of other primary food ingredient sources are shown for comparison. The key points to note in Table 8, largely confirming Burtin's overview and the indications given by Morris (2010, see Figure 5) are:

- Protein levels are low for all macroalgal divisions compared with other types of feed ingredient (except perhaps basic soyabean), with some of the red algae offering the highest levels
- Lipid levels are also very low in terms of being a readily extractable component, although some of the brown macroalgae have slightly higher levels of lipid
- Carbohydrate levels are generally very high, and would be the 'bulk' component of milled seaweed products. This bulk might cause challenges for finfish feed formulators.

[66] http://ejeafche.uvigo.es/component/option,com_docman/task,doc_view/gid,208/

Table 3. Composition of a range of macroalgae species

		COMPOSITION as % Dry Weight		
Division	Species	Protein	Lipid	Carbohydrate
Brown	*Ascophyllum nodosum*	5	5	57
Brown	*Sargassum ilicifolium*	23.3	34.9	41.9
Brown	*S. polycustum*	33.3	24.4	42.2
Brown	*Dictyota bartayresiana*	25.0	10.4	64.6
Brown	*Fucus spp*	36.4	22.7	40.9
Brown	*Padina gymnospora*	27.1	4.2	68.8
Brown	*Egregia menziesli*	-	0.9	-
Brown	*Laminaria*	7.0	2.2	-
Brown	*Dictyota dichotoma*	9.0	1.3	16.0
Brown	*Padina pavonica*	12.0	1.3	15.0
Brown	*Turbinaria ornata*	13.0	1.5	17.0
Green	*Chaetomorpha spp*	28.6	14.3	57.1
Green	*Cladophora fascicularis*	36.5	6.1	57.4
Green	*Ulva lactuca Linn*	40.4	1.0	58.6
Green	*Caulerpa racemosa*	34.1	2.2	63.7
Green	*Caulerpa seertulariodes*	42.5	0.9	56.6
Green	*Valoniopsis pachynema*	34.9	0.9	64.2
Green	*Ulva reticulata*	8.5	1.7	50.2
Green	*Eneteromorpha intestinalis*	13.8	0.1	52.1
Green	*Eneteromorpha intestinalis*	5.2	0.1	57.0
Green	*Eneteromorpha intestinalis*	9.6	0.2	42.4
Green	*Eneteromorpha intestinalis*	12.8	0.3	33.5
Green	*Eneteromorpha intestinalis*	7.5	0.1	48.4
Green	*Eneteromorpha intestinalis*	11.4	0.2	38.5
Green	*Ulva lactuca*	11.6	0.4	45.8
Green	*Ulva lactuca*	6.9	0.3	48.3
Green	*Ulva lactuca*	8.3	0.7	43.8
Green	*Ulva lactuca*	11.0	1.1	24.3
Green	*Ulva lactuca*	7.9	0.5	42.0
Green	*Ulva lactuca*	9.8	0.7	38.7
Green	*Eneteromorpha intestinalis*	-	6.0	-
Green	*Eneteromorpha intestinalis*	-	2.5	-
Green	*Eneteromorpha intestinalis*	9.4	3.5	29.0
Green	*Eneteromorpha intestinalis*	20.6	4.4	40.0
Green	*Eneteromorpha intestinalis*	11.0	2.9	-
Green	*Ulva lobata*	-	2.0	-
Green	*Derbesia spp*	33.0	8.0	-
Green	*Cladophora spp*	11.0	3.0	-
Green	*Ulva lactuca*	15.0	2.0	-
Green	*Enteromorpha spp*	6.0	-	-
Green	*Ulva*	21.0	6.0	-
Green	*Enteromorpha compressa*	12.0	0.8	17.0
Green	*Ulva reticulata*	13.0	1.4	15.0
Green	*Cladophora glomerata*	20.0	1.2	14.0
Green	*Halimeda macroloba*	28.0	0.2	17.0
Green	*Halimeda tuna*	23.0	3.5	17.0
Green	*Ulva reticulata*	25.0	-	21.0
Green	*Chaetomorpha crassa*	13.0	-	16.0
Red	*Porphyra necnamessis*	48.3	0.3	51.4
Red	*Scinaia farcellata*	61.2	0.5	38.3
Red	*Champia compressa*	58.7	0.5	40.8
Red	*Porphyra spp*	40.4	0.7	58.8
Red	*Liagora erecta*	45.7	0.5	53.8
Red	*Acanthophora delilei*	54.2	0.7	45.1
Red	*Soliera robusta*	53.7	0.3	46.0
Red	*Catanella repens*	14.2	0.1	33.7
Red	*Catanella repens*	4.2	0.2	26.4
Red	*Catanella repens*	10.3	0.3	28.6
Red	*Catanella repens*	12.2	0.2	21.7
Red	*Catanella repens*	4.6	0.2	29.0
Red	*Catanella repens*	11.5	0.2	23.6
Red	*Chondracanthus canaliculatus*	-	0.2	-
Red	*Gracilaria sp*	16.0	2.0	-
Red	*Hypnea spp*	18.0	1.0	-
Red	*Gracilaria cylindrica*	11.0	2.0	-
Red	*Gracilaria*	15.0	4.0	-
Red	*Porphyra spp*	-	0.8	-
Red	*Gelidiella acerosa*	30.0	1.8	16.0
Red	*Gracilaria crassa*	15.0	1.9	16.0
Red	*Hypnea musciformis*	14.0	1.2	-
Red	*Gracilaria crassa*	13.0	-	33.0
Red	*Eucheuma denticulatum*	8.0	-	24.0
Brown	**Average**	**19**	**10**	**40**
Green	**Average**	**18**	**2**	**40**
Red	**Average**	**25**	**1**	**34**
Meat		**43**	**34**	**1**
Fish		**55**	**38**	**0**
Fish Meal		**66**	**8**	**0**
Soyabean		**37**	**20**	**30**
Egg		**49**	**45**	**3**

Main Source Material[67]

[67] http://ejeafche.uvigo.es/component/option,com_docman/task,doc_view/gid,616/, http://ir.lib.sfu.ca/bitstream/1892/5999/1/b14306049.pdf
http://scialert.net/fulltext/?doi=ajb.2008.26.31, http://www.arramara.ie/technical.asp,.,,
http://www.google.co.uk/url?sa=t&source=web&cd=3&sqi=2&ved=0CC4QFjAC&url=http%3A%2F%2Fwww.vliz.be%2Fimisdocs%2Fpubl

4.13 The brown alga *Chorda filum* is relatively well distributed around the coasts of the UK, and especially in Scotland. A related species, *C. tomentosa*, found off the coast of Spitsbergen, has a relatively high lipid content at 8.6% of dry weight[68], quite a lot higher than most other macroalgae in northern waters. It would be interesting to ascertain whether the Scottish species has a similarly high lipid level. It is not one of the species being investigated for macroalgal bio-fuel production in Scotland[69].

4.2.3 Fatty Acid Composition of Macroalgae Lipids

4.14 Although the cost-effective extraction of lipids from raw materials with relatively low lipid contents is a technical and commercial challenge (Section 5), the issue of global supply of marine-originated n-3 HUFA rich lipids is so pressing (Section 3) that it is appropriate to consider the composition of macroalgae lipids: new developments or use of by-products *might* make these a potential source in the future.

4.15 It is interesting to consider the species of algae most likely to contain enough lipid to make extraction hypothetically feasible. Table 3 clearly shows that two species of *Sargassum* and at least one of the fucoids contain relatively high lipid quantities compared with most macroalgae. Figure 6 illustrates the fatty acid composition of *Sargassum marginatum*. It is interesting to note that:

- There is a small amount of EPA 20:5 n-3 (c. 1.5%)
- There is no detectable DHA 22:6 n-3

4.16 Some arctic and Antarctic species of macroalgae do appear to have some DHA[70].

Table 2 — Fatty acid composition (% wt of total fatty acids) and different lipid classes of *Sargassum marginatum*

Fatty Acid	*S. marginatum*[*]			
	TL	NL	GL	PL
12:0	0.12	0.34	bd	bd
14:0	6.18	5.73	6.25	4.45
15:0	0.45	0.56	0.40	0.37
16:0	43.76	38.10	47.99	33.43
18:0	0.62	1.31	0.64	1.08
19:0	0.84	0.64	0.60	0.71
20:0	0.25	0.35	0.19	0.34
22:0	0.30	0.22	0.40	0.29
Total SFAs	*52.52*	*47.25*	*56.47*	*40.67*
16:1 n-7	8.28	8.51	8.45	5.86
18:1 n-9	9.50	6.99	10.81	9.95
18:1 n-7	0.66	0.60	0.53	1.22
18:1 n-5	0.71	0.64	0.49	1.54
20:1 n-11	0.45	0.35	0.30	1.16
22:1 n-11/n-13	0.65	0.20	0.98	0.52
24:1 n-9	0.42	1.38	0.26	0.57
Total MUFAs	*20.67*	*18.67*	*21.82*	*20.82*
16:2 n-4	1.09	0.58	1.43	0.45
16:3 n-4	0.70	0.40	0.78	0.68
18:2 n-6	4.90	4.45	4.77	6.43
18:3 n-3	2.14	2.16	2.44	1.13
18:4 n-3	1.11	1.12	1.30	0.20
20:2 n-6	0.27	0.24	0.17	0.76
20:3 n-6	0.84	0.94	0.47	2.20
20:4 n-6	7.76	9.34	4.62	16.62
20:3 n-3	bd	bd	bd	bd
20:4 n-3	0.30	0.47	0.25	0.48
20:5 n-3	1.52	1.54	1.63	1.03
22:6 n-3	bd	bd	bd	bd
20:2 NMI[#]	0.91	0.87	0.51	2.62
Total PUFAs	*21.54*	*22.11*	*18.37*	*32.60*
Un-identified	5.27	11.97	3.30	5.81

NL = Neutral lipids; GL = Glycolipids; PL = Phospholipids; [*]: n = 5; All values are the mean of 5 individual samples; bd = below detection level (<0.1%). SFAs = saturated fatty acids; MUFAs = Mono unsaturated fatty acids; PUFAs = Poly unsaturated fatty acids. [#]NMI = non-methylene interrupted fatty acid.

Figure 6. Fatty Acid Analysis of *Sargassum marginatum*. Source[71]

ications%2F40680.pdf&rct=j&q=lipid%20content%20of%20macro%20algae&ei=NJ9ATZnxLsPChAehtYHpCA&usg=AFQjCNEJjwXctj-h13mP6YVyAkFXmq1VNQ&cad=rja, http://www.idosi.org/ajbas/ajbas1%285-6%2909/3.pdf, http://www.idosi.org/mejsr/mejsr4%282%29/4.pdf, http://www.iopan.gda.pl/oceanologia/37_2.html, http://www.iopan.gda.pl/oceanologia/421Haroo.pdf, http://www.sblimno.org.br/acta/my_web_sites/acta_limnologica_contents1703E_files/Art01_17%283%29.pdf http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6WJH-4CC7T3X-3&_user=10&_coverDate=02%2F28%2F2005&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1621028718&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=8f7c602ebdc9b35c8b4952a2a9e73cb4&searchtype=a, http://www.scribd.com/doc/30333304/Oilgae-Guide-to-Fuels-From-Macro-Algae, http://www.sudevab.eu/filestrg/publications/galway/courtois_macroalgae-sustainable-diets.pdf

[68] http://www.google.co.uk/url?sa=t&source=web&cd=1&ved=0CB0QFjAA&url=http%3A%2F%2Fwww.polarresearch.net%2Findex.php%2Fpolar%2Farticle%2Fdownload%2F6923%2F7756&rct=j&q=lipid%20content%20of%20chorda%20filum&ei=hYHBTaGOAcy18QPuxrG5BQ&usg=AFQjCNHLr01IF9ZoGgYLH4zd2ApdoU_mYg&cad=rja

[69] http://www.biomara.org/

[70] http://epic.awi.de/Publications/Gra2002c.pdf

[71] http://nopr.niscair.res.in/bitstream/123456789/1690/1/IJMS%2033%284%29%20355-360.pdf

4.17 Table 4 presents an overview of some of the key fatty acids in a range of macroalgal species, and Figure 7 shows a summary of this by macroalgal division.

Table 4. Key fatty acids in several macroalgae.

		% of Total Fatty Acids			
Division	Species	18:3 n-3	20:4 n-6	20:5 n-3	22:6 n-3
Brown	*Egregia menziesii*	7.625	-	4.575	-
Brown	*Laminaria saccharina*	3.6	13.7	6.2	-
Brown	*Laminaria digitata*	7.9	8	8.3	-
Brown	*Fucus vesiculosis*	5.2	8.7	4.7	-
Brown	*Undaria pinnatifida*	10.3	17.5	8.2	-
Brown	*Halidrys siliquosa*	5.8	11.5	3.6	-
Brown	*Analipus japonicus*	7.6	13.8	13.2	-
Brown	*Laminaria dentigera*	4.1	9.5	10.4	-
Brown	*Hedophyllum sessile*	2.1	9.6	3.1	-
Brown	*Macrocystis integrifolia*	6.5	14.3	8.7	-
Brown	*Postelsia palmaeformis*	5.9	7.9	7.2	-
Brown	*Alaria marginata*	8.7	14.2	15.5	-
Brown	*Egregia menziesii*	8.7	14.7	9.9	-
Brown	*Fucus distichus*	7.5	14.1	10.9	-
Brown	*Cystoseira osmundacea*	9.7	18.6	5.5	-
Green	*Ulva lobata*	21.7	0.625	0.775	0.15
Green	*Ulva rotundata*	9.6	0.3	1	-
Green	*Enteromorpha intestinalis*	15.5	0.7	1	-
Green	*Ulva lactuca*	11.1	0.3	1	-
Green	*Enteromorpha compressa*	21.9	0.5	1.4	-
Green	*Chaetomorpha linum*	0.5	1.2	1.3	-
Red	*Chondracanthus canaliculatus*	0.675	-	18.875	-
Red	*Porphyra umbilicatus*	0.2	10.9	48	-
Red	*Chondrus crispus*	1.1	22.5	18.7	0.3
Red	*Palmaria Palmata*	1	1.4	46.6	0.5
Red	*Gracilaria verrucosa*	0.5	5.3	25.8	0.2
Red	*Prionitis linearis*	0.2	23.4	27.8	-
Red	*Prionitis lanceolata*	0.2	19.8	32.2	-
Red	*Iridaea cordata*	0.2	5.3	45.4	-
Red	*Gigartina harveyana*	0.2	10.4	37.2	-
Red	*Plocamium violaceum*	0.5	8.2	37.2	-
Red	*Odonthalia floccosa*	0.2	14.8	31.6	-
Red	*Cryptopleura violaceae*	0.2	19.4	32.5	-

Main Source Material: [72]

[72] http://www.reference-global.com/doi/abs/10.1515/BOT.2002.007, http://www.springerlink.com/content/r26245415280k186/, http://www.vliz.be/imisdocs/publications/40667.pdf

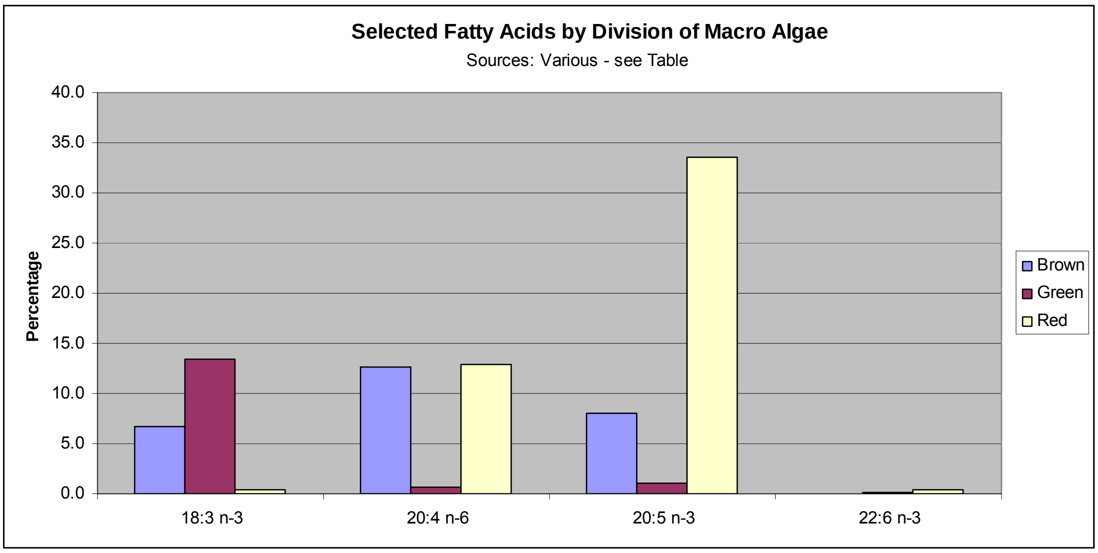

Figure 7. Selected fatty acids by division of macroalgae.

4.3 Microalgae

4.3.1 Overview of Microalgae

4.18 Microalgae include an extensive range of single-celled phototrophic or heterotrophic organisms[73]. Traditionally microalgae are thought of as 'phytoplankton' in oceanic food chains and webs, and also in freshwater systems[74]. Among the common kinds are cyanobacteria, silica-encased diatoms, dinoflagellates, green algae, and chalk-coated coccolithophores.

4.19 Just as macroalgae have been utilised by humans for many years, first through wild harvesting but latterly through artificial cultivation (mainly in Asia), so to have some species of microalgae. Early attempts to artificially enhance marine fisheries through release of juveniles from land-based hatcheries commenced around the end of the 19th Century[75], and it was soon realised that to feed the delicate finfish larvae once their yolk sac had been absorbed, an 'artificial' plankton system would have to be created in the rearing tanks. This required primary producers – the phytoplankton – as food for the herbivores – the zooplankton – which the fish larvae could ingest and digest. This was the start of a long history of developing techniques for cultivating different species of microalgae in laboratories and hatcheries.

4.20 In a parallel development, efforts to artificially grow the juvenile stages of several species of bivalve molluscs also started many years ago[76], and these shellfish hatcheries also required cultured microalgae – although for direct ingestion by the main reared species in this case.

4.21 The main point to emphasise is that whilst macroalgae cultivation was developed on a large scale in Asia, and has been relatively little practised or understood in other parts of the world, there is a very long tradition of growing microalgae in culture in countries such as the United Kingdom, the United States of America (USA), France, Norway and more recently

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[73] See for example: http://rsif.royalsocietypublishing.org/content/7/46/703.full and http://www.oilgae.com/ref/glos/microalgae.html (which also links to a useful glossary of terms that are relevant to this entire study)
[74] http://www.sciencedaily.com/articles/p/phytoplankton.htm
[75] See http://icesjms.oxfordjournals.org/content/28/1/50.extract for a good history of marine larval rearing
[76] http://www.oysterhatchery.com/

Greece, Spain, Turkey and many other countries. The scale of cultivation is sometimes very large[77], and the microalgae produced has to be carefully defined in terms of its nutritional value, but also in terms of its cost. Algae rearing is one of the largest costs in a shellfish hatchery[78]. These points are stressed because it is important to note that:

- There is a good level of knowledge about microalgae composition, and its nutritional value, either for direct consumption by herbivorous shellfish or via the intermediary step of cultured zooplankton animals
- There is a good level of knowledge about the best and most effective ways to culture large volumes of microalgae
- There is a very good understanding of how much it costs to produce microalgae in different systems (discussed in more detail in section 5).

4.22 This section focuses on the composition of microalgae, and its possible uses as components in salmonid finfish diets. It is important to note that all microalgae used for other purposes is 'cultivated' in one way or another, and that **different culture conditions** can substantially modify the final chemical composition of the harvested microalgae[79]. The same may prove to be increasingly true for cultivated macroalgae, although the potential for operator-intervention in growing conditions would seem to be more limited in open-sea cultivation, which is the most likely route for macroalgae. For the microalgae, this aspect of culture conditions is inherently taken into account in the information presented in the remainder of this section.

4.3.2 Proximal Composition of Microalgae

4.23 This is a very wide field, however, there are two important observations about microalgae that can be introduced at this early stage:

- In the case of some species the **protein** content of the harvested microalgae can be very high, whether on a wet or a dry weight basis. The best example is *Spirulina*, which can have a protein content of **55-70%** of the 'dried' powder[80]
- In the case of other species, growth can be undertaken in such a way that the final **lipid** content is very high, "up to **60%** by weight"[81]

4.24 Both of these classes of nutritional component are potentially important when considering algal raw materials for aquaculture finfish diets:

- If the protein content is high, and the indigestible 'bulk' rather low, then this opens up the prospect for inclusion in salmonid diets – provided the protein is sufficiently digestible, and priced correctly, taking into account production and drying costs
- Lipid has already been identified as a globally limiting factor for aquaculture finfish feeds, and high levels of lipid in the harvested microalgae suggest that, just as with fish oils and vegetable oils, it might be possible to extract the lipid cost-effectively – at least in terms of the manufacturing process itself. The cost of growing the microalgae and getting it to the lipid extraction facility, and the nutritional value of the lipids, are matters that also have to be taken into consideration.

4.25 Information from a wide range of literature sources has been collated, and is presented in a consistent format in Table 5. There are some important points to note about the table:

[77] http://www.innovativeaqua.com/Publication/clam.pdf
[78] http://www.cefas.co.uk/publications/techrep/tech122.pdf
[79] See for example: http://www.scottglynn.com/1997%20Kilham%20et%20al%20Freshwat%20Biol%2038%283%29%20591-596.pdf, but there are many references
[80] http://www.nbent.com/nutritio.htm. Note that 'dried' Spirulina powder actually has some 6% remaining water content.
[81] http://www.fuelandfiber.com/Athena/biodiesel_from_algae_es.pdf

- Some of the references provide a range of values for protein, lipid or carbohydrate
- These have been numerically averaged to give a single number for use in the table
- In many cases the range is relatively limited
- **In the cases where the range is quite wide, the cells in the table have been highlighted with a yellow shade.**

4.26 The issue of range of possible component percentages is important in light of the reference to variability depending upon culture conditions, as previously noted. Some species of microalgae appear to have good potential to achieve high protein contents, and others have good potential to achieve high lipid contents.

4.27 A comparison between the potential of micro and macroalgae to provide suitable materials for finfish diets is considered in section 4.4

Table 15. Proximal analysis of a range of microalgae.

	COMPOSITION as % Dry Weight		
Species	Protein	Lipid	Carbohydrate
Chaetoceros calcitrans	34	16	6
Chaetoceros gracilis	12	7.2	4.7
Nitzchia closterium	26	13	9.8
Phaeodactylumtricornutum	30	14	8.4
Skeletonema costatum	25	10	4.6
Thalassiosira pseudonana	34	19	8.8
Dunaliella tertiolecta	20	15	12.2
Nannochloris atomus	30	21	23
Chroomonas salina	29	12	9.1
Nannochloropsis oculata	35	18	7.8
Tetraselmis chui	31	17	12.1
Tetraselmis suecica	31	10	10
Isochrysis galbana	29	23	12.9
Isochrysis aff. Galbana (T-iso)	23	20	6
Pavlova lutheri	29	12	9
Pavlova salina	26	12	7.4
Ankistrodesmus TR-87		34	
Botryococcus braunii		52	
Chlorella sp.		29	
Chlorella protothecoides		35	
Cyclotella DI		39	
Dunaliella tertiolecta		39	
Hantzschia		66	
Nannochloris		31	
Nannochloropsis		49	
Nitzschia TR-114		39	
Phaeodactylum tricornutum		31	
Scenedesmus TR-84		45	
Stichococcus 33		33	
Tetraselmis suecica 15-32		23	
Thalassiosira pseudonana		26	
Crpthecodinium cohnii		20	
Neochloris oleoabundans		45	
Schiochytrium		64	
Scenedesmus obliquus	53	13	13
Scenedesmus quadricauda	47	1.9	
Scenedesmus dimorphus	13	28	37
Chlamydomonas rheinhardii	48	21	17
Chlorella vulgaris	55	18	15
Chlorella pyrenoidosa	57	2	26
Spirogyra sp.	13	16	52

	COMPOSITION as % Dry Weight		
Species	Protein	Lipid (Avg)	Carbohydrate
Dunaliella bioculata	49	8	4
Dunaliella salina	57	6	32
Euglena gracilis	50	17	16
Prymnesium parvum	36	30	29
Tetraselmis maculata	52	3	15
Porphyridium cruentum	33	11	48
Spirulina platensis	55	6	11
Spirulina maxima	66	7	15
Synechoccus sp	63	11	15
Anabaena cylindrica	49	5	27
Anabaena cylindrica	49	5	27
Chlamydomonas rheinhardii	48	21	17
Chlorella vulgaris	55	18	14
Chlorella pyrenoidosa	57	2	26
Dunaliela salina	57	6	32
Euglena gracilis	50	17	16
Porphyridium cruentum	33	12	48
Scenedesmus obliquus	53	13	13
Arthrospira maxima	66	6	14
Spirulina platensis	54	6	12
Spirogyra sp.	13	16	48
Synechoccus sp	73	11	15
Tetraselmis suecica	41		
Isochrysis galbana	39		
Dunaliella tertiolecta	54		
Chlorella stigmatophora	39		
Micro Algae Average	**41**	**20**	**18**
Meat	**43**	**34**	**1**
Fish	**55**	**38**	**0**
Fish Meal	**66**	**8**	**0**
Soyabean	**37**	**20**	**30**
Egg	**49**	**45**	**3**

Main Source Material [82]

4.3.3 *Fatty Acid Composition of Microalgae Lipids*

4.28 As with the consideration of macroalgae, the primary focus for microalgae remains the quantity, cost and nutritional suitability of the lipid fraction. Fatty acid profiles are very much subject to modifications in the culture conditions[83]. Limitations in nitrogen availability near

[82] http://www.fao.org/docrep/003/w3732e/w3732e06.htm, http://www.oilgae.com/algae/oil/yield/yield.html, http://www.oilgae.com/algae/comp/comp.html, http://www.algae4feed.org/brief/microalgae-in-feeds/57

[83] http://www.obs-vlfr.fr/~claustre/fichiers%20PDF/Mayzaud_et_al_MEPS_90.pdf

the end of the production cycle, for example, can enhance the production of lipids, and particularly long chain n-3 HUFA, in some species[84]. On the other hand, limitations of nitrogen earlier on in the cycle can inhibit algal cell growth and therefore overall productivity.

4.29 Table 6 presents an overview of some of the key fatty acids in a range of cultured microalgae. As with the macroalgae, the focus is on 4 main fatty acids: 18:3 n-3; 20:4 n-6; 20:5 n-3 and 22:6 n-3. The source references generally provide the full fatty acid profiles, and these should be accessed by readers who require a wider understanding of what the particular microalgae contains. There are many literature sources that can be examined on this subject[85].

Table 6. Fatty acid composition of a range of microalgae.

	% of Total Fatty Acids			
Species	**18:3 n-3**	**20:4 n-6**	**20:5 n-3**	**22:6 n-3**
Nitzschia ovalis	0.37	4.4	26.67	4.2
Thalassiosira sp	1.1	0.12	16.65	1.33
Tetraselmis sp	16.17	0.99	4.7	-
Dictyospaerium pulchelum	26.49	-	-	-
Stichococcus sp	25.71	-	-	-
Chlorella sp	20.02	-	-	-
Scenedesmus sp	20.79	-	-	-
Anacystis sp	23.18	-	-	-
Synechococcus sp	-	-	-	-
Synechocystis sp	-	-	-	-
Chlorella MFD-1 15 C	27.45	-	-	-
Chlorella MFD-1 20 C	21.6	-	-	0.15
Chlorella MFD-1 25 C	14.6	-	1.1	0.3
Chlorella MFD-1 30 C	18.05	-	-	-
Chlorella MFD-1 35 C	18	-	-	-
Pavlova lutheri (TAG)	0.14	-	8.42	3.31
Biddulphia aurica	-		26	-
Chaetocerus sp	0.5	4.1	8	1
Nannochloropsis sp	0.7	-	34.9	-
Monodus sp	-	-	37.1	-
Chlorella sp	23	-	-	-
Chlorella vulgaris	10	-	-	-
Parietochloris incisa	1	58.9	-	-
Emiliania huxleyi	7	-	-	11
Isochrysis galbana	-	-	5	14
Phaeomonas parva	-	2.9	56	11
Glossomastrix sp	-	5.5	39.2	-
Aphanocapia sp	-	-	-	-
Spirulina platensis	-	-	-	-
Trichodesmium sp	12	-	-	-
Hemiselmis rufescens	11	-	11	-
Rhodomonas sp	16	-	13	-
Gymnodinium sanguieum	0.3	0.5	14.1	24.2
Scrippsiella sp	0.2	-	1.8	18.8
Schizochytrium limacinum	2.72	-	3.55	21.23

Main Source Material[86]

[84] http://www.aseanbiodiversity.info/Abstract/51012084.pdf
[85] http://www.ncbi.nlm.nih.gov/pubmed/11767135, http://www.begellhouse.com/journals/7dd4467e7de5b7ef,6f0b90b03ae39b76,6634da8a2c95512d.html, http://onlinelibrary.wiley.com/doi/10.1002/bit.22809/abstract, http://pubs.acs.org/doi/abs/10.1021/jf200910p, http://onlinelibrary.wiley.com/doi/10.1002/bit.22809/full, http://www.mendeley.com/research/fatty-acid-composition-14-strains-marine-microalgae/,
[86] **:** http://www.rdoapp.psu.ac.th/html/sjst/journal/27-6/06-microalgal-species.pdf, http://www.cib.espol.edu.ec/Digipath/D_Papers/CC1007.pdf, http://www.esb.ucp.pt/twt/CBQF/MyFiles/MeusDocumentos/ArtigosCientificos/2003, http://www.tamu.edu/faculty/tpd8/BICH407/algaltriglycerides.pdf, http://ddr.nal.usda.gov/bitstream/10113/16569/1/IND44071542.pdf

4.4 Other Components of Macro and Microalgae

4.30 The major focus in section 4 thus far has been on overall **proximal analysis**, and on **fatty acid composition** of the lipids of macro and microalgae. The first gives a general indication if there is any chance of being able to use the dried product in aquaculture finfish feeds (or extract its lipids effectively), and the second gives an insight into how valuable the lipids (if they could be extracted) would be in terms of the current limitations of n-3 HUFA rich lipids.

4.31 There are many other 'nutritional components' in any raw material, and these are discussed in brief below in relation to macro and microalgae. It is important to stress that our research has not discovered the confirmed existence of any 'micro' nutrient or similar in macro or microalgae that is:

- Not already known about on the part of the feed companies, whether they choose to use them or not
- Not yet accepted by the feed companies because they either believe the evidence for use is not sufficiently compelling, or because they have concerns about indigestible bulk, or because the products are too expensive.

The issue of products that are currently being promoted for use in aquaculture finfish feeds is covered elsewhere in this report.

4.4.1 Proteins

4.32 Algal proteins appear to vary considerably in terms of digestibility when fed experimentally to animals[87], with protein efficiency ratios[88] (PER) ranging from 0.68 to 1.98 for *Chlorella* material – which compares with a PER of around 2.15 for heated soybean meal and 2.5 for casein. Current research in this area is underway to see if algal proteins can be produced and used effectively[89], although unfortunately one of the key laboratories contacted directly for this study did not respond. One commonly used algal product is dried *Spirulina*, which as a PER of between 1.8 and 2.6[90], and it is not unreasonable to assume that other microalgae, when cultured in the right way and prepared appropriately, would have similarly high levels of digestibility.

4.33 The amino acid composition of some algae is presented in Figure 8, in comparison with other protein sources[91]. The ability of feed formulators to either blend other protein sources[92] or to balance amino acids more directly should ensure that if an algal meal with the right overall amount of protein were available, at the right price, its possible use in aquaculture finfish diets should not be ruled out.

[87] See for example http://jn.nutrition.org/content/95/3/374.full.pdf and http://jn.nutrition.org/content/105/6/688.full.pdf
[88] PER = gain in body mass/protein intake
[89] http://www.nutraingredients.com/Product-Categories/Nutritional-lipids-and-oils/TNO-to-explore-meat-alternatives-and-oils-from-algae
[90] http://www.antenna.ch/en/documents/AspectNut_UK.pdf
[91] http://www.algae4feed.org/brief/microalgae-in-feeds/57
[92] http://www.antenna.ch/en/documents/AspectNut_UK.pdf

	Leu	Val	Arg	Lys	Ile	Phe	Thr	Met	Try	His
WHO/FAO	7	5		5,5	4	6,0		3,50	1	
Egg	**8,8**	**7,2**	6,2	5,3	**6,6**	**5,8**	**5**	**3,2**	**1,7**	2,4
Meat	7,8	5,3	6,6	**8,2**	5,1	4,2	4,5	2,4		**3,2**
Milk	9,2	5,7	3,3	7,8	4,3	5,6	4,5	2,5		2,6
Soybean	7,7	5,3	**7,4**	6,4	5,3	5	4	1,3	1,4	2,6
Fish-meal	4,48	2,77	3,82	4,72	2,66	4,35	2,31	2,31	0,57	1,45
Chlorella vulgaris	8,8	5,5	6,4	8,4	3,8	5	4,8	2,2	**2,1**	2
Dunaliella bardawil	11	5,8	7,3	7	4,2	5,8	5,4	2,3	0,7	1,8
Scenedesmus obliquus	7,3	6	7,1	5,6	3,6	4,8	5,1	1,5	0,3	2,1
Arthrospira maxima	8	6,5	6,5	4,6	6	4,9	4,6	1,4	1,4	1,8
Spirulina platensis	9,8	**7,1**	7,3	4,8	**6,7**	5,3	**6,2**	**2,5**	0,3	2,2
Tetraselmis suecica	9,3	5,6	7,6	9,8	4,1	5,9	5,3	1,5		**2,5**
Isochrysis galbana	10,5	6	**8,7**	12,1	4,9	6,1	6,1	0,7		**2,5**
Dunaliela tertiolecta	**10,7**	5,3	7,2	**13,6**	4,2	**6,6**	2,6	0,8		**2,5**
Chlorella stigmatophora	9,3	5,7	8,6	13,4	3,8	5,5	4,9	1,4		2,3

Figure 8. Amino acids in some algae.

4.4.2 Pigments

4.34 The requirement for carotenoid pigments in salmonid diets is well understood, and these can be sourced in various ways. Interest has been growing in the use of natural pigments produced by various species of algae[93], and commercial products are available[94] on the international market, based on the microalga *Haematococcus pluvialis*[95]. It is a matter for the UK feed manufacturers to decide whether or not to use pigments sourced from algae, and perhaps in the future they will do so.

4.4.3 Vitamins and Minerals

4.35 There are many sources of information about using algae as a rich source of vitamins and minerals, and there are many commercial products on the human health foods market[96]. These products all appear to be dried and milled whole algae, and once again the question of the indigestible 'bulk' that carries these micro nutrients becomes an issue for salmonid feed manufacturers. Future use of algal-sourced micro nutrients in the sector cannot be ruled out, but at the present time there is apparently no compelling need for the feed companies to turn to this source.

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[93] See for example: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6T4D-49NPH0M-44&_user=10&_coverDate=10%2F31%2F1979&_rdoc=1&_fmt=high&_orig=gateway&_origin=gateway&_sort=d&_docanchor=&view=c&_searchStrId=1735002826&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=ed229efd7a72e284faf5933b92042299&searchtype=a and http://www.incropsproject.co.uk/documents/Events/AlgaeOct09/Smith%20Algal%20prods%20Oct09%20secured.pdf

[94] http://www.cyanotech.com/

[95] http://www.brineshrimpdirect.com/Natural-Astaxanthin-c84.html

[96] See for example: http://www.naturalhealthontheweb.com/seaweed/kelp.html

4.4.4 Other Materials – 'Bioactive Compounds'

4.36 There is a relatively large amount of literature about the beneficial aspects of a range of other ingredients found in algae – generally those contained within the complex 'carbohydrates' fraction of the algae. Holdt and Kraan (2011)[97] provide a comprehensive review of the whole subject[98]. Some work has been done on possible 'natural anti-oxidants' that could be obtained from macroalgae[99]. In terms of the objectives of this study, our research has not identified a specific new ingredient that might be applied to the aquaculture finfish feeds sector as a 'major-inclusion' component of the formulation. However, research on the possible future value and inclusion of bioactive compounds should be kept under review by the feed manufacturers. Referring back to the Scottish feed trial (section 3.9), use of these products would be facilitated by their being available as extracted or refined materials.

4.5 Summary

4.37 Section 4 has presented a concise assessment of what is an extremely broad and very diverse subject: the chemical composition and possible nutritional values of all types of algae. It has tended to focus on the two key aspects in terms of possible commercial utilisation, for the reasons already outlined:

- The overall amounts of protein, lipid (and carbohydrate) in different types of algae
- The fatty acid composition of the algal lipids.

4.38 The main summary points from section 4 are:

- **There is a large variation in both the proximal makeup and the fatty acid makeup of algae, whether macro or micro. On that basis, it is impossible to rule out the future use of algae of either type as a source of components for aquaculture finfish feeds**

- **The composition of algae various considerably within a single species, depending upon environmental conditions – often culture conditions in the case of microalgae**

- **The implication is that culture conditions, for the best species, could be enhanced for the purposes of producing a nutritional component for future use in aquaculture finfish feeds, particularly considering that:**
    - o **Whilst algal proteins might need some blending with other sources, or amino-balancing in some other way, some of them appear to be of interest for animal feed formulations**
    - o **Fatty acids are basic nutritional building blocks, and for those that are required in finfish diets, whether they are sourced from marine animals or from algae is relatively unimportant, as long as the cost is competitive**

- **In theory the possibility of optimising culture conditions for certain selected species could apply to macroalgae as well as microalgae**

- **However:**

[97] Op cit reference 52.
[98] http://www.springerlink.com/content/x2xj34726k636p58/fulltext.pdf
[99] http://skemman.is/stream/get/1946/4139/11867/1/Final_fixed.pdf

- **It is likely to be more difficult to control culture conditions in the locations that macroalgae will be cultivated – although perhaps selection of the best strains could have a positive effect**
- **The average protein level in a macro alga species (as found in our literature review) is around 18-25% of dry matter, as compared with 41% for all the microalgal species considered**
- **The average lipid level in macroalgae is only 1 or 2% of dry matter in the red and green algae, and 10% in the brown algae although only c.2% in the species being cultivated. The average across all the microalgae is 20%**
- **There are some 18:3 n-3; 20:4 n-6 and 20:5 n-3 fatty acids in both macro and microalgae – although very much dependent upon species, and generally at a low level in the macroalgae. However, there is little evidence of much 22:6 n-3 fatty acid in any macroalgae, although some microalgae contain very high amounts of it**
- **Species with much higher levels of protein or lipid exist in both types of algae – but there would appear to be more chance of finding high-yielding candidates within the microalgae, in terms of materials for finfish diets.**

5 ALGAL RESOURCES – CURRENT PRODUCTION AND USES

5.1 Introduction

5.1 The current to medium-term opportunities for use of algae into aquafeeds obviously depends on what is currently available in sufficient quantities through existing production industries and technologies. This section thus provides an analysis of what might be utilisable given current and medium-term technologies and products, while section 6 looks at longer term future trends.

5.2 It is important to reiterate that information provided in this section is drawn from a combination of sources, including grey literature, scientific literature, and public domain databases. The accuracy of data presented in some of the public domain sources has already been highlighted in this report, and will be commented-upon again where relevant in section 5.

5.2 Macroalgae: Global Supply and Trends – Volume and Value

5.2.1 Background

5.3 Macroalgae have been harvested from the sea for centuries. Traditional uses have been for human consumption, animal fodder and soil fertiliser, as discussed earlier. It is only in the last few decades that interest has been shown in the use of macroalgae as sources of hydrocolloids, principally agars, carrageenans and alginates, which have a wide range of applications as thickeners and stabilisers in the food and medical industries. Recent decades have also seen a general decline in harvesting from the wild and a large increase in production by farming at sea, using various long-line systems, most notably in low-cost production countries in Asia.

5.2.2 Wild sources

5.4 Fresh or stranded seaweed has been collected for the traditional uses mentioned earlier. The general decline in production is thought to be through a combination of increased opportunities for alternate sources of income in production areas, alternative sources of food and fertiliser and large-scale, low-cost farming of seaweeds in Asia, making wild harvesting, particularly in cooler northern areas, uncompetitive. Concerns over environmental impact and sustainability of the collecting fresh growing species, itself an important habitat for many other inter-tidal plants and animals, have also played a part.

5.5 Most wild harvesting has been of brown species, due to their bulk. Areas where there is still significant wild collection (i.e. over 20,000 tonnes per year) in 2009 is as follows[100]

Area	**Harvest (tonnes per annum)**	**Variety**
Chile	340,000	mostly kelp
China	275,000	n.d.
Ireland	29,000	mostly *Ascophyllum*
Japan	104,000	mostly kelp

[100] FAO, including estimates for some species or areas

5.2.3 Farmed sources

5.2.3.1 Global overview of farmed production

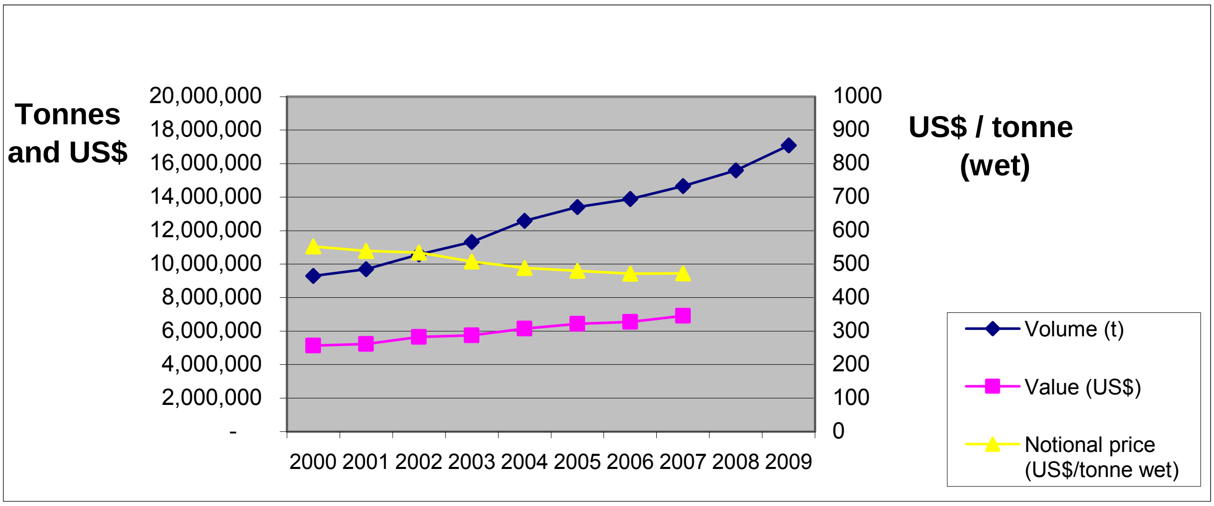


Figure 9. Total global production of farmed macroalgae

5.6 Production is climbing towards **18 million tonnes wet weight** and has almost doubled since 2000 and is over 20-fold the residual recorded collection of wild seaweeds.

5.7 Significant caution is needed in interpreting value and notional price information. This is because the FAO has sharply reduced value estimates for 2008 and 2009 downwards for some species in China. The dominant position of China as a producer impacts the global picture. The revisions are said to be based on more realistic information becoming available and confusion between reporting ex-farm and processed prices. It appears that values were over-estimated prior to 2008. Thus the recent values are omitted from the above graph and it is reasonable to assume that trends are correctly illustrated as opposed to absolute values[101]. More detailed discussion of prices is shown for each main species below.

5.2.3.2 Macroalgae farmed production by region

5.8 The following table shows the breakdown in farmed production around the world in 2009.

Table 7. Macroalgae farmed production by region

Region	2009 production (t)	Global share
Africa	113,902	0.67%
Americas	88,148	0.52%
Asia	16,890,040	98.79%
Europe	868	0.01%
Oceania	2,378	0.01%

5.9 As can be seen from the table, the vast majority of production is in Asia. The only significant production outside Asia is some red seaweed in Zanzibar, Tanzania (*Eucheuma* spp, raw material for carrageenan) and in Chile *Gracalaria* spp, raw material for agar).

[101] The study has tried to confirm the position with the government in China and with the producers association, but have not received a response

Given this position, if macroalgae is to be considered as a potential bulk ingredient to the UK aquafeeds industry, then it seems likely that the most viable source in the short-medium term will be farmed product from Asia. The rest of this review thus considers this source alone.

5.2.3.3 Macroalgae farming in Asia

5.10 Almost all farmed production in Asia is derived from red and brown macroalgae.

Red macroalgae production in Asia

5.11 Figure 10 shows the trends in production and value since 2000. Expansion in production has been rapid, roughly quadrupling over the last decade. Figure 11 shows how production is distributed across Asia.

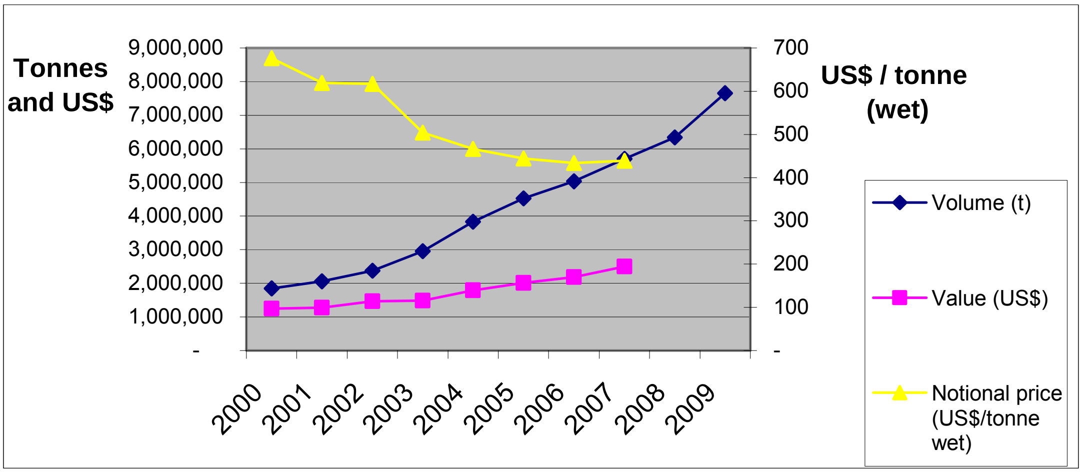


Figure 10. Total production of farmed red macroalgae in Asia

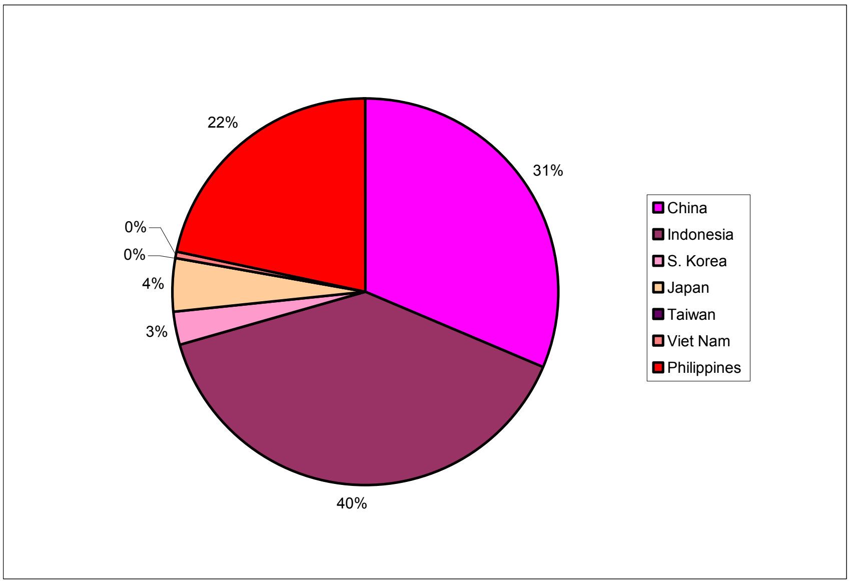


Figure 11. Distribution of farmed red macroalgae production in Asia.

5.12 Production is dominated by China, Indonesia and Philippines, which share 93% of production between them. Within this group, Indonesia has been growing production share in recent years.

Figure 12. Typical production site in the Philippines for *Kappaphycus alvarezii.*

5.13 Table 8 summarises production and uses by country for red algae in Asia.

Table 8. Farmed red macroalgae in Asia: production, uses and notional prices, 2009.

Country	Latin name	2009 prod (t)	Main use	Notional price ($ / tonne wet)
China	Eucheuma / Kappophycus spp	65,900	Carrageenan	460
	Gelidium spp	1,200	Agar	450
	Porpyra spp	1,074,750	Food	490
	Graciliaria verrucosa	1,253,520	Agar	486
S Korea	Porpyra spp	211,444	Food	667
Indonesia	Eucheuma / Kappophycus spp	2,791,688	Carrageenan	284
Philippines	Eucheuma / Kappophycus spp	1,733,806	Carrageenan	115
	Graciliaria spp	2,308	Agar	104
Japan	Porpyra spp	342,620	Food	2,250
Vietnam	Graciliaria spp	33,600	Agar	500

5.14 All species except for *Porphyra* are used for industrial use. *Porphyra* (also known as Nori) is a delicacy in Japan and much of the Chinese and Korean production is dried and exported there. Prices ex-farm are not very reliable for China and prices for the same species in other countries are considered more informative.

5.15 Most species have a wet:dry ratio of around 7:1. Industrial grade material is part-dried to save weight and bulk in transport and to prevent deterioration. At a low water content, relevant for consideration as a bulk ingredient, the indicative price for industrial species of reds is thus around $700-2,000 per tonne (dry) at first sale. This is before any milling or other process that might be necessary for ease of transport and use in aquafeeds production. Also transport costs are excluded.

5.16 Table 3 shows the nutritional profile of various macroalgae. Of the species currently available in bulk from the culture industry, *Porphyra* is potentially attractive with protein content of over 40%, but with very low fat content. However the stated wet value of between $667 (Korea) and $2,250 per tonne (Japan), taken to be more reliable than values in China, the cost dry would be in the region of $4,500 to $16,000 per tonne. This makes it prohibitive compared to costs of fish meal at some $1,700 per tonne and a higher protein content, (section 5).

5.17 *Gelidium* is only produced in small quantities in China at present. The nearest species for comparison of nutritional profile is *Gelidiella acerosa* which has a protein content of 30% and again low fat. The (possibly unreliable) indicative price at some $450 per tonne wet would indicate a dry price of some $3,000 dry, so again not an attractive proposition compared to fish meal.

5.18 *Gracalaria* has a protein content of some 15%. The Philippines price data is considered the most reliable indication and at just over $100 per tonne wet would make a dry price around $700/tonne. Milling, packing and transport is likely to add around $300-500 per tonne, so would be competing with other protein sources in Europe at roughly $1,000 per tonne. Several terrestrial plant sources offer higher protein contents at lower prices (Figure 5 and Table 7 for prices of soya, rapeseed etc).

5.19 *Eucheuma* spp, (also known as *Kappophycus*) also seems a poor prospect, although available in massive quantities. Protein content is only 8% and no data for lipids. The price at around $700 / tonne dry from FAO coincides with the team's direct observations of producer data in the Philippines around 2007. Thus with a similar or higher price structure than *Gracalaria,* this species is not attractive.

5.20 Other information on prices suggests that *Eucheuma*, and probably other seaweeds farmed in bulk, has been influenced by the general trends in all food commodity prices. Therefore even if acceptable for inclusion in aquafeeds, feed companies would have to be attuned to potential large swings in unit cost of this source. By way of example, *Eucheuma* in the Philippines moved very rapidly upwards in 2007-2008 from prices around $700 to around $2,400 per tonne dry, only to fall in the global recession to $1,200 per tonne at the start of 2010, but was already back up to $1,700 per tonne by April of that year[102]. Similar price movements are also reported from Indonesia. As with other commodities, price changes were said to be driven in part by speculative traders.

Brown Macroalgae production in Asia

5.21 Figure 13 shows the trends in brown algae production and value since 2000, and Figure 14 shows the distribution of production in Asia.

[102] Philippines Seaweed Producers Association, http://siap.com.ph/

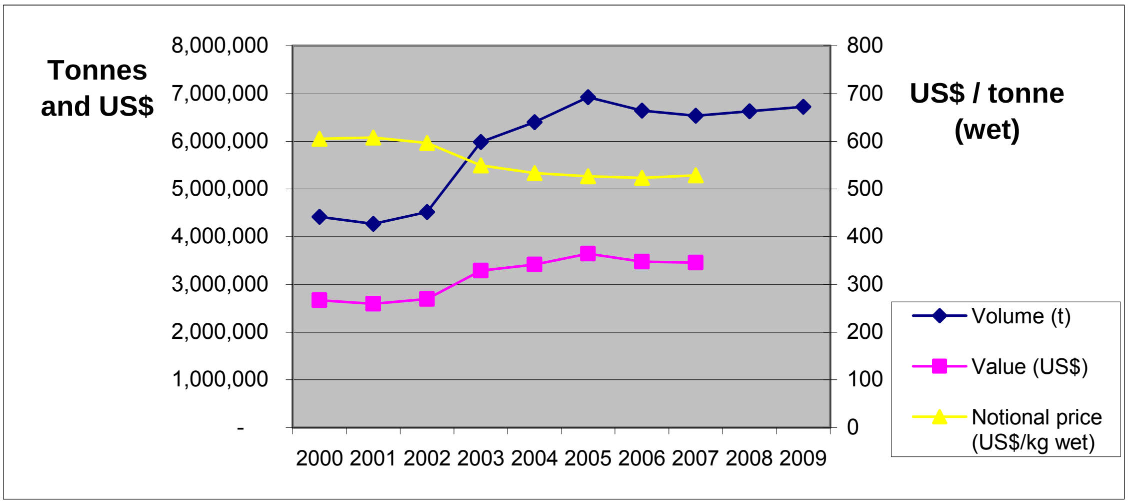


Figure 13. Total production of farmed brown macroalgae in Asia.

5.22 Production has grown in the last decade but nothing like as fast as for that seen in reds. Some of the same data problems apply to browns as mentioned earlier for reds, so unit values are probably falling but absolute values are unclear, particularly in China.

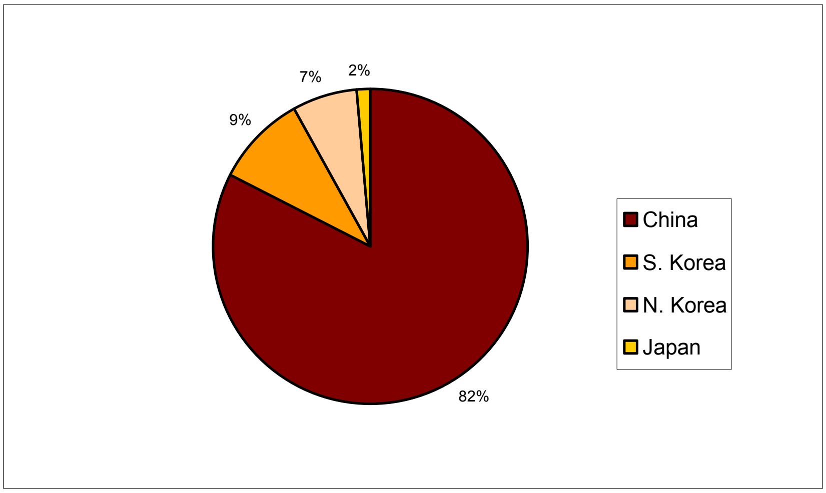


Figure 14. Distribution of farmed brown macroalgae in Asia.

5.23 Production of brown algae is dominated by China. Most of the production is in the cooler waters of the north, with some in neighbouring countries. Table 9 summarises production and uses by country for brown algae in Asia.

Figure 15. *Laminaria japonica* grown in longline culture in China.

Table 9. Farmed brown macroalgae in Asia: production, uses and notional prices, 2009.

Country	Latin name	2009 prod (t)	Main use	Notional price ($ / tonne wet)
China	Sargassum fusiforme	79,490	Food and alginate	460
	Laminaria japonica	4,139,825	Food and alginate	660
	Undaria pinatifida	1,324,170	Food	460
S Korea	Laminaria japonica	306,183	Alginate	150
	Undaria pinatifida	309,155	Food	107
N Korea	Laminaria japonica	444,300	Alginate	75
Japan	Laminaria japonica	40,397	Food	2,000
	Undaria pinatifida	61,215	Food	1,650

5.24 Production is dominated by *Laminaria* (kelp) in China, which is produced on a huge scale in coastal waters. Industry sources suggest that the main effort is in supply product for human consumption as prices are better in that market than for raw material for alginates. Because of confusion over value reporting to FAO by China, the South Korean prices are considered more indicative of the actual ex-farm price. Reported trade flows from China are very light compared to production, suggesting the bulk is consumed by domestic markets, both food and industrial.

5.25 *Laminaria* has a low protein content at around 7%, within lipid also low at around 2%. With an ex-farm price of around $150 per tonne wet and so a dry price in the order of $1,000 per tonne, it ranks with the less attractive red algae as a prospect for a feed ingredient, i.e. there are other plant based proteins available with higher protein content and lower price.

5.26 *Undaria* (local name Wakame) is a large kelp-like brown algae, grown using similar methods to *Laminaria,* has a somewhat better protein content at around 15%[103]. The vast majority is consumed as food. Indicative prices would suggest around $700 per tonne dry. Allowing 300-500 per tonne for milling, packing, transport etc it would cost around $1,200 per tonne in Europe and like reds of a similar price and protein content, remain unattractive compared to terrestrial plant sources.

5.27 *Sargassum fusiforme* is reported to be at quite low production levels in China, compared to other species. It has a protein content of around 15% and crude lipid quoted at under 1%[104],

[103] http://www.ftb.com.hr/42/42-57.pdf
[104] http://en.cnki.com.cn/Article_en/CJFDTOTAL-SCKX200204016.htm

the latter value is surprising given the apparent high lipid of a species in the same genus in Table 8. As an alginophyte it is said to be a source of last resort[105], with *Undaria* and *Laminaria* considered superior, which may explain its relatively low production volume. A realistic ex-farm price is likely to be as for the other kelp species, at around 100-150 per tonne wet, and so is likely to be of similar potential as an ingredient as described for *Undaria.*

5.3 Microalgae: Global Supply and Trends – Volume and Value

5.3.1 Microalgae Introduction

5.28 The first use of microalgae by humans dates back 2000 years to the Chinese, who used Nostoc to survive during famine. However, microalgal biotechnology only really began to develop in the middle of the last century[106].

5.29 This section of the report will consider global production and use of microalgae. It should be noted that unlike 'fisheries' products, including edible marine plants, the FAO database does not provide comprehensive statistical coverage of microalgae. There is apparently no other global database that incorporates microalgae statistics.

5.3.2 Microalgal Production

5.30 Information on global microalgal production can be found in the review paper of Spolaore *et al*, (2006)[107]. Their table is copied in its entirety here as Figure 16 (*note that references in the figure are not reproduced in the current report*).

TABLE 5. Present state of microalgal production (10, 48, 63, 69)

Alga	Annual production	Producer country	Application and product
Arthrospira	3000 t dry weight	China, India, USA, Myanmar, Japan	Human and animal nutrition, cosmetics, phycobiliproteins
Chlorella	2000 t dry weight	Taiwan, Germany, Japan	Human nutrition, aquaculture, cosmetics
Dunaliella salina	1200 t dry weight	Australia, Israel, USA, China	Human nutrition, cosmetics, β-carotene
Aphanizomenon flos-aquae	500 t dry weight	USA	Human nutrition
Haematococcus pluvialis	300 t dry weight	USA, India, Israel	Aquaculture, astaxanthin
Crypthecodinium cohnii	240 t DHA oil	USA	DHA oil
Shizochytrium	10 t DHA oil	USA	DHA oil

Figure 16. Present state of microalgal production.

5.31 Figure 16 provides some interesting insights into which species of microalgae are being produced, and what they are used for. The authors also comment that: "*Nowadays, the microalgal biomass market produces about 5,000 t of dry matter/year and generates a turnover of approximately $\$1.25\times10^9$/year (processed products not included in this figure)*". A simple calculation therefore suggests that microalgae, as currently cultured and used, cost some \$250,000 per tonne, or around £150,000 per tonne. This would appear to render them prohibitively expensive for aquaculture finfish feeds (see section 3). Benemann (2008) estimates that current world production of single celled microalgae amounts to around 10,000 tonnes.

[105] FAO Fisheries Technical Paper No 441, 2003, A guide to the seaweed industry, Dennis J McHugh
[106] http://www.aseanbiodiversity.info/Abstract/51005627.pdf
[107] http://www.aseanbiodiversity.info/Abstract/51005627.pdf

5.32 The question of scale and price is important:

- 5,000 or 10,000 tonnes a year of microalgal dry material, with its lipid not yet extracted, costing £150,000 per tonne, is inappropriate for both:
    - The quantity of n-3 HUFA lipid required by the salmon industry: almost 10,000 tonnes a year in Scotland alone (section 3)
    - And the price it could afford for that lipid: £2,200 per tonne

5.3.3 *Spirulina*

5.33 The high protein content of the blue-green alga *Spirulina* has been noted (section 4), and this is an available cultivated microalgal product. The finfish feed companies stated that it was too expensive to incorporate into salmon diets, and this is confirmed by further research. . Price ranges available on-line include:

- £321 for 25 kg = £12,800 per tonne[108]
- £139.97 for 5 kg = £27,994 per tonne[109]
- $US 10 per kg FOB Shanghai = £6,007 per tonne[110]

5.34 Production costs range from $10 to $20 per kilo for commercial farms, depending on size and location. Farms with resource advantages like those in alkaline lakes may have lower production costs, ranging from $5 to $15 per kilo. Farms with year-round tropical growing seasons, energy and nutrient advantages, and extraction facilities for high-value products, may be able to produce a protein by-product for a few dollars per kilo[111].

5.35 With favourable production parameters, this source still appears to cost at least three times the current price of fish meal. Figure 1 shows that fishmeal has roughly doubled in price in ten years, and the apparent increment will be less than this after inflation is taken into account. It seems likely that *Spirulina* costs will come down as volume goes up, but on current trends it would seem that there may be another 10 years or so before the lines cross and *Spirulina* has a price advantage.

5.36 Volume is also an issue. The same source suggests that production around the world is a few thousand tonnes, with ~1000 tonnes consumed on the USA market, where the largest farm can produce 500 tonnes per year, followed by Hawaii at 400 tonnes. Significant quoted outputs are: Thailand 150 tonnes, Myanmar 100 tonnes, China said to have *capacity* in the thousands of tonnes, likewise India and Taiwan have a capacity of a few hundred tonnes and a few tens of tonnes production elsewhere. Thus total global production at present would only go a small way toward meeting the protein needs of the Scottish fin fish industry. It would take major steps in quantum for it to become a serious contender.

5.4 Marine Hatcheries

5.4.1 *Product Ranges*

[108] http://purebulk.com/spirulina-powder
[109] http://www.buywholefoodsonline.co.uk/organic-spirulina-powder-5kg-bulk-price.html
[110] http://www.alibaba.com/product-gs/200026168/Spirulina_powder_natural_blue_green_alga.html
[111] : http://www.spirulinasource.com/earthfoodch7a.html

5.37 Section 4 presented a brief history of the development of microalgae production for marine finfish and shellfish hatcheries. It has been estimated that in 1999, up to 1,000 tonnes of microalgae was being used in aquaculture[112]. The most frequently used species in finfish and shellfish hatcheries *are Chlorella, Tetraselmis, Isochrysis, Pavlova, Phaeodactylum, Chaetoceros, Nannochloropsis, Skeletonema and Thalassiosira*. As section 4 has indicated, these species are often chosen because of their useful nutritional composition in terms of proteins, and particularly lipids. In our experience, there is sometimes a compromise choice between species that are relatively easy to culture at high density, where the fatty acid profile might not be as good as one would wish, and species rich in DHA but difficult to cultivate reliably, particular during high temperatures in the summer. *Nannochloropsis* or *Phaeodactylum* would be good examples of the former, and *Pavlova lutheri* probably the best example of the latter.

5.4.2 Production Methods

5.38 All the species cultivated for use in hatcheries are photosynthetic, and cultures can vary in scale from 100 L polythene bags, to much larger bags, to outdoor ponds and raceways. More recent developments have been in continuous culture systems[113]. Figures 17 to 19 illustrate the various types of culture unit. Nutrients are supplied to pre-sterilised seawater, and the culture is inoculated with a pure strain of the required alga. The production cycle is commonly 5-7 days, by which time the algal cells have multiplied up through the logarithmic growth phase, and have entered their stationary phase. It is generally unnecessary to concentrate or store the algal cells, since the entire culture volume is usually used in feeding larvae or rotifer tanks. It is important to note this point: the cost of production is one issue, but any additional cost to de-water, dry or otherwise process the algae culture water volume would have to be taken into consideration if it were intended for use as a raw material for aquaculture finfish feeds – section 5.12 considers this issue in more detail.

[112] Muller-Feuga, A.: Microalgae for aquaculture. The current global situation and future trends, p. 352–364. In Richmond, A. (ed.), Handbook of microalgal culture. Blackwell, Oxford (2004)
[113] http://www.variconaqua.com/bioreactors.htm

Figure 17. Typical marine finfish hatchery algal culture in bags. Source: Seafish.

Figure 18. Outdoor algal culture in raceways[114].

[114] Source: http://www.mriglobal.org/energy/Pages/Biomass.aspx

Figure 19. A modern photobioreactor[115].

5.4.3 Production Costs

5.4.3.1 Photosynthetic Production

5.39 There have been several recent studies into the cost of producing microalgae for marine hatcheries, and these have taken on a new importance and a potentially wider audience with the increasing interest in microalgae for use as a feedstock for bio-fuel production. Sweetman (2009)[116] has presented an effective overview article on this subject. She quotes Behrens (2005), who has estimated that the energy costs alone of producing 1 kg of dry algal biomass is $11.22 if using artificial light (and only $2.01 per kg if growing algal cells heterotrophically).

5.40 A more complete overview of microalgal production costs has been compiled by the FAO, with costs per kg of dry algal matter ranging from $4 to $300, depending upon whether the culture was indoors or outdoors. The indoor cultures would probably be important for UK production, if microalgal lipid was going to be produced for Scottish salmonid feed manufacturers. The FAO report suggests that costs of around $150 to 200 per kg would have been the norm at the time of the report (late 1980's). Taking the mid point ($175) and applying inflation from 1990 to 2011, that would translate to something like **$325 per kg dry material** now, based on an average annual inflation rate of 3%[117].

5.41 Using the slightly more optimistic estimate in the FAO report relating to summer/winter production (i.e. using natural light where possible), which was $23 to 115 per kg in 1990, that would still inflate to $42 to $213 per kg today. Averaging that over a year would come to $127 per kg for dry algal biomass, which **is £76 per kg**.

5.42 If a high lipid yielding phototrophic micro alga was being produced, with perhaps 50% yield of lipids, that would amount to a cost of £76 x 1,000 / .5 = **£152,000 per tonne for algal lipid.** The lipid might be relatively rich in EPA and DPA, but probably not more than 30% of the two combined. The cost of extracting the lipid has not been included in this calculation.

115 Source: http://www.variconaqua.com/bioreactors.htm
116 http://www.docstoc.com/docs/8416738/Microalgae-its-application-and-potential
117 http://www.economicsalevel.co.uk/Revision%20sheets/Inflation.doc

5.43 The main point to highlight is that using current technologies from the marine hatchery sectors, the cost of an extracted lipid would be considerably higher than the aquaculture finfish feeds sector could afford to pay. UK researchers have confirmed their view of both the opportunities and challenges, and have particularly stressed the cost of the nutrients to grow the microalgae[118]. Work on this area continues, as does work on cost-effectively extracting lipid from algal biomass.

5.4.3.2 Heterotrophic Production

5.44 Reference has been made to 'heterotrophic' microalgal production, and this introduces the type of algae generally referred to as oleaginous – although it is particularly focused on thraustochytrid species such as *Schizochytrium limnaca*[119] (referred to in some papers as a 'fungus'), or even yeasts such as *Rhodotorula glacialis*[120]. Some species of *Chlorella* can be grown heterotrophically, such as *C.protothecoides*[121]. The dinoflagellate *Crypthecodinium Cohnii* also produces DHA-rich lipid[122].

5.45 These 'algae' do not require sunlight for energetic purposes, but instead use a nutrient mix based upon carbon and nitrogen, where the carbon is an easily metabolisable form such as glucose or even glycerol[123]. Although light is not required, and the production of DHA-rich oil can be enhanced, the costs of production still appear to be very high, based upon the selling price of the materials produced by people using this approach – see section 5.3. Whether they all fall within the strict definition of 'algae' for the purposes of this project is debatable, but their potential to supply DHA-rich oils cannot be ignored in this study. Cost of production, however, still apparently remains an issue to be addressed. There is a UK-based producer of such products[124], and the company was approached to provide further information to help assist this study. Unfortunately it declined to respond.

5.46 The marine finfish hatchery sector has been using some these products for many years, in dried form. Dried *Schizochytrium* is a good enrichment product for cultured rotifers and *Artemia salina*[125], but it is not cheap by bulk finfish feed ingredient standards: almost $10 for a 50g pack at pet sector retail[126], although no doubt considerable cheaper in hatchery bulk purchases.

5.5 Animal Feeds, Nutraceutical/Pharmaceutical and Cosmetic Markets

5.5.1 Products

5.47 Figure 16 provided a very useful overview of where microalgal products are being used: human nutrition and cosmetics, as well as some specialised animal feeds.

5.48 For animal feed use, *Spirulina*[127] is commonly used for many types of animal: cats, dogs, aquarium fish, ornamental birds, horses, cows and breeding bulls. *Spirulina* is said to

[118] Pers comm.: R.J.Shields
[119] http://pubs.acs.org/doi/abs/10.1021/ef900704h
[120] http://www.google.co.uk/url?sa=t&source=web&cd=6&sqi=2&ved=0CEcQFjAF&url=http%3A%2F%2Fwww.aidic.it%2Fibic2010%2Fwebpapers%2F52Amaretti.pdf&rct=j&q=Rhodotorula%20glacialis&ei=9dC6Tf3CEcit8gO10KnTBQ&usg=AFQjCNHq_HH8wUCdTc7Hlmahlfpb3G4Ijw&cad=rja
[121] http://www.sandia.gov/news/publications/white-papers/Separation%20of%20Heterotrophic%20Biomass%20Working%20Paper%20APR.pdf
[122] http://www.algaebase.org/search/species/detail/?species_id=52213
[123] http://ddr.nal.usda.gov/bitstream/10113/16569/1/IND44071542.pdf
[124] http://www.newhorizonsglobal.com/
[125] http://www.aquafauna.com/Diets-AlgaMac-3050.htm
[126] http://www.seahorsesource.com/cgi-bin/shop/search.cgi?&category=Foods-Enrichments
[127] http://haberlandt.blablablab.org/2010/03/20/arthrospira-platensis-a-k-a-spirulina-an-introduction/

positively affect the physiology of the animals by providing a good profile of natural vitamins, minerals, and essential fatty acids. The cost of *Spirulina* powder has been discussed in section 5.3.

5.49 Some microalgal products enter the cosmetics market, particularly in the area of skin care[128]. It is interesting to note that some products have entered this sector when they had originally been targeted at the emerging bio-fuels sector[129]. Presumably the economics were compelling. The main species seem to be *Spirulina, Chlorella* and more recently *Nannochloropsis* and *Dunaliella*. The scale of this sector is difficult to ascertain.

5.50 The largest growth area appears to be in what might be termed the ‘nutraceutical’ market. This is defined as the use of any substance that is a food or a part of a food and provides medical or health benefits, including the prevention and treatment of disease. Such products may range from isolated nutrients, dietary supplements and specific diets to genetically engineered designer foods, herbal products, and processed foods such as cereals, soups and beverages[130]. In the case of n-3 HUFA rich lipids, there seem to be two main sub-markets:

- Direct consumptions of the lipids, mainly in capsule form
- Inclusion of the lipids, or their enhancement, in everyday food items, such as bread or eggs or milk[131] – so-called ‘functional foods’[132]

5.51 There is no ready way to separate the sub-markets directly in statistical terms, but their combined recent growth has been significant. They use ‘refined’ oils, and the nature of change in that market was covered in the recent MCS workshop, based on data from GOED. Figure 20 illustrates this trend quite well.

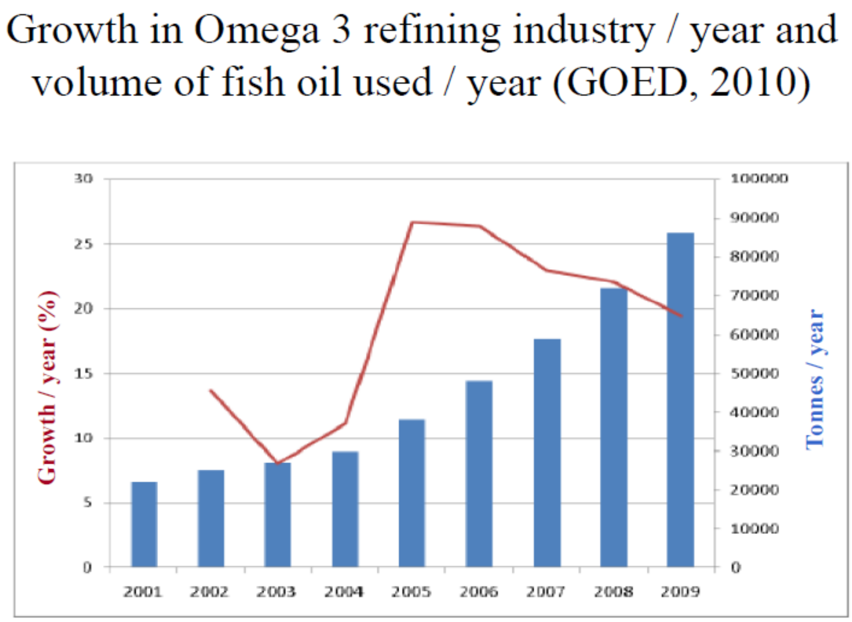


Figure 20. Growth in the use of refined N-3 HUFA Lipids.

5.52 The rate of growth of consumption of these refined lipids may have declined since 2005, but the growth in absolute terms continues. This is set against a backdrop of a finite amount of ‘wild caught’ marine n-3 HUFA oil availability, as Figure 21 indicates.

[128] http://www.cosmeticscop.com/cosmetic-ingredient-dictionary/definition/56/algae.aspx
[129] http://www.fastcompany.com/1735480/how-an-algae-bio-fuel-company-ended-up-in-the-cosmetics-business
[130] http://chemistry.about.com/od/chemistryglossary/a/nutraceuticaldf.htm
[131] http://www.guardian.co.uk/society/2005/may/24/food.foodanddrink
[132] See for example: http://www.dha-in-mind.com/australia+and+nz+n-3 HUFA+dha+enriched+foods.aspx

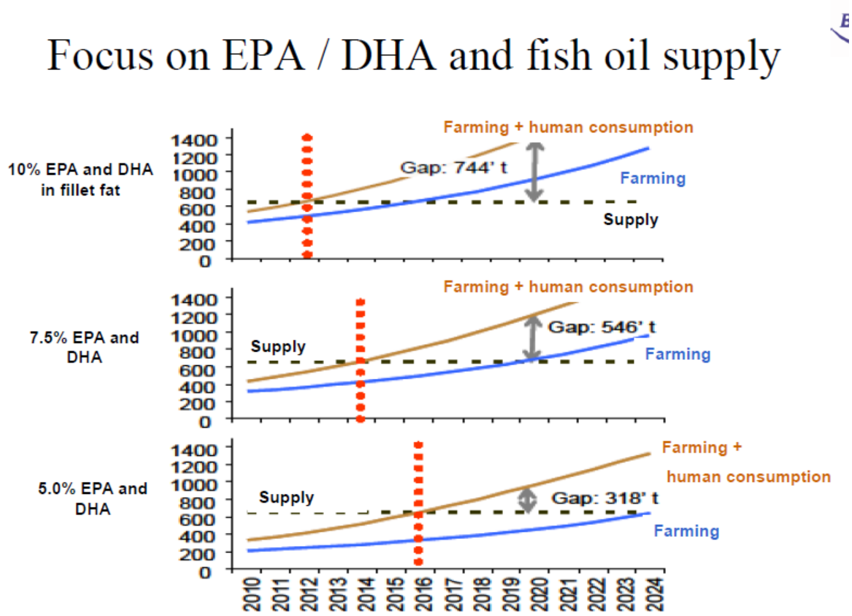


Figure 21. The potential gap between the needs of the fish farming sector and the combined needs of farming and direct human consumption, based on a range of assumptions about desired n-3 HUFA content in salmon fillets.

5.53 Nearly all of the new wave of refined n-3 HUFA lipids are based on the **same wild fisheries sources** as the aquaculture finfish feeds sector. There are specialised companies, including one major player in Scotland, Equateq Ltd[133], dedicated to the transformation of raw marine lipids into high quality specialised products. All of these are eating into the basic raw material resource that the aquaculture feed manufacturers also needs to access. The Scottish company was contacted as part of this study, and indicated that

- It specialises in the concentration of lipids
- The source is not important, apart from the end product target application and market positioning of the product
- The company could be interested in using a bulk algal oils, but obviously issues such as cost, fatty acid profiles, impurity profiles, and regulatory status would all need to be looked at before making any firm commitments
- The company could use its technologies in principle to "tweak" the fatty acid profiles of algal lipids, however, the cost of doing so is likely to be too high for the animal/aquaculture feed companies
- The premium for a high EPA/DHA lipid rises exponentially as the purity goes up.

5.54 Although most of the direct human consumption raw material is coming from wild-caught sources of marine lipids, there are some specialised producers of algal-originated lipids. The UK company New Horizons Global Ltd has already been discussed, but the world-leading company in this sector, at the moment, is Martek of the USA[134].

5.5.2 Economics

5.55 It is difficult to obtain a clear picture of the overall economics of this sector of 'human-use' n-3 lipids. However it is relatively easy to see what the consumer pays for a capsule of algal-originated DHA lipid: some $29.71 for a bottle containing 12 g of DHA lipid – which equates to around £1.5 million per tonne. This is clearly well outside the buying capacity for aquaculture finfish feed manufacturers.

[133] Equateq.com.
[134] http://www.martek.com/

5.56 What is unknown is the cost of production is for such algal-originated lipids. Clearly the DHA-only oil is a very specialised and refined product, and there is reference to less refined products on the Martek website. The company was contacted for further information for this study, but declined to respond.

5.57 The Scottish salmonid feed companies have expressed a hope that a 'new' source of n-3 HUFA rich lipid, from algae or anywhere else, could be diverted to the human consumption sectors, taking the pressure off the traditional raw materials sourced from wild-caught fish. Taking into account the vastly different value scales of the sectors, and the business logic that nobody would voluntarily move their sourcing from a modest cost raw material to a very expensive one (unless that could be passed on to customers), it seems unlikely this hope is warranted. The main hope must be to make n-3 HUFA rich algal lipids so widely available, at the right price, that all user-sectors can take advantage of it – section 5.7.

5.6 Algal Products In Aquaculture

5.6.1 Introduction

5.58 The interest in finding new feed sources for aquaculture species is acknowledged, and the concept that some of these *might* come from primary production (algae) in the marine environment is reasonable. Species such as salmon (and particularly species such as bass, bream and turbot) need to have n-3 HUFA rich lipids in their diet, and these originate from primary production in the marine environment rather than the terrestrial environment.

5.59 As this study has already reported, the basic building blocks of the main feed components are abundant in algae: key essential amino acids, and a range of unsaturated fatty acids of the n-3 series. Micro nutrients such as vitamins, minerals, pigments and others are also abundant in different types of algae. The **challenge** is to be able to offer these to finfish feed manufacturers in suitable and affordable forms, without incurring any negative impact on overall diet formulation or environmental and growth performance once the feed is used on the fish farm.

5.60 There have been a number of examples of attempting to incorporate algal components into finfish diets, and also animal diets. This section of the report considers some of these examples. By and large they are proposed as 'additives' to feed formulations, not necessarily as bulk replacers of traditional sources of protein and lipid. Section 3.9 has already considered the Scottish trial with the Ocean Harvest product.

5.6.2 Algal Proteins v. Menhaden

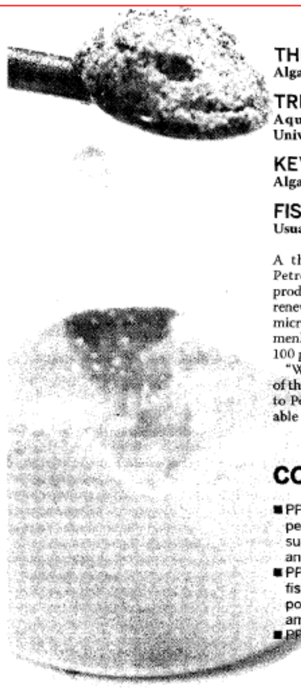
5.61 Several consultees to this project mentioned a recent report in Fish Farming International (FFI)[135], copied here as Figure 22. It was clear and unequivocal: a trial of **algae protein** v. menhaden protein with tilapia. It cited the algae protein producer as PetroAlgae, one of the high tech bio-fuel companies in the USA. The company has a website[136], and one of its downloadable fact sheets provided some helpful images. The key photograph is shown in Figure 23. Examination of the photograph suggested:

[135] http://www.intrafish.no/login/?lots=ffinews
[136] http://www.petroalgae.com/

- That the product appeared to be a floating multi-cellular aquatic plant, rather than an ‘alga’
- That it looked similar to the duckweed that is so commonly seen in freshwater ponds in the UK.

FFI February 2011

FeedUpdate



THE TRIAL:
Algae protein vs menhaden fishmeal

TRIALLED BY:
Aquaculture Research Institute, University of Idaho, U.S.A.

KEY INGREDIENT:
Algae

FISHMEAL CONTENT:
Usual levels against 0 percent

A third party study has found that PetroAlgae protein concentrate (PPC) produced as a co-product along with the renewable fuel feedstock by the company's micro-crop technology system can replace menhaden fishmeal protein at levels up to 100 percent in feeds for tilapia.

"We are very encouraged by the results of this extensive study because they point to PetroAlgae protein as a highly desirable replacement for fishmeal at a time when feed demand is expected to increase dramatically in the face of limited traditional supply," said Dr. Ronald W. Hardy who conducted the study.

The study also found that PPC would be suitable as a fishmeal replacement for other farmed fish species.

Tilapia is one of the largest-volume farmed fish species, and tilapia production is expected to grow from 2.8 million metric tons to more than 9 million metric tons by 2020, requiring 13 million tons of feed (up from 8 million tons in 2010).

Environment-friendly

PetroAlgae's micro-crop technology employs indigenous, aquatic micro-organisms suitable to local climates and is designed to enable its technology licensees to produce a cost-effective alternative to fossil fuels as well as a high-value protein co-product, while absorbing carbon dioxide from greenhouse gas emissions.

PPC allows for a shortened supply chain and reduces business risk, because micro-crop farms using PPC can be sited locally, close to consumption centers, according to the company.

Therefore, PPC has the ability to reduce the industry's carbon footprint, and its steadystate production allows for greater quality control and just-in-time inventory management.

PPC's other environmental benefits include lower pressure on ocean fisheries, lower risk of zoonotic disease, a positive carbon balance and a route to renewable fuel that is additive to the food and feed chain.

In addition to its uses in the aquaculture industry, the company expects PPC to be suitable for nursery swine, poultry, and, ultimately, for direct human consumption.

Hardy, who heads the Aquaculture Research Institute, directed the nine-week comprehensive University of Idaho PPC study.

CONCLUSIONS

- PPC is capable of replacing fishmeal protein up to 100 percent in feeds for tilapia, without the need for amino acid supplementation or other adjustments to the formulation, and can provide growth performance similar to fishmeal.
- PPC, when combined with fishmeal, supports higher fish weight gain than with fishmeal alone, suggesting a positive synergistic effect most likely related to favorable amino acid balance in the feed.
- PPC does not change the composition of tilapia and does not increase tilapia mortality rates. Together, these findings indicate that PPC is a safe feed ingredient with (no toxic indications after nine weeks of feeding).
- PPC yields nutrients that are highly digestible, demonstrating significant potential as a feed component for other farmed fish species.
- PPC has excellent suitability for producing low pollution feeds that reduce environmental contamination in dense aquaculture areas.

Figure 22. An extract from Fish Farming International, February 2011.

Figure 23. An image from the PetroAlgae downloadable PDF.

5.62 The scientist involved in the trial reported in FFI was contacted, and confirmed that the raw material was duckweed – which had apparently proved to be the most effective plant material to grow for PetroAlgae's main requirements[137]. For the avoidance of doubt, duckweed is not an 'alga', but is an aquatic flowering multi-cellular plant[138].

5.63 PetroAlgae's decision to use duckweed as a producer of plant biomass and as a remover of other industrial process wastes is completely in line with other initiatives[139]. Most kinds of plant biomass can enter the bio-fuel sector as a raw material, and whether it is technically an alga or not is irrelevant. Nutritionally, duckweed is an interesting product, with a long history of exploitation for human and animal nutrition in Asia and farther afield. There is at least one institute devoted to it[140]. There is a wide range of literature relating to the use of duckweed, including in aquaculture diets for species such as carp and tilapia[141,142,143,144,145,146,147]. The following points should be noted:

- Duckweed is a nutritionally interesting plant. The protein content of duckweeds is one of the highest in the plant kingdom, but it is dependent on growth conditions.
- It is potentially useful in the diets of species such as carp and tilapia, but its protein digestibility might be rather low in terms of a raw material for salmon diets.

5.64 Table 10 provides a proximal analysis range for duckweed[148].

Table 10. Proximal Analysis of Duckweed.

Organic composition in the Lemnaceae, % of dry weight	
protein	6.8 — 45.0
lipid	1.8 — 9.2
crude fibre	5.7 — 16.2
carbohydrate	14.1 — 43.6
ash	12.0 — 27.6

5.65 Duckweed is an interesting raw material, and the research that was reported was also interesting and worthwhile. The FFI article raised expectations about "feeding algae to finfish", which in the Scottish context would inevitably raise thoughts about its use with salmon. It illustrates the care that must be taken when reading grey literature.

5.6.3 Other Aquaculture Projects Involving Algae

5.66 There have been other literature references to incorporation of algal material into finfish aquaculture diets.

137 Personal communication, Ron Hardy
138 http://www.naturia.per.sg/buloh/plants/duckweed.htm
139 http://www.lcic.com/projects-bio-fuel-from-duckweed
140 http://ftp.sunet.se/wmirror/www.cipav.org.co/lrrd/lrrd7/1/3.htm
141 http://www.trjfas.org/pdf/issue_4_2/105_109.pdf
142 http://ebookbrowse.com/marilyn-rameet-samad-analysis-of-the-nutritional-content-of-duckweed-pdf-d50044305
143 http://www.fao.org/ag/AGAinfo/resources/documents/DW/Dw2.htm
144 http://www.mobot.org/jwcross/duckweed/nutritional-composition.htm
145 http://www.lrrd.org/lrrd7/1/3.htm
146 http://www.pjbs.org/ijps/fin1860.pdf
147 http://www.fitday.com/fitness-articles/nutrition/healthy-eating/the-nutrition-of-purslane.html
148 http://www.mobot.org/jwcross/duckweed/nutritional-composition.htm

5.67 In one study reported in 1994[149] that incorporation of *Ascophyllum* and *Spirulina* ingredients into sea bream diets proved beneficial. However, the main benefit was from the use of *Spirulina*, and as this report has already discussed, this is an expensive product. Another current website[150] refers to the 'discerning palates' of fish, without providing any details or references to peer reviewed science. Patents exist[151] – although whether they translate into useable products remains to be seen. Other authors discuss 'small scale' opportunities[152]. There are of course many references to the use of microalgae in marine hatcheries, but that subject has been covered elsewhere in this report.

5.68 A new initiative in Hawaii, based on microalgae and operated by Cellana LLC, has stated its intentions to grow materials suitable for animal and aquaculture feeds, as well as raw materials for bio-fuels[153]. Located adjacent to a power plant where it can obtain waste carbon dioxide, and taking advantage of Hawaii's high level of natural sunshine, this project should be re-assessed after it is in full production.

5.7 Bio-Fuels

5.7.1 Introduction to Algal Bio-Fuels

5.69 The concept of algal materials as a source of bio-fuels is currently a major global topic, and there are websites devoted to sharing information about it. OilAlgae is a good example[154].The site is a source of peer-reviewed and grey reference material. The websites of other organisations can also be useful sources of information: the Algal Biomass Organisation[155](ABO) and GOED[156] for example. The study has investigated the material on these websites quite extensively, and the ABO members' list was used as the basis of the individual contacts made with some commercial companies and research organisations.

5.70 It is perhaps helpful to locate the efforts to produce bio-fuels from algae within the history and structure of bio-fuels in general. There have been several phases of development, commonly referred to as 'generations'[157]:

- First generation: Derived from vegetable fats, starch, and sugar, examples of first generation bio fuels would be: Bio-gas, bio-diesel, and vegetable oil. First generation fuels are also derived from animal fats
- Second generation: Mostly derived from waste biomass, second generation bio fuels are a more balanced option compared to the first generation. Second generation fuels are made up of various kinds of alcohols and diesel generated from wood.
- Third generation: Environmentally friendly, third generation bio fuels are derived from algae. The algae is farmed on a large scale specifically for creating these alternative fuels **– this is the 'generation' of interest to the present study**
- Fourth generation: are derived by a method in which micro-organisms are raised to work with carbon dioxide to generate fuel.

5.71 Whilst there is a large body of information about the potential use of algal biomass for the production of bio-fuel (which could be in the form of bio-butanol[158], bio-ethanol[159] or bio-

[149] http://rms2.agsearch.agropedia.affrc.go.jp/contents/JASI/pdf/academy/53-0548.pdf
[150] http://www.aurorainc.com/solutions/animal-feed/
[151] http://finfish.org/blog/algae-patents-describe-aquaculture-feed-protein-source/
[152] http://www.fao.org/docrep/012/i1141e/i1141e00.htm
[153] http://www.aquafeed.com/read-article.php?id=3896&sectionid=1
[154] http://www.oilgae.com/
[155] http://www.algalbiomass.org/
[156] http://www.goedomega3.com/about-us.html
[157] http://bio-fuel-seaweed-algae.blogspot.com/

diesel[160]), the main focus for the current study is a recognition that if 'algal oils' can be produced at a cost that suits the requirements of the bio-fuels sector, they could be affordable for animal feed manufacturers – as long as they can be extracted from the process before they become bio-fuel. This is one of the fundamental potential routes forward for affordable n-3 production, and the possibility of an algal lipid co-product or even by-product from the algal bio-fuels sector was one of the key points raised for discussion with the consultees in the sector.

5.72 The challenges in cost terms remain significant at the present time:

- This study has already discovered that phototrophic microalgal lipid could cost as much as **£152,000 per tonne** to produce. This could possibly be considerably lower in a region with year-round sunshine and warmth: a figure of US$ 5,000 per tonne for algal material is noted in one source[161], which would need to be at least doubled to arrive at an algal lipid cost, excluding extraction costs – so at least $10,000 or **£6,150 per tonne**
- Heterotrophic production might be cheaper, because energy for artificial lighting is not required. However, current producers in this sector are selling products that retail at **£1.5 million per tonne**. Light must be replaced with potentially expensive sources of digestible carbon and other nutrients
- However, **crude oil** one (one year forecast) is $116 per barrel = $0.73 per litre = $810 per tonne[162], or some **£486 per tonne**.

There is clearly some way to go to bridge the gap between the likely production cost of microalgal biomass, and the needs of the bio-fuels sector in terms of affordable prices. Other studies have also examined the likely costs of production of algal bio-fuels[163,164]. The algal bio-fuels sector remains largely confident, and is working on economies of scale, high yielding strains, optimal locations, research grants and assistance from instruments such as carbon offsets[165].

5.7.2 Bio-Fuels: Products and Production Methods

5.7.2.1 Macroalgae

5.73 Although this section of the study has so far been primarily concerned with microalgae grown for the purpose of bio-fuel production, because of the potential for high value protein or lipid co-products, it is important to note that there is a significant global interest in producing **macroalgae** for use as a raw material for bio-fuel – including the UK/Irish based BIOMARA project[166]. This broad study is covering aspects of both macro and microalgal cultivation, and particularly looking at the processes to convert the biomass to bio-fuel. For example, with respect to macroalgae, there are three main study themes:

- **Sub-project 1 - Seaweed (Macro-algae) culture**
  Culture seaweeds, EIA assessment, and polyphenol analysis

[158] See for example: http://www.icis.com/Articles/2009/02/23/9195088/biobutanol-development-makes-headway.html
[159] See for example: http://www.britishsugar.co.uk/Bioethanol.aspx
[160] http://www.esru.strath.ac.uk/EandE/Web_sites/02-03/bio-fuels/what_biodiesel.htm
[161] http://www.dotyenergy.com/Markets/Microalgae.htm
[162] 1 barrel = 159 L; 900 kg crude in 1 m^3
[163] http://www.google.co.uk/url?sa=t&source=web&cd=1&ved=0CBgQFjAA&url=http%3A%2F%2Fwww.ascension-publishing.com%2FBIZ%2FAlgae-EBI.pdf&rct=j&q=T.J.!Lundquist12%2C!I.C.!Woertz1%2C!N.W.T.!Quinn2%2C!and!J.R.!Benemann3!&ei=_8q7TeD0Lsi38gOjg8jGBQ&usg=AFQjCNHjviI5GeJ3rr5nt1XF0ubS9FH9qQ&cad=rja
[164] http://www.fao.org/bioenergy/aquaticbio-fuels/recursos/detail/es/item/41030/icode/2/
[165] http://www.carbonoffsetsdaily.com/news-channels/usa/using-carbon-to-fight-carbon-39905.htm
[166] http://www.biomara.org/

- **Sub-project 2 - Anaerobic Digestion (AD)**
  Establish operational bench digesters; estimates of methane production potential; maximizing methane yield through nutrient content; and semi-commercial scale trials
- **Sub-project 3 Bioethanol Production**
  New bacterial isolates, chemical mutagenesis, small batch scale, bench top fermentation and large-scale fermentation.

5.74 The suitability of the existing species of UK seaweeds is addressed. Current attention[167] is focused on:

- *Laminaria digitata* and *hyperborea*
- *Alaria esculenta*
- *Saccharina latissima,*
- *Palmaria palmate*
- *Ulva lactuca*

5.75 Although section 4 has provided an overview of general algal composition, it is worthwhile re-visiting that subject in connection with UK seaweeds being considered for bio-fuel production. Table 11 illustrates this for most of the species, highlighting the analysis for protein and lipid (fat) content.

Table 11. Proximal analysis of some UK/Irish seaweeds[168]

	Ascophyllum nodosum	*Laminaria digitata*	*Alaria esculenta*	*Palmaria palmata*	*Porphyra yezoensis*	*Ulva* species
Type	Brown	Brown	Brown	Red	Red	Green
Water (%)	70-85	73-90	73-86	79-88	nd	78
Ash	15-25	73-90	73-86	15-30	7.8	13-22
Total carbohydrates	-	-	-	-	44.4	42-46
Alginic acid	15-30	20-45	21-42	0	0	0
Xylans	0	0	0	29-45	0	0
Laminaran	0-10	0-18	0-34	0	0	0
Mannitol	5-10	4-16	4-13	0	0	0
Fucoidan	4-10	2-4	nd	0	0	0
Floridoside	0	0	0	2-20	nd	0
Other carbohydrates	c. 10	1-2	1-2	nd	nd	nd
Protein	5-10	8-15	9-18	8-25	43.6	15-25
Fat	2-7	1-2	1-2	0.3-0.8	2.1	0.6-0.7
Tannins	2-10	c. 1	0.5-6.0	nd	nd	nd
Potassium	2-3	1.3-3.8	nd	7-9	2.4	o.7
Sodium	3-4	0.9-2.2	nd	2.0-2.5	0.6	3.3
Magnesium	0.5-0.9	0.5-0.8	nd	0.4-0.5	nd	nd
Iodine	0.01-0.1	0.3-1.1	0.05	0.01-0.1	nd	nd

5.76 Table 11 confirms the general findings in section 4: macroalgae generally have low levels of protein, and low levels of lipids. The UK/Irish species considered in Table 11 are quite low in these components, even compared with some other macroalgae considered in section 4. The inference as far as this study is concerned is that even if **these** species were cultured on a large scale in UK coastal waters, the cost-effective extraction of useful lipids from

[167] http://www.biomara.org/the-science/Bioethanol%20from%20seaweed%2010_2010%20PS.pdf
[168] http://www.seaweed.ie/nutrition/index.html

them, aimed at the animal feeds sector, would be challenging. Similarly, their protein value as a 'dried and milled' product would be generally considered unacceptable because of the large indigestible bulk of carbohydrate material. The only hope would be that some useful feed ingredient could be obtained as a by or even waste product from one of the other extractive processes that these seaweeds might be subjected to – whether for bio-fuel production, or for any other purpose. This would be more likely if species of macroalgae with higher levels of lipid were being grown for bio-fuel production – section 4 discusses species such as *Chorda*.

5.77 Production techniques for macroalgae are still under investigation[169], and whilst adaptation of typical mussel long line cultivation might be the first approach, further developments might be required to facilitate efficient harvesting – see Figure 24. Novel ideas have been put forward by various organisations, including NASA[170]. Although production in the UK might be aimed at providing wet material for digesters, as a source of dried raw material for animal feed ingredients it seems unlikely that UK could compete on scale or cost terms with China: it might be cheaper to import dried, milled seaweeds.

Figure 24. Harvesting *Macrocystis pyrifera* in California for alginate production (© Kelco, Ltd)[171].

5.7.2.2 Microalgae

5.78 For microalgae there are four main study themes within the BIOMARA project:

- **Sub-project 1- Screening of microalgae cultures**
  Screening of oil-producing microalgae by flow cytometry and oil hyperproductive strain collection
- **Sub-project 2 - Development of gene probes for monitoring oil production**
  Protype gene probe development, confirmation of efficacy
- **Sub-project 3 - Analysis of oil content**
  Lipid content and composition of algal oils in selected strains
- **Sub-project 4 - Optimising growth conditions**
  Optimal growth conditions for selected strains, oil yields achievable in two-stage or one-stage cultivation or under continuous cultivation in selected strains and completion of small pilot trial.

[169] See for example: http://www.thecrownestate.co.uk/scotland_bulletin_winter_spring_2011.pdf
[170] http://www.scribd.com/doc/33699641/How-Algae-Can-Clean-And-Make-Oil
[171] http://www.seaweed.ie/uses_general/alginates.html

5.79 Extensive studies have been carried out for the cultivation of different marine microalgae using a variety of cultivation systems including both **open ponds** and various types of **closed photobioreactors**[172], [173]. A few examples of marine microalgal species that have been studied for microalgal farming include red marine alga *Porphyridium sp*., N-fixing cyanobacterium *Anabaena*, macrophytic marine red alga *Agardhiella subulata*, marine green algae *Chlorella spp*, *Dunaliella tertiolecta*, and marine phytoplankter *Tetraselmis suecica*

5.80 The concept of combining a requirement to produce microalgal biomass with opportunities to obtain 'free' nutrients from other process waste streams, and even to potentially mitigate the environmental effect of those waste streams, is one that has been recognised by many companies around the globe[174]. An interesting example of this in Scotland is the work done by Scottish Bioenergy Ltd[175]. The company has applied its algal photobioreactor techniques, in the first instance, to the waste streams of Scottish whisky distilleries, with a pilot unit being located at the Glenturret distillery near Crieff. The company has been an active consultee during this study, and has provided a significant amount of background information about its plans.

5.81 Microalgal production for bio-fuels generally adopts variations on the normal microalgal production methods illustrated for marine hatcheries. The conceptual scale, however, is generally much larger, as Figure 25 illustrates.

Figure 25. Artist concept for large scale Microalgal production[176].

5.7.3 Economics and Bio-Fuels

5.82 This report has already touched on various aspects of the economics of algal production, as well as the level of cost that would be required to be able to supply products into the aquaculture finfish feeds sector. The challenge for prospective algal bio-fuel producers has also been highlighted, but if it can be overcome for bio-fuel production, it will help the animal feeds sector as well.

[172] http://faculty.washington.edu/stevehar/Bio-fuels%20from%20Microalgae.pdf
[173] http://edition.cnn.com/2008/TECH/science/04/01/algae.oil/index.html#cnnSTCText
[174] http://www.uk-cpi.com/
[175] http://www.scottishbioenergy.com/home
[176] http://www.altdotenergy.com/2009/01/international-bio-fuel-partnership-between-primafuel-and-ben-gurion-university/

5.83 The report prepared by Bruton *et al* for SEI in 2009 (see Table 5) provides some helpful overviews about the economic feasibility of algal bio-fuel production. Key summary points are:

Macroalgae

- *"The principal energy process considered for seaweed is fermentation, either anaerobic digestion (AD), to create biogas, or ethanol fermentation. The presence of salt, polyphenols and sulphated polysaccharides would need to be carefully managed in order to avoid inhibition of the fermentation process*
- *Biogas production is a long-established technology and previous trials have indicated that AD of seaweed is technically viable. It should initially be possible to incorporate seaweed resources into existing AD plant to allow for smaller quantities and seasonal availability. This is the closest process to commercialisation for conversion of macroalgae to energy, though there is still a need to reduce the cost of the raw material by at least 75% over current levels*
- *Alcoholic fermentation is more difficult. The lack of easily fermented sugar polymers such as starch, glucose or sucrose means there is little point in pursuing standard sugar fermentation processes*
- *The competitiveness of macroalgal biomass for alcohol fermentation must be viewed in the context of other available cellulosic biomass such as wood, straw and dry organic waste which are also potential ethanol feedstocks."*

Microalgae

- *"There is no consensus concerning optimum systems for microalgae cultivation. Scientists disagree over whether open or closed or some combination of cultivation systems is most favourable. Open-pond systems, such as raceways, entail low capital and operating cost, but also low productivity and lack of control over cultivation. Closed systems, such as photo-bioreactors (PBR) are much more expensive but offer higher productivity*
- *Nutrients and carbon are other key requirements for microalgal growth. For carbon, exhaust gas from power plants which contain significant quantities of low-cost CO2 can be used. This is part of the business model of most bio-fuel projects, which also allows power plants to recycle CO2*
- *Algal slurry is 15-25% dry weight after collection. Dry lipids are necessary for esterification and removal of water is expensive. Development of lipase for direct esterification or other extraction techniques could remove the drying step. Unsaturated fatty acid content is high in algal oils and their presence lowers esterification yields*
- *It is also possible to produce protein-rich feed for both animal and human consumption*
- *Many barriers to development and areas of research were identified. It is difficult to understand the high levels of commercial activity and investment in marine algae at present as a bio-fuel resource, in light of the research advances still required."*

5.84 Looking more closely at the economic calculations undertaken by Bruton *et al*, they cite the recent publication by Borowitzka (2008), which estimates that current 'cost gap' between what microalgal biomass can deliver, as compared with second generation raw materials (rapeseed, palm oil), is over $4,000 per tonne of bio-fuel – almost an order of magnitude. On the other hand, it is claimed that in a best-case scenario in a sunny climate such as Hawaii, using a species such as *Haematococcus pluvialis,* algal oil could theoretically be produced at $140 per bbl. The speculative nature of this projection is noted, as would be the need for further research. If this proved to be feasible, reliable and capable of implementation at some scale, **it would be of interest to this study: this would be a cost of £586 per tonne for algal oil**.

5.85 Another recent study by James (2010) for the Scottish Government considered bio-fuel and other non-food uses of algae, with relevance to R&D and policy in Scotland. The report concludes that:

- *"There are some cogent strategic policy and economic drivers to support further, more commercially oriented and well co-ordinated research, development and pilot scale deployment in the area of macroalgae production in Scottish waters*
- *No commercial production of microalgae has yet taken place and significant technical and economic barriers remain*
- *Future public expenditure on R&D should be informed by a detailed and commercially oriented techno-economic assessment which should be used as the basis for a credible development framework*
- *A legislative and regulatory framework for aquaculture, marine renewable energy and terrestrial bio-fuel production from biomass exists. This framework will need to be amended to include sources of marine biomass*
- *There is a growing consensus that pilot scale macroalgal "farms" should be established to assess the technical viability of large scale cultivation in Scottish waters and to provide further data to support economic assessment*
- *The development of a credible commercially oriented techno-economic model together with Life Cycle Analysis (LCA) should be regarded as a high priority*
- *The most obvious "route to market" for algal biomass appears to be the use of macroalgae as part of a <u>mixed feedstock</u> for anaerobic digestion. Anaerobic digestion of macroalgae alone is not considered economically viable*
- *The potential to integrate large scale macroalgal culture with other forms of aquaculture should be actively encouraged, if there is evidence to support mutual economic and environmental benefits."*

5.86 In addition to the studies already considered above in connection with algal bio-fuel activity, a number of other statements about the economics of the sector have been reported in the public domain. These are presented in tabular form in Annex 4, with the relevant source references. It is important to note that Annex 4 contains a range of colour of references, from grey (press articles) to white (peer reviewed papers). It would not ordinarily be appropriate to present press articles as references in a research project report, but in this case, where the article is quoting a leading figure in the sector, it is thought to be acceptable to disclose the details of the statement. Whether the leading figure is saying anything based upon peer-reviewed science is another matter, and readers of this report should consider the following points in that light. Noteworthy comments extracted from Annex 4 include:

- *"Fuel-grade products made from algae of mid-range lipid content (35%) at $5000/ton would cost over $50/gal in large volume*
- *The main conclusions are that: (i) the biochemical composition of the biomass influences the economics, in particular, increased lipid content reduces other valuable compounds in the biomass; (ii) the "bio-fuel only" option is unlikely to be economically viable; and (iii) among the hardest problems in assessing the economics are the cost of the CO2 supply and uncertain nature of downstream processing*
- *Fundamental thermodynamic constraints make it impossible for such approach to be commercially viable for fuel prices below **$800/bbl,** even if flawless technological implementation is assumed*
- *The costs of harvesting microalgal biomass can be a major component of production, accounting for up to 20–30% of the total cost*
- *Presently the lowest cost for biomass production of the widely used algae Dunaliella salina in open pond systems is £2-3 per kg of biomass*

- *Based on a UNH research project, Briggs estimates the total cost of producing 140.8 billion gallons of oil (unrefined) for biodiesel at $46.2 billion*
- *Capital costs are expected to be approximately $45,000 – $60,0000 (a 2 – 16 times improvement over competing systems) and profitable oil production costs are estimated at only $0.08 – $0.12/pound. These oil costs compare to recent market prices of feedstock oils anywhere from $0.25 – $0.44/pound*
- *With our fast growing algae and our advanced photo-bioreactor, it only takes four days to be in full production and to collect the first algae. And the cost of biodiesel feedstock will only be 5-10 cents a litre.*
- *Although the venture capital firm invests heavily in bio-energy technology, "we just haven't gotten very comfortable that algae is going to come down the cost curve."*
- *BP also doesn't like photosynthetic algae. "We don't think that [technology] will ever reach the kind of cost or supply that we think people are prepared to pay,"*
- *Matt Horton, CEO of Propel and a principal at @Ventures, said his view of algae hasn't changed in the last few years. "It's one of the most promising opportunities in the liquid fuels arena, but the timelines for true commercialization are still years down the road," he said. It's tough for a company like Propel to work with algae companies at this point because it's difficult to predict – with any certainty – when algae-based fuels might realistically be delivered*
- *Algae bio-fuel start-up Solix, for instance, can produce bio-fuel from algae right now, but it costs about $32.81 a gallon. But it said the production cost can be brought down to $5.50 a gallon, by exploiting waste heat at adjacent utilities. It's only in phase II of Solix's business plan that it will be able to drop production costs to $3.30 to $1.57 a gallon, or around $60 to $80 a barrel.*
- *The current cost of a barrel of algae bio-fuel ranges from $140 a barrel to $900 per barrel."*

5.87 There is clearly a wide range of views and opinions about the cost of algal bio-fuel production, either as it is today, or as it might be in the future. The fundamental concerns about the energetics of photosynthesis are noted, and in particular the paper written by Dimitrov (2007)[177], who states that it is impossible to produce photosynthetic bio-fuel for less than $800 per bbl., which would translate to some **£3,390 per tonne**. The assertions that Dimitrov makes are fundamental to any further consideration of possible sourcing of aquaculture finfish feed ingredients from microalgae, and it is important to decide whether future R&D efforts should continue to focus on both photosynthetic processes **and** heterotrophic processes, or just on the latter.

5.8 Harvesting and Processing

5.8.1 Introduction

5.88 Algal biomass is a plant material, originally located at wherever it is being cultivated or harvested, and containing 75% or more water. In order to transform the raw material into an algal lipid or other algal product, ready to use at a finfish feed manufacturing plant, there are several key steps that might have to be undertaken, all of which have cost implications. It is also important to consider that harvested wet algae is a biological material, which will begin to decompose relatively quickly unless some sort of stabilisation approach is taken[178]. The main considerations include:

[177] http://www.nanostring.net/Algae/CaseStudy.pdf
[178] See for example:
http://www.google.co.uk/url?sa=t&source=web&cd=28&ved=0CEYQFjAHOBQ&url=http%3A%2F%2Fresearch.myfwc.com%2Fengine%

- Harvesting
- Drying
- Extracting lipid
- Milling
- Lipid enhancement
- Any other extraction for micro nutrients

5.8.2 Harvesting

5.8.2.1 Harvesting Macroalgae

5.89 Section 5.7 has briefly introduced the idea that some care will be needed when designing macroalgae cultivation systems, in order to ensure that harvesting can be carried out effectively. An image of a large vessel cutting and harvesting ‘wild’ *Macrocystis* is shown in Figure 24. A variety of more labour-intensive harvesting approaches are illustrated in Figures 26 to 28.

Figure 26. Harvesting seaweed in Indonesia[179].

2Fdownload_redirection_process.asp%3Ffile%3D50williamses7_4819.pdf%26objid%3D28200%26dltype%3Dpublication&rct=j&q=seaweed%20rots%20quickly&ei=cZq9Tf6LN9Sn8QOqh9TbBQ&usg=AFQjCNEWThhjDpCUtwvlB4uE5-KRENdjUA&cad=rja

[179] Source:http://www.surfersvillage.com/surfing/25554/news.htm

Figure 27. Harvesting seaweed from an IMTA project in Canada[180].

Figure 28. Harvesting seaweed in the Western Isles[181].

5.90 Harvesting wild macroalgae has a cost[182]. A recent study has suggested costs of 39 to 104 Euro per tonne of dry matter[183], and it is interesting to speculate on the implications of such an assumption in terms of 'algal lipid' for finfish diets. Taking a mid-point of some 70 Euros per tonne, for a species such as *Laminaria* with a lipid content of 2% of dry matter, the harvesting cost alone would amount to some 3,500 Euros per tonne for the algal lipid – or around **£3,120 per tonne**. This would be before any lipid extraction had been undertaken.

5.8.2.2 Harvesting and Dewatering Microalgae

5.91 Microalgae offer a different challenge: whilst a macroalga can be physically removed from its culture medium (the sea) by hand or with machinery, microalgae are single celled

[180] http://reference.findtarget.com/search/Integrated%20Multi-Trophic%20Aquaculture
[181] http://www.ceuig.com/archives/2672
[182] See for example: http://www.cne-siar.gov.uk/minch/seaweed/seaweed-04.htm
[183] http://www.google.co.uk/url?sa=t&source=web&cd=13&ved=0CC8QFjACOAo&url=http%3A%2F%2Fwww.presentations-dlgbenelux.com%2FCongres%2Fdownload%2Fcadf0c17621bb6784c54beb0981c4344%2F21042011055928%2F569&rct=j&q=cost%20of%20harvesting%20seaweed&ei=b6O9TdqLKsu48gPlg73KBQ&usg=AFQjCNEAsCsdZE82PJMxjCWkn0j2apjU4g&cad=rja

organisms suspended in their culture medium. The dilute nature of harvested microalgal cultures creates a potentially large operational cost during dewatering. Currently there is no superior method of dewatering microalgae. A technique that may result in a greater algal biomass may have drawbacks such as a high capital cost or high energy consumption[184]. Methods of removing the cells from the aqueous culture medium are the subject of research activity, particularly with the growing interest in high volume bio-fuel production[185]. A range of techniques are under consideration:

1. Centrifugation
2. Flocculation
    1. Polyelectrolyte flocculants
    2. Inorganic flocculants
    3. Combined flocculation
    4. Autoflocculation
    5. Marine microalgal flocculation
3. Filtration and screening
    1. Tangential flow filtration
4. Gravity sedimentation
5. Flotation
    1. Dissolved air flotation
    2. Dispersed air flotation
6. Electrophoresis techniques
    1. Electrolytic coagulation
    2. Electrolytic flotation
    3. Electrolytic flocculation

5.92 One study[186] suggests that an agreed ‘sectoral’ target cost for dewatering should be $5 per bbl. ($34 per tonne), and another report suggests the figure is $50 per tonne[187]. Real-life assessments of various filtration and floatation techniques produce actual costs in the range of $12 per bbl., or $81 per tonne. There is clearly more development work required in this area, and some of this is taking place in the UK[188]. $81 per tonne is **£48 per tonne**.

5.8.3 Drying

5.8.3.1 Drying Macroalgae

5.93 Drying harvested macroalgae can be done very simply by hanging or spreading in the sun in appropriate parts of the world, but it is generally assumed that if the macroalga needs to be dried for a modern bio-extraction requirement (bio-fuel, feed production), this will have to be done using some energy input, unless the harvested alga can be used wet, probably close to source. Ryther *et al (*1984)[189] provide a basic energy requirement calculation which shows that the energy needed to dry 1 kg of macroalgae (to 20% moisture) is 1,980 KJ assuming 100% efficiency, which in 1984 amounted to $0.075 per kg of ‘dry’ algae. They point out that if normal efficiencies of systems such as drum driers are taken into account (around 60%), that figure would be higher – perhaps **$100 to $125 per tonne**. The cost of energy per KJ (or often expressed as ‘per million BTU) has risen since 1984, as Figure 29

[184] http://jrse.aip.org/jrsebh/v2/i1/p012701_s1?track=MAR10NL
[185] R.J.Shields, pers comm
[186] http://etd.ohiolink.edu/send-pdf.cgi/Jeffrey%20Bargiel.pdf?case1238702010
[187] http://www.algaevs.com/algaeventure-awarded-loan-for-algae-dewatering-systems
[188] http://www.algaektc.com/A4B%20Microalgal%20Biotechnology,%20Technology%20Review%20and%20Road%20Map.pdf
[189] http://www.nrel.gov/docs/legosti/old/2360.pdf

indicates for natural gas, and if Ryther *et al*'s energy use fundamentals remain applicable, the cost to dry macroalgae would be higher today.

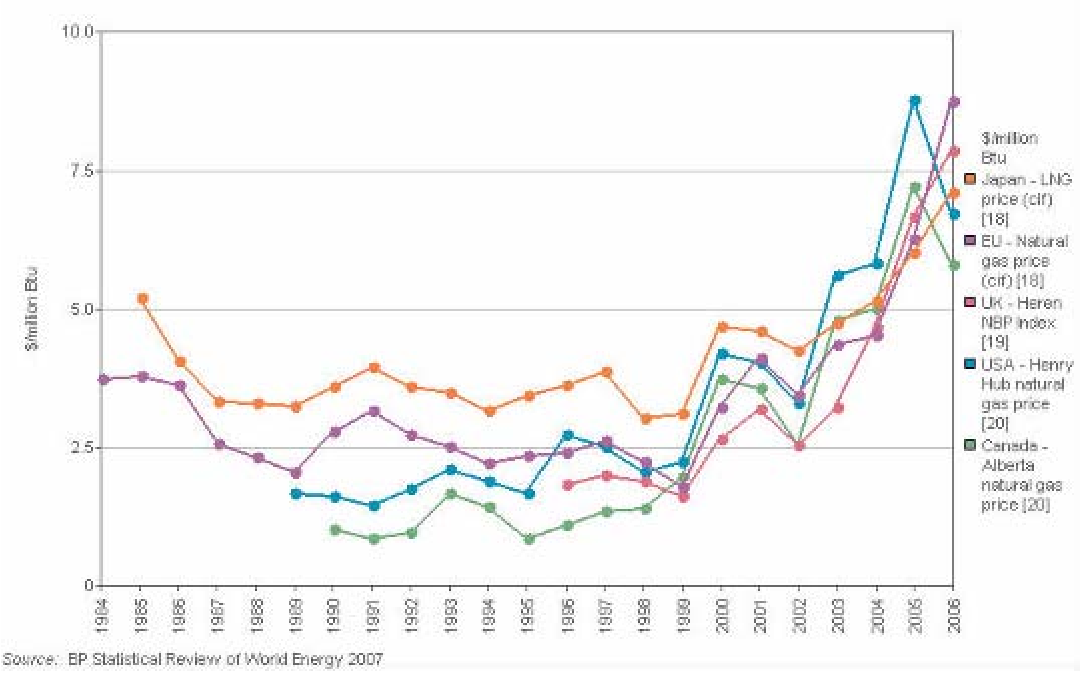


Figure 29. Natural gas prices.

5.94 A more recent study[190] seems to be at odds with the drying costs outlined above, quoting studies that have suggested the overall cost of producing 'dried' algal biomass is in the region of $75 to $150 per tonne – implying that this includes the actual costs of setting up the production unit (seaweed farm), operating it, harvesting the seaweed, and then drying it. This seems very optimistic: Ryther *et al*'s calculations on the energy requirement to remove 80% of the water from the plant biomass were fundamental mass-transfer energy calculations. It is impossible for this study to take this discussion any further, but an examination of some of the basics in future peer-reviewed research would seem to be warranted.

5.8.3.2 Drying Microalgae

5.95 Having dewatered cultured microalgae into a moist slurry, there are various ways to then properly dry it, leaving a powder with perhaps 9% moisture content. These can range from simple solar drying for pond-produced *Spirulina*, to a range of modern processes such as rotary drum driers and even freeze driers. Various studies suggest cost ranges for such processes:

- Freeze drying is expensive, at some $0.45 per lb of water removed[191]. Hypothetically, if 1 tonne of dried microalgae came from a slurry which had to have 80% of its weight removed as water, that would be 4 tonnes of water, which would cost $3,968, or some £2,381 per tonne of dried algal powder
- Drum drying costs are estimated at $0.4 to 0.6 per kg of dried material[192], which would be some £300 per tonne of dried algal material.

[190] http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19944.pdf
[191] http://www.phase-technologies.com/html/comments38.html

[192] http://books.google.co.uk/books?id=KAKx4I7NWEYC&pg=PA170&lpg=PA170&dq=driers+for+micro+algae&source=bl&ots=0-gzXIJXIK&sig=FSJbfjwlB4pDGSZQJgGEjezZgWc&hl=en&ei=0Hh4TbXEJdOEhQfNytTpBg&sa=X&oi=book_result&ct=result&resnum=3&ved=0CC8Q6AEwAg#v=onepage&q&f=false

5.96 There is a recognition that drying (and indeed initial dewatering) costs are a bottleneck, and claims are made that 'new processes' can considerably reduce these costs[193,194]. This study cannot make any critical assessment of these new developments.

5.8.4 Extracting Lipids

5.97 There is a wide range of literature concerning extracting lipid from plant materials. Traditionally this has been a well-known process for many years in terms of terrestrial plants, and the normal techniques involve physically squeezing lipid out with some type of press, often combined with a solvent-based process to improve yields. The plants used are generally in the form of seeds, and the original lipid content can be quite high: 40% in rapeseed[195]. Figure 30 shows a typical press. It is also interesting to consider the process that currently provides nearly all the n-3 HUFA rich lipid in the world: fish oil production. A useful overview report is available from the FAO[196]. The Vincent Corporation in the USA has an interesting website, detailing many types of extractive machinery and the novel uses to which they can be put[197].

Figure 30. A typical press for extracting plant lipid.

5.98 The key to extracting lipid from algae is disrupting the cell walls so that the lipid can be readily released. Figure 31 illustrates some of the processes that are being considered[198], and others include[199, 200]: autoclaving; freeze fracture; surfactants; microwaving; and ultrasonics. Estimates of cost of extracting lipid from algae cells[201] suggest $1.80 per kg, compared with $0.50 per kg for palm oil, or around $0.37 to $0.48 per kg for fish oil[202].

5.99 It is difficult for this study to take a critical view of this issue of extraction costs for algal lipid. It is the subject of much research, and at the present time there is a focus, particularly in the UK, on techniques that do not require solvents[203]. Many other references are also available on this topic[204],[205],[206],[207],[208]. If appropriately priced techniques can be developed there is little doubt they will be applied.

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193 http://newenergyandfuel.com/http:/newenergyandfuel/com/2009/03/30/an-algae-production-cost-breakthrough/
194 http://www.algaevs.com/wp-content/uploads/2009/03/avs_harvester_tech_expl.pdf
195 http://www.ipipotash.org/udocs/No%2016%20Oilseed%20rape.pdf
196 http://www.fao.org/docrep/003/X6899E/X6899E04.htm
197 http://www.vincentcorp.com/content/full-list-applications
198 http://www.biomara.org/the-science/QUESTOR%20BioMara%20Poster%20Oct10.pdf
199 http://biogas.ifas.ufl.edu/Internships/2010/files/kaitlynsummerfield.pdf
200 http://www.emsustains.co.uk/downloads/Hampton_study_report.pdf
201 http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6T4X-4N20704-1&_user=10&_coverDate=06%2F30%2F2007&_rdoc=1&_fmt=high&_orig=gateway&_origin=gateway&_sort=d&_docanchor=&view=c&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=862b35141e0e6f4a2da257e8b35afe62&searchtype=a
202 http://www.fao.org/docrep/003/X6899E/X6899E10.htm#9.3%20Annual%20Production%20Costs
203 Pers com: R.J.Shields.
204 http://www.originoil.com/technology/single-step-extraction.html
205 http://www.cleanwatertech.com/publications/2005-09-19-new_developments_in_mixing.pdf
206 http://content.lib.utah.edu/cgi-bin/showfile.exe?CISOROOT=/ir-main&CISOPTR=43299&CISOMODE=print
207 http://www.scribd.com/doc/37274828/00085-Extraction-of-Pigments-and-Fatty-Acids-From-the-Green-Algae-Scene-Des-Mus

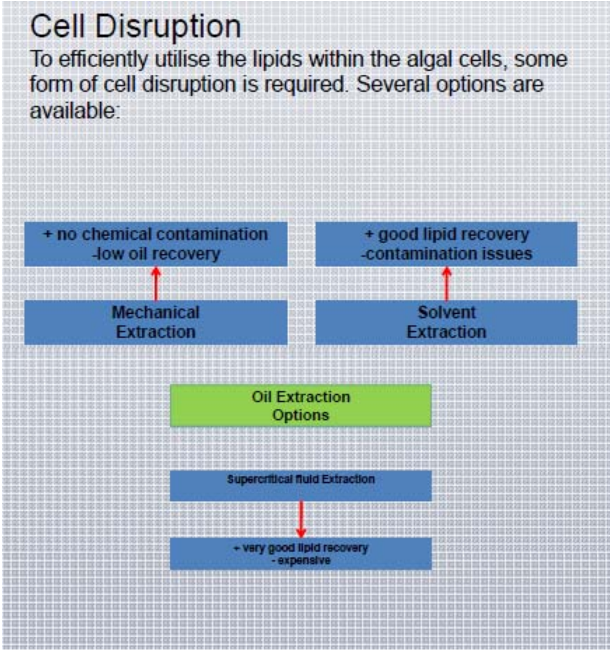

Figure 31. An example of some processes for algal cell disruption.

5.8.5 Improving Algal Lipids

5.100 Although this subject is something of a specialised sub-set of the production and use of lipids for human and animal nutrition, it is appropriate to discuss it at this stage of the report. Once a lipid has been extracted, there are possibilities to chemically treat it in order to improve its fatty acid profile or degree of purity, such that it has additional applications in certain markets. Reference has already been made to the work of Equateq on the Western Isles[209], and the company has been helpful in responding to this study. The problem for the aquaculture finfish feeds sector is that the processes used by Equateq are generally very expensive, and their products are required by very specialised and high value markets.

5.101 The technique of cold filtration of fish oils can yield interesting products, and the term 'winterisation' is normally used – and indeed adopted as a corporate name by one of the main companies involved[210]. There are clearly a range of interesting options in terms of products, but unfortunately it has been impossible to obtain any idea of cost. The company was contacted as part of this study, but declined to respond.

5.9 By-Products from Other Processes

5.102 Almost all of the analysis undertaken as part of this study suggested that unless some of the new microalgal bio-fuel projects obtain the cost of production efficiencies they are searching for, and also focus some of their production thinking on other markets such as animal feeds, protein or lipids obtainable from algal sources as a primary business activity would tend to be too expensive for the aquaculture finfish feeds sector. This may not be true for some micro ingredients, a good example of which is pigment obtained from microalgal culture.

[208] http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19944.pdf.
[209] http://www.equateq.com/
[210] http://www.winterisation.com/EN-Presentation-201.html

5.103 Recognising this challenge, the study also began to investigate the opportunities for obtaining some useful material, especially lipid, as a result of it being a by-product, co-product or even waste product from an existing process using algae – one which up until now has had no focus on products for animal feeds. The rationale is that if the core process is already commercially viable, then a by-product, if available, might be obtained at reasonable cost. The main areas or processes considered included:

- **Press cake**: a simple notion that there might be some leftover material at the end of a process, which if harvested and dried could find some application in animal feed formulation
- **Hydrocolloid Production** (Alginate and similar): a traditional industry, and relatively large scale on a global basis
- **Bio-fuel** production, and principally:
    - Methanol-to-gas via anaerobic digestion
    - Ethanol production following pre-treatment and fermentation
    - Hydrothermal liquefaction to produce 'bio-crude' oil
    - Bio isobutanol production
    - Bio diesel production

5.9.1 Press Cake

5.104 Two broad opportunities were considered: existing press cake being sold as animal feeds, and high value press cake from sophisticated microalgal processes. The latter was recommended by consultees to this project[211], and was followed up by direct contact with one of the key industry experts.

5.105 One existing range of products is Vivergo's pellets for animal feeds[212], a by-product from bio ethanol production. The challenge from an aquaculture finfish feeds manufacturing point of view is the proximal analysis of these pellets, as Table 12 indicates. The feed companies might want to consider these products, but it would appear that the indigestible bulk issue is relevant. Also, the digestibility of the protein is unknown. The company was contacted for further information, but declined to reply. If the bulk issue is limiting, this might tend to apply to <u>all</u> simple press cake solutions from bio ethanol production. It does however imply that **there is some lipid remaining in a 'useable' form after the processes involved in bio ethanol production**, and that is important to note. The Scottish finfish feed companies should obtain some of this material and have the lipid analysed for its fatty acid content. If it does appear to be interesting, it would be worth contacting the Vivergo Partnership (or BP) and ascertaining whether there is any cost-effective way to obtain the lipid, before it is incorporated into the animal feed pellets.

Table 12. Proximal analysis of Vivergo pellets.

Dry Matter	92%
Energy (MJ ME/kg DM)	13.7
Crude protein	32%
Oil	6.5%
NDF	29%
Starch	2%
Sugars	1%

5.106 The other approach was to ascertain whether there was any 'press cake' opportunity from processes that were already focused on production of n-3 rich lipids, such as the DuPont-

[211] Pers com: Prof. G. Bell, Institute of Aquaculture
[212] http://www.vivergofeeds.co.uk/vivergo-pellets.html

led project[213]. The leader of the project was contacted, but has not responded. There may be two fundamental problems with this opportunity:

- This particular operation is based on an 'engineered' micro-organism, and thus falls into the area that is covered in Section 6
- Recalling Figure 16, there is only a relatively small volume of product coming from these advanced microalgal processes, probably 5,000 – 10,000 tonnes per year excluding *Spirulina*. The 'press cake' waste material might be small in overall volume, and therefore might not offer a mainstream opportunity for modern salmonid feed producers.

5.9.2 Hydrocolloid Production

5.107 The earlier review of bulk volumes of macroalgae immediately available suggested that they are uncompetitive with terrestrial plant proteins as ingredients. Those species with interesting protein concentrations are currently marketed into human food use at prices far above possible ingredients for salmonid feeds, while those with lower protein content would have too much bulk and still are moderately expensive compared to other sources.

5.108 The study has thus researched the use of by-product from current extractive processes to examine whether there is any very cheap waste or low value product flowing from the process which might have some residual protein or lipid and so be of interest as a very low grade and cheap marine ingredient.

5.109 Hydrocolloids are currently extracted from a range of red and brown macroalgae. The hydrocolloid industry was originally based on wild seaweed, but apart from the relatively low volumes still gathered from the wild, the majority of the supply is from farmed product in Asia.

Hydrocolloid	**Source genera**
Agar	*Geledinium* *Gracalaria*
Carrageenan	*Kappaphycus / Eucheuma*
Alginate	*Laminaria*

The process flow for each product is shown in Figures 32 and 33[214].

[213] http://sim.confex.com/sim/raft8/techprogram/P13173.HTM
[214] FAO Fisheries Technical Paper No 441, 2003, A guide to the seaweed industry, Dennis J McHugh.

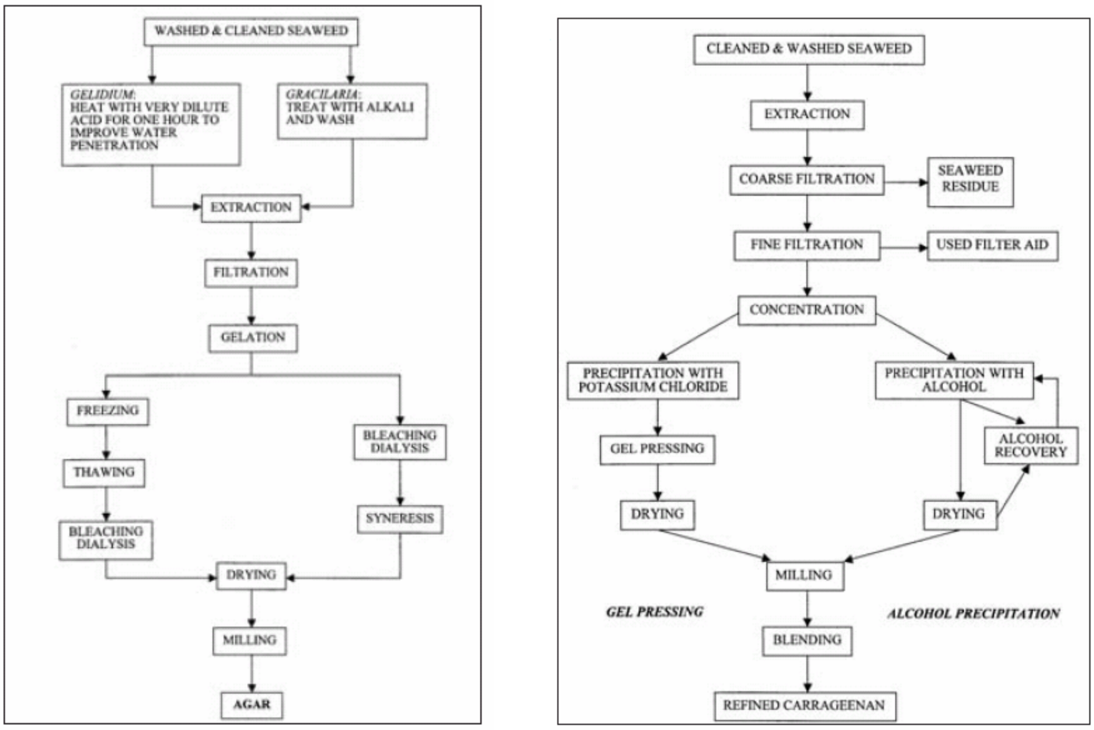

Figure 32. Process flow for extraction of agar (L) and carrageenan (R).

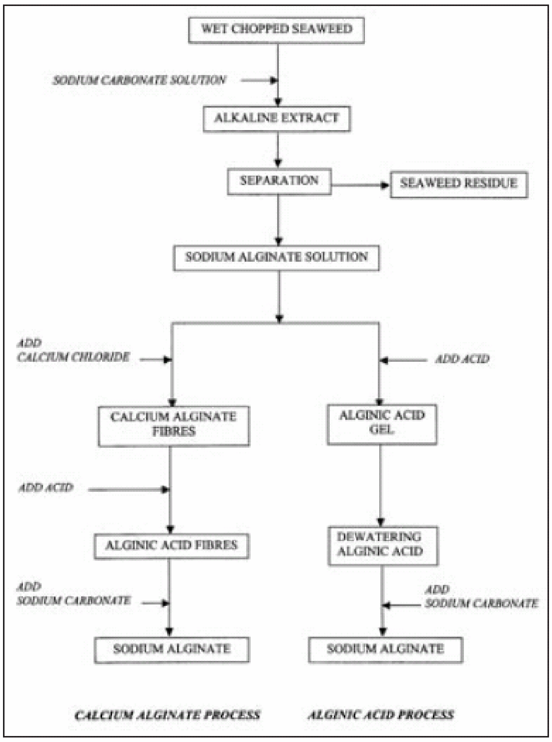

Figure 33. Process flow for extraction of alginate.

5.110 All three processes use a fairly hash alkaline extraction step early in the process. Industry and academic sources consulted[215,216] suggest that this may de-nature or oxidise the low levels of lipids contained within the algae.

5.111 The agar process uses predominantly *Gracalaria*, with *Gelidinium* only being produced in small quantities in China, so the route suggesting acid treatment of the latter species is not commonly used. Heat is applied in the alkali extraction process, around 85-90°C for one hour. It seems likely that this would denature any proteins present. Filtration is used to remove the remaining solid fractions of the seaweed, and diatomaceous earth is commonly used as a filter aid. The resultant waste is thus a sludge of filter aid and seaweed particles. This has no commercial value, but even if dried and milled it seems that the protein and lipid content would too low to consider further.

5.112 The carrageenan process varies according to the grade of material desired. Refined carrageenan is produced in steps not unlike that for agar, and with a similar filtration and filter waste being produced. Semi-refined carrageenan is produced by immersing whole plants in alkali, in this case potassium hydroxide, but the potassium salts bind with the carrageenan. Any solubles are washed away and then the residual plant, containing carrageenan is dried, chopped and sold, either as a binder in canned pet foods or to producers of refined carrageenan, where it will go through the conventional process. Current uses for the filter waste in the Philippines is as a soil conditioner[217].

5.113 The alginate process also uses a hot alkali extraction process at the start. In this case the filtrate product is usually very fine pieces of cellulose which become mixed with diatomaceous earth and large quantities of water that are needed in the process to dilute the sodium alginate sufficiently for filtration to take place, (sodium alginate forms a thick gel). The waste is thus an alkaline slurry and is of no commercial use, in spite of research into possible uses for treating heavy metal wastes and using the cellulose as a source for ethanol production. Some production facilities evidently simply discharge the slurry to sea, or where environmental sensitivities are greater, evaporate the water in ponds and send the residue to land fill[218]. The useful nutrient content for fish in this residue is likely to be very low indeed.

5.9.3 Bio-Fuel Processes

5.114 This is a potentially very complex area, particularly if there are any ‘alternative options’ for the way one or other of the bio-fuel production processes are applied. In summary:

- **Methanol-to-gas via anaerobic digestion**. The process itself is chemically harsh from the start[219], and is not likely to yield residual lipid in any useable form
- **Ethanol production** following pre-treatment and fermentation. As noted above for the Vivergo product, there is a hope that a fermentative process (acting on carbohydrates) would leave the lipid relatively intact, and potentially useable. The concern was whether the ‘pre treatment’ required to convert the carbohydrate into a form that could be fermented would denature the lipids. This would not be an issue if the lipid was pressed out before this step, which appears to be an option[220]. On balance, this process should be explored further with respect to algal lipid production for animal feeds

[215] Pers com: Prof. K.Black, SAMS
[216] info@cybercolloids.net
[217] Pers comm: Desmond Tan, CPKelco,
[218] Pers Comm, Dennis McHugh, former alginate plant operator and FAO seaweed industry expert.
[219] http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19944.pdf
[220] See particularly: http://www.oilgae.com/algae/pro/eth/eth.html

- **Hydrothermal liquefaction (HTL)** to produce 'bio-crude' oil. Once again the initial HTL reaction is a harsh one: 120 to 180 bar of pressure, and temperatures of 300-350 C. The end product is described as a 'bio crude oil', but it is unclear whether this retains any of the n-3 HUFA fatty acids needed for the nutrition sector
- **Bio isobutanol production**. This process is seen as being one of the main ways to go in terms of bio-fuel production from algal biomass (and other raw materials)[221]. Once again it is a fermentative process (so called ABE anaerobic fermentation using a strain of *Clostridium* as the active microorganism), and since it is fermenting carbohydrates, the role of any lipid in the process is secondary. Further investigation is warranted.
- **Bio diesel production**. There is slightly confusing or conflicting information about the process used in this approach. On the one hand[222]: "*In this process the green crude is mixed with a catalyst, such as sodium hydroxide and an alcohol, such as methanol, resulting in biodiesel mixed with glycerol*"; on the other hand[223] the oil can be extracted first, and then trans-esterified with sodium hydroxide and an alcohol. The point is perhaps moot, since the algal oil is quickly turned into something else – useful for bio-fuel but of no interest to animal feeds. It is noted, however, because if a producer of bio diesel thought there was a more valuable market for a percentage of the oil he extracts as a first step, there may be opportunities. Further investigation is warranted.

5.115 The summary above is very brief, because the entire area is complex. It is important to stress that the study team, recognising its limitations in understanding all the chemistry involved, contacted all the companies and researchers it could identify in the bio-fuels sector, to ask for assistance and further information. Many did not reply, but some did, and were very helpful.

5.116 The initial indications are that the prospects of tapping into one or other bio-fuel production process in order to obtain feed-grade lipids are interesting, and will be reflected in this report's final recommendations. This assumes that the core production costs of microalgae for bio-fuels come down to a reasonable level, and that is still a matter of some concern.

5.10 Trade Issues

5.117 No particular barriers to trade are foreseen. Trade of fish meals and fish oils is already international, and it is difficult to imagine why there would be any restriction on new algal-based products that were intended for animal feeds.

5.11 Regulatory Issues

5.118 There are perhaps two main 'regulatory' areas to consider:

- Regulations that do or could impact on the ability to cultivate macro or microalgae, particularly in Scotland
- Regulations that relate to the nature of the algal product(s), and whether or not they can be authorised for use in aquaculture finfish feeds – and if so, under which particular category of ingredient.

5.119 James (2010) covers the issue of regulation for macroalgae production in Scotland, and clearly identifies that some existing regulatory regimes will have to be adapted. This is

[221] http://www.bio-fuelstp.eu/butanol.html
[222] http://www.oilgae.com/algae/oil/biod/biod.html
[223] http://www.scribd.com/doc/24843618/Algae-biodiesel

unlikely to be a bottleneck as far as the objectives of this study are concerned, and is unlikely to be major hurdle for production aimed at bio-fuels.

5.120 The regulations that relate to animal feed production in EU27 are very well summarised on the Food Standards Agency website[224], and there is a useful summary of specific algal regulatory issues in Holdt & Kraan (2010)[225]. Most of the focus in Holdt and Kraan is on EU and international legislation that pertains to the use of algal products as direct food for humans, or as additions to other food products to enhance their nutritional properties, i.e. functional foods. The relevance of these provisions for an algal product that is intended for use as a component of an aquaculture finfish diet is difficult to assess, but the overall review is comprehensive and interesting.

5.121 This study does not propose to investigate this issue further, for two main reasons:

- Discussions with the finfish feed manufacturers in Scotland touched on this specific issue, and it is clear that the experts within the companies already have a clear understanding of their legislative obligations: this issue would not be a bottleneck or constraint, if suitable products were to become available
- The study shows that emphasis on further work should focus on actually identifying products that can be sourced cost effectively, perhaps as co-products from other processes. The challenges in that area are sufficiently daunting for the time being, and probably for some years to come. Animal feed regulations can be re-examined when or if products look as though they are going to be available.

5.12 Summary

5.122 Section 5 has covered a broad area of research on both macroalge and microalgae, including: current production quantities and value; current uses; future uses; economics of using algae; processes involved in harvesting or using algae; trade and regulations.

5.123 The focus has consistently been on the opportunities for producing algal materials that could enter the aquaculture finfish feeds sector at affordable prices and of an appropriate quality, although this has necessitated a consideration of the wider economics of algal production for other purposes.

5.124 Macroalgae are overall considered unsuitable as ingredients for aquaculture finfish feeds. Their protein content is too low to compete with other plant sources and it appears that of those species immediately available in bulk, the lipid content is too low to make them interesting. The majority of the seaweed produced goes through various extractive processes but these are too harsh to produce by-product of any significant nutritional value.

5.125 Microalgae are nutritionally more interesting than macroalgae, but the current cost of production is too high to provide any bulk material input to aquaculture finfish feeds. However, if bio-fuel production from microalgae becomes, in the future, commercially viable, there would be potential to tap into its processes in order to obtain materials (mainly lipid but perhaps protein) that could be used as bulk components in aquaculture finfish feeds.

[224] http://www.food.gov.uk/foodindustry/farmingfood/animalfeed/animalfeedlegislation
[225] Op cit reference 52.

6 FUTURE TRENDS

6.1 Introduction

6.1 All the basic nutritional building blocks for feeding finfish species such as salmon exist within the cells of marine algae – although not all within a single species of alga, in the right combination. The challenge is to obtain each of them in a form that is realistically affordable, and that would not compromise other key attributes of salmon diets.

6.2 The main pressure on the entire sector at the moment is seen to be the general global supply situation for n-3 HUFA rich lipids. It is particularly pressing for the Scottish salmon farming sector. However, the long term future for secure supply of n-3 HUFA lipids is a global issue for all salmon farming, and for all sectors involved in human and animal nutrition. Solutions are required, and there is a sense of urgency, at least in the medium term, to find them.

6.3 On the basis of what has been learned during the course of this study, there appear to be three core options open for mainstream provision of n-3 HUFA rich lipids from algal or plant sources:

- Increased efficiency or economy of scale on the part of the companies that are already producing EPA and DHA rich lipids, moving the cost of production to the point where their products could be sold affordably in the aquaculture finfish feeds sector

- Co-products or by-products from a developed and efficient microalgal-based bio-fuels sector – with perhaps a slight opportunity from macro-algal based bio-fuels

- 'Engineered' products that can deliver the lipids required as a 'primary' industrial process.

6.4 The first area has already been covered, and it should be noted that some of the companies are undoubtedly aware of the market opportunity. The costs associated with their processes are currently high, both setup and operation, including raw materials as nutrients. The sector will no doubt develop and change, and if product comes onto the market at the right price it will be quickly taken on board by the aquaculture finfish feeds sector. There are hopeful signs that this sector is increasingly looking at products that can go into the aquaculture feeds sector, as well as into the human nutrition market[226]. Strictly speaking, some of the organisms involved in this area are not 'algae'.

6.2 Bio-fuel Developments

6.5 The algal bio-fuel sector is potentially very large, and as this study has shown, there might be possible opportunities for products to flow as co-products from some of the bio-fuel production processes. There is little more that can be covered at this stage, but the subject is included in the recommendations in Section 7. The main cautionary note is whether bio-fuel production from microalgae is itself likely to be profitable in the long term. If it proves not to be so, the point about animal feed co-products becomes moot: without the foreseen economies of scale from the bio-fuel sector, the costs of production for animal and finfish

[226] http://www.msnbc.msn.com/id/42557922/ns/business-us_business/

feeds alone would appear to be prohibitive. This also has relevance to the specialised lipid producers discussed in Section 6.1: can stand-alone microorganism production ever deliver n-3 HUFA rich lipids at a cost that aquaculture feed manufacturers can afford?

6.6 Benemann (2008 see Table 5) summarises his position on this area, based on his research and experience, as: "*The cultivation of microalgae for bio-fuels in general, and oil production in particular, is not a near-term commercial prospect. Aside from some niche but significant applications in wastewater treatment, this technology still requires a considerable R&D effort. This is due in part to the high costs of even simple algae production systems (unlined, open, paddle wheel-mixed, raceway-type ponds), in even larger part due to the presently undeveloped nature of algal mass culture technologies, from the selection of algal strains that can be stably maintained in the open ponds, to their low-cost harvesting, and, most importantly, due to the need to achieve very high productivities of algal biomass with a high content of vegetable oils or other bio-fuel precursors, required to cover the high capital and operating costs of algae production. However, R&D efforts to overcome these limitations are justified by the potential of this technology and its non-competition with food crops."* The last point is important, and echoes the comments made by Olsen (2010): the increasing need to conserve terrestrial crop production for human nutrition in the future.

6.3 Genetically Modified Organisms

6.7 There is work on 'engineered' microalgal organisms[227], and algae in general[228]. The sensitivity of the issue of genetic modification is acknowledged, but there is another caveat attached to this type of development: the overall high cost of production of microalgae (or related microorganisms). There are existing non-engineered microalgal species and related organisms that can produce high yields of lipids, and some that can produce high yields of DHA-rich lipids. There is only so much lipid an algal cell can hold, and therefore only so much EPA or DHA that can be 'engineered' into the cell. Such improvements in yield could be in the area of tens of % points – but the cost-reduction required to make EPA/DHA lipid available to the finfish feeds sector requires order-of-magnitude changes at the present time. The work that is underway is of course not focused on the aquaculture sector, and so some of the improvements that are sought through use of engineered micro-organisms will be beneficial to other sectors.

6.8 **This is not necessarily as limiting an issue in the case of terrestrial plants**, where there is a long tradition of harvesting and extraction of lipids, as attested by the fact that vegetable oils are common and affordable household and industrial ingredients. The transport and extractive infrastructure already exists, and if a vegetable oil production facility were presented with a raw material that was genetically enhanced to contain high levels of n-3 HUFA lipids, it could process them just as easily as it currently does for sunflower or olive or any other vegetable oil – some of which are affordable for the finfish aquaculture feeds sector. Consultees to this study have strongly supported this line of thinking: if there is to be useable n-3 HUFA rich lipid available from plant sources at an affordable price in the mid-term, it is going to come from 'engineered' terrestrial plants in the first instance.

6.9 On the basis that the most likely source of DHA/EPA will be from engineered terrestrial plants, any further consideration of this topic would be outside the remit of this project.

[227] http://sim.confex.com/sim/raft8/techprogram/P13173.HTM
[228] http://www.eolss.net/ebooks/Sample%20Chapters/C17/E6-58-03-03.pdf

However, because of the pressing need for EPA and DHA in the salmonid aquaculture sector, it is worthwhile noting that research in this area is progressing rapidly[229,230].

6.10 Although not an initial objective of the research, the Project Steering Group suggested that a consideration of the regulatory framework for engineered feed ingredients would be appropriate. Whilst this would now appear to be outwith the remit of the project if the source is likely to be terrestrial plants, it is worth commenting briefly that full details on this subject are available from the FSA[231]. Of particular interest is the statement that: *"Products such as meat, milk and eggs from animals fed on GM animal feed also do not need to be labelled."*

6.4 Other Opportunities

6.11 This study has led to the general conclusion that the macroalgae are unlikely to supply materials that are appropriate or affordable for salmonid finfish aquaculture feeds, at least as a major component of diets. This certainly appears to be the case for the species of macroalgae that are being considered for bio-fuel production in Scotland. However, it is important to be certain that, from a Scottish perspective, no potential opportunities are being missed or overlooked.

[229] http://www.ecosmagazine.com/?act=view_file&file_id=EC118p34.pdf
[230] http://www.nottingham.ac.uk/ncmh/BGER/pdf/volume_24/12-Qiu-BGER.pdf
[231] http://www.food.gov.uk/gmfoods/gm/gm_labelling

7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

7.1 This research project has covered a very wild field of scientific and commercial activity, the main results of which can be summarised as:

- Lipids are the most limiting global commodity for aquaculture finfish feeds – especially n-3 HUFA rich lipids containing EPA and DHA

- All the other nutritional ingredients in finfish diets are not so limiting, although they could come from algal sources if the specifications and cost are appropriate

- Salmonid finfish diets are high energy, designed to produce optimum fish growth whilst minimising environmental impacts. Potential new feed components should deliver high nutritional advantages in relation to the percentage volume of inclusion in the diet

- The Scottish industry's main requirement is for up to 10,000 tonnes per annum of EPA and DHA rich lipids – from whatever source

- The industry could currently justify paying something in the region of **£2,200 per tonne** for a lipid containing just EPA and DHA at prevailing market prices, although it should be noted that market prices fluctuate considerably, and that this figure is indicative only.

- There is a very large variation in both the proximal makeup and the fatty acid makeup of algae, whether macro or micro. On that basis, it is impossible to rule out the future use of algae of either type as a source of components for aquaculture finfish feeds

- The composition of algae varies considerably within a single species, depending upon environmental conditions – often culture conditions in the case of microalgae

- The implication is that culture conditions, for the best species, could be enhanced for the purposes of producing a nutritional component for future use in aquaculture finfish feeds, particularly considering that:
    - Whilst algal proteins might need some blending with other sources, or amino-balancing in some other way, some of them are inherently quite 'useable' in animal feed formulations
    - Fatty acids are basic nutritional building blocks, and for specific fatty acids that are required in finfish diets, whether they are sourced from marine animals or from algae is relatively unimportant – as long as the cost is competitive

- In theory the possibility of optimising culture conditions for certain selected species could apply to macroalgae as well as microalgae

- However:
    - It is likely to be more difficult to control culture conditions in the locations that macroalgae will be cultivated
    - The average protein level in a macro alga species (as found in our literature review) is around 18-25% of dry matter, as compared with 41% for all the microalgal species considered

  - The average lipid level in macroalgae is only 1 or 2% of dry matter in the red and green algae, and 10% in the brown algae, although only around 2% in those commonly cultured. The average across all the microalgae is 20%
  - There are 18:3 n-3; 20:4 n-6 and 20:5 n-3 fatty acids in both macro and microalgae – although very much dependent upon species. However, there is little evidence of much 22:6 n-3 fatty acid in any macroalgae, whereas some microalgae contain very high amounts of it
  - Although there are examples of both micro and macroalgal species with much higher levels of protein or lipid it is likely that microalgae would provide the high yielding candidates most suitable for use in finfish diets.

- Macroalgae are overall considered unsuitable as ingredients for aquaculture finfish feeds. Their protein content is too low to compete with other plant sources and it appears that of those species immediately available in bulk, the lipid content is too low to make them interesting.

- The majority of the seaweed produced goes through various extractive processes but these are too harsh to produce by-product of any significant nutritional value.

- The production of microalgae is much more limited in volume terms than macroalgae: estimated at a few thousand tonnes a year of *Spirulina*, mainly in Asia, and some 5,000 – 10,000 tonnes a year of other species intended for use in the nutracueticals and related markets

- The sales price of all current microalgae products renders them too expensive for use in aquaculture: no less than **£5,000 per tonne**, but usually much more, for *Spirulina*, and averaging **£150,000 per tonne** for the remainder, with much higher prices for specialised DHA-rich products

- There is a long tradition of culturing and using microalgae for marine finfish and shellfish hatcheries, and even with the most realistic estimates and a microalga with a lipid content of 50%, the cost of the lipid might be between **£6,150** and **£152,000 per tonne,** before taking into account processing costs. This may be affordable for hatcheries, but does not meet the cost requirements of the finfish ongrowing sector

- Heterotrophic microalgal species are also produced, but the cost of end products is very high at the present time. As lipids, they are entering the direct human consumption markets as ‘nutraceuticals’ for incorporation into ‘functional foods’ and other products such as capsules, and these markets can pay considerably more than the finfish feed producers can

- The expectation that algal-oils could be produced for the human market, and somehow take the pressure off prices for n-3 HUFA rich oils from traditional sources, would seem to be optimistic. An abundance of n-3 HUFA rich oils would seem to be the solution

- The algal bio-fuels sector is of interest to this study, because <u>if</u> it can deliver product at the prices its market can afford, there is a chance that it can also deliver algal feed components to the aquaculture finfish feeds sector at the right price

- The economics of algal bio-fuels is still a matter of some conjecture, and there are some obvious basic ‘laws of nature’ issues that should be addressed, including the question of whether the focus should be on phototrophic or heterotrophic production of ‘microalgae’

- Some of the fundamental ‘processing’ steps that are required to transform a raw algal material into a useable product are reviewed – all of them have cost

- Whilst it does not seem likely that useable by-products or waste products can be obtained from industrial processes that are or could be applied to macroalgae, this is not necessarily the case for bio-fuel production from microalgae, and further research is warranted

- The constraints to taking the idea of algal materials for aquaculture feeds forward are probably not, at least at this stage, regulatory or trade issues

- There are algal products that could already be used in the finfish aquaculture feeds sector, and these are either micro nutrients such pigments, or ‘additives’ based on macroalgae, for which the evidence for inclusion at even a level of 15% is not yet enough to persuade the feed companies. Other aquatic plant-based products are considered, and whilst their use should not be anticipated in salmon diets, they may have some applications in animal feeds in the future

- Genetic engineering is briefly considered, and its hypothetical use would be most appropriate in terrestrial plants, where the infrastructure to extract lipids cost-effectively is already in place

- No opportunities should be ruled out, and although the present study’s overview might appear to advise against certain types of algae or system, exploration of the possibilities that could be presented by unusual ‘outlier’ species and novel technologies cannot and should not be ignored.

7.2 Conclusions

7.2 That algae contain the basic nutritional building blocks for carnivorous finfish species such as salmon is clearly not in doubt. That modern salmon diets can use as much vegetable materials as they currently do is the result of good science applied in the field of animal nutrition. Finfish nutrition is an innovative sector, and it is backed by good science. It will not ignore a real opportunity, wherever that might arise. It is also a sector that keeps a very careful watch over what is happening with raw materials. **If algal-originated products are developed and come on to the market at the right price, there is no doubt the aquaculture finfish feeds sector will take them up.** In the longer decadal term, the need to move finfish species aquaculture further down the trophic gradient is also very clear.

7.3 This study has found no obvious **current** opportunities to use new algal materials in aquaculture finfish diets for species such as salmon – or rather, none that are mainstream in terms of percentage inclusion, or that have been somehow overlooked.

7.4 On the other hand, the study has identified areas where such products could potentially become available in the future, and some of these are covered in this report’s final recommendation. Key points are:

- Microalgae (or related organisms) grown primarily for a future commercially viable bio-fuels sector offer good prospects – although most experts agree that this is a challenging area, and success is likely to be some way in the future

- If microalgae *could* be cost-effectively grown to supply the bio-fuel sector, it is certain that they could be specifically grown cost-effectively to produce animal feeds, including feeds for finfish such as salmon

- If that were the case, judicious choices of species might offer the prospect of supplies of both n-3 HUFA rich lipids **and** high quality proteins

- Engineered terrestrial plants offer the potential to provide n-3 HUFA rich lipids at affordable prices in the near future, although their use in salmon diets in Scotland requires further work on consumer and regulatory issues

7.5 The frustrations of researchers and would-be developers in all fields of algal production, whether for food, feeds, bio-fuels or waste treatment are well-articulated by Wellinger (2009)[232], who points out that there is so much activity, most of it with little commercially relevant output yet, that there is a great danger of wasteful overlapping or duplicated expenditure on effort. Nevertheless, the long term need to extract much more human food from the marine environment is also very clear (Olsen 2010), and therefore research remains necessary. As far as algal materials for finfish diets is concerned, research effort should be focused on priority topics that offer some well-identified opportunities. It is also important to stress that despite the fact this sector would benefit from the development of a successful algal bio-fuels sector, there is little merit in specifically investing in mainstream research in this area: others are already doing that, and **on a very large scale**. Rather more focused investigation of exactly how aquaculture feed ingredients could be extricated from bio-fuel process (if they did become commercially viable), on the other hand, would be warranted.

7.3 Recommendations

7.6 On the basis of the current state of knowledge about the subject of algal materials for incorporation into aquaculture finfish feeds, there is no compelling argument for a specific policy initiative on the part of the Scottish Government, other than for it to maintain its ongoing interest in algal bio-fuel production potential in Scotland, and to maintain its support for applied aquaculture research, especially if that can be used to ‘fold’ nutritional aspects into the mainstream work on algal bio-fuels.

7.7 The following specific research topic is considered important**:**

- **An expert and critical review of the various bio-fuel production processes, with a focus on the potential of any of them to provide a side-stream capacity for extracting algal lipids that could be used in finfish diets.**

[232] http://www.iea-biogas.net/_download/publi-task37/AlgaeBiomass8-09.pdf

ANNEXES

Annex 1. Steering Group Members

Mark James – SARF
Piers Hart – SARF / WWF
Michael Wright – Marine Scotland
Alex Adrian – The Crown Estate
Dawn Purchase – Marine Conservation Society
Richard Luney – Marks and Spencer
Hannah MacIntyre – Marks and Spencer
Niall MacDonald – EWOS
Paul Morris – Skretting
Nick Bradbury - BioMar

Annex 2. Consultation Contact Details

Table A1. Finfish feed manufacturers.

Organisation	Date	Format	Response
Skretting	25 Jan 2011	Meeting	Yes; helpful
Ewos	26 Jan 2011	Meeting	Yes; helpful
Biomar	1 Feb 2011	Meeting	Yes; helpful

Table A2. Research organisations.

Organisation/Individual	Date	Format	Response
SAMS Dunstaffnage: K. Black; A. Hughes	8/9 Feb 2011	Meeting	Yes; helpful
Institute of Aquaculture: G.Bell	15 Feb 2011	Meeting	Yes; helpful
University of Swansea: R.J.Shields	8 Apr 2011	Telephone	Yes; helpful
TNO, Netherlands	Jan 2011	Email	No
Robert Ackman, Canada	9 Mar 2011	Email	No
NAABB, USA	9 Mar 2011	Email	No
University of Idaho, USA: Ron Hardy	March 2011	Email	Yes; helpful
Los Alamos Nat Lab, USA: E.Sullivan	25 Mar 2011	Email	Yes; but no follow-up yet
Plymouth University: S.Davies	28 Mar 2011	Email	No
Murdoch University, Australia	28 Mar 2011	Email	No

Table A3. Commercial organisations 1: Macroalgae-related.

Company	Country	Method	Activity	Response
Agarpac	Chile	email	Agar extraction	
CPKelco	USA with plant in Philippines	on line form	Carrageenan, alginate extraction	✓
Cargill Texturising solutions	USA with plants in Phils, China	on line form	Carrageenan, alginate extraction	
Danisco	Denmark / international	on line form	Carrageenan, alginate extraction	
Estagar	Estonia	email	Agar extraction	
FMC bioploymer	USA with plants in Phils, China	on line form	Carrageenan, alginate extraction	
Gelymar	Chile	on line form	Carrageenan extraction	
Iberagar SA	Portugal	email	Agar extraction (wild)	
Meron Group	India	on line form	Agar extraction (wild)	✓
Qingdao Bright Moon Seaweed (	China	email	various extractive	
P.T. Agarindo Bogatama	Indonesia	email	Agar extraction (cultured)	
PT Amarta Carrageenan	Indonesia	email	Carrageenan extraction	
Roko SA	Spain	on line form	Agar extraction (wild)	
Shemberg Corp	Philippines	email	Carrageenan extraction	
SNAP Ltd	India	email	Alginate extraction (wild)	
TBK	Philippines	email	Carrageenan extraction (cult)	

Table A4. Commercial organisations 2.

Organisation/Individual	Date	Format	Response
Origin Oil, USA	11 Feb 2011	Email	No
Solix Bio-fuels, USA	11 Feb 2011	Email	No
BA Lab, USA	9 Mar 2011	Email	No
PetroAlgae, USA	9 Mar 2011	Email	No
Source-Omega, USA	9 Mar 2011	Email	No
Vedan, Taiwan	9 Mar 2011	Email	No
Algenol Bio-fuels, USA	9 Mar 2011	Email	No
Heliae, USA	9 Mar 2011	Email	No
Sapphire Energy, USA	9 Mar 2011	Email	No
BioProcess Algae, USA	9 Mar 2011	Email	No
Phycal, USA	9 Mar 2011	Email	No
Solazyme, USA	9 Mar 2011	Email	No
Targeted Growth, USA	9 Mar 2011	Email	No
Ocean Harvest, Ireland	12 Mar 2011	Email	Yes; helpful
Algae At Work, USA	12 Mar 2011	Email	No
Algaedyne, USA	12 Mar 2011	Email	No
AlgaeVS, USA	12 Mar 2011	Email	No
Aquatic Energy, USA	12 Mar 2011	Email	No

Aurora Inc, USA	12 Mar 2011	Email	No
BioAlgene, USA	12 Mar 2011	Email	No
Cellana, USA	12 Mar 2011	Email	No
Evodos, USA	12 Mar 2011	Email	Yes; helpful
Greenwater Global, USA	12 Mar 2011	Email	No
Independence BioProducts, USA	12 Mar 2011	Email	No
Kent BioEnergy, USA	12 Mar 2011	Email	No
Kuehleangro, USA	12 Mar 2011	Email	No
OpenAlgae, USA	12 Mar 2011	Email	No
PhycoBiosciences, USA	12 Mar 2011	Email	No
Solix Bio-fuels, USA	12 Mar 2011	Email	No
Verno Systems, USA	12 Mar 2011	Email	Yes; not relevant
Scottish Bioenergy, Scotland: David Van Alstyne	12 Mar 2011	Email/Tel	Yes; helpful
Dupont, USA: Michelle Reardon	13 Mar 2011	Email	No
AB Agri, UK: Richard Cross	13 Mar 2011	Email	No
Seaweed Health Foundation, UK: Craig Rose	25 Mar 2011	Email/Tel	Yes; helpful
Winterisation, France	28 Mar 2011	Email	No
BAL/Statoil	28 Mar 2011	Email	No
Cyanotech, USA	28 Mar 2011	Email	No
New Horizons Global, UK	28 Mar 2011	Email	No
Equateq, UK	28 Mar 2011	Email	Yes; helpful
Dupont, USA: Ethel Jackson	28 Mar 2011	Email	No
Cybercolloids, Ireland	28 Mar 2011	Email	Yes; helpful
ExAlgae, UK: Steve Rist	28 Mar 2011	Email	No
Seaweed Ireland	28 Mar 2011	Email	Yes; helpful
National Algae Association, USA	7 Apr 2011	Email	Yes; helpful
FMC Biopolymers, UK	7 Apr 2011	Email	Yes; no follow-up yet

Annex 3. Example of a Structure Contact Message

RESEARCH INTO ALGAL INGREDIENTS FOR AQUACULTURE DIETS

Dear Sirs,

We are conducting a research project for the Scottish Aquaculture Research Forum (SARF), details of which can be found here: http://www.sarf.org.uk/Docs/Final%20Press%20Release%20SARF077%20-%2015-12-10%20v1b.pdf.

Proteins and lipids for animal feedstuffs, including finfish such as salmon, are a large market globally, and they command reasonable prices. Lipids with long chain fatty acids (EPA and DHA) are particularly important, since there is a finite supply from traditional sources.

We have noted with great interest your company's active involvement in the field of algal cultivation, and would be grateful if you could answer the following questions:

1. What is the main purpose of your research or production?
2. What is the main market for the products you are or will produce: bio-fuels; pharmaceuticals; nutraceuticals; etc?
3. Have you considered whether the processes you are using are capable of providing food grade proteins or lipids for the animal and finfish nutrition market:
    a. Either as a deliberate production process – either for extracted protein, or lipid, or both?
    b. Or as a by-product or even suitable waste product from your process (e.g. a 'press cake', filtrate, or similar) which could be incorporated into finfish feeds?
4. If you do have a potentially suitable product or by-product, what quantity would be available per year?
5. What happens to such products or by-products at the moment?
6. Do you have any data on the nutritional profile of products or by-products, particularly fatty acid profiles?
7. Are there any scientific publications relating to your products, and if so could you please provide references?
8. Could your product or by-product be dried or otherwise rendered suitable for exported?
9. If so what would be the unit cost CIF to Europe?

Our sincere thanks in advance for your help with this important research project. All individual responses will be collated on a non-attributable basis, unless you indicate that you would like to be specifically referenced in our report.

Yours faithfully,

Annex 4. Extracts from Bio-Fuel Resources

The cheapest algae available today, supplements for the food industry, costs about \$5000/ton. Fuel-grade products made from algae of mid-range lipid content (35%) at \$5000/ton would cost over \$50/gal in large volume. To the best of our knowledge, the best actual photosynthetic algal oil production that has been demonstrated thus far over a period of two years or more, from an area greater than 1 acre, is less than 250 gal/acre/yr. We do not know that that level has been achieved yet, as we cannot find hard evidence (and we have searched extensively), but it seems reasonable, based on other real data.	[233]
Following scrutiny of present bio-fuels, algae are seriously considered as feedstocks for next-generation bio-fuels production. Their high productivity and the associated high lipid yields make them attractive options. In this review, we analyse a number aspects of large-scale lipid and overall algal biomass production from a biochemical and energetic standpoint. We illustrate that the maximum conversion efficiency of total solar energy into primary photosynthetic organic products falls in the region of 10%. Biomass biochemical composition further conditions this yield: 30 and 50% of the primary product mass is lost on producing cell protein and lipid. Obtained yields are one third to one tenth of the theoretical ones. Wasted energy from captured photons is a major loss term and a major challenge in maximising mass algal production. Using irradiance data and kinetic parameters derived from reported field studies, we produce a simple model of algal biomass production and its variation with latitude and lipid content. An economic analysis of algal biomass production considers a number of scenarios and the effect of changing individual parameters. Our main conclusions are that: (i) the biochemical composition of the biomass influences the economics, in particular, increased lipid content reduces other valuable compounds in the biomass; (ii) the “bio-fuel only” option is unlikely to be economically viable; and (iii) among the hardest problems in assessing the economics are the cost of the CO2 supply and uncertain nature of downstream processing. We conclude by considering the pressing research and development needs.	[234]
Biodiesel production from microalgae is an emerging technology considered by many as a very promising source of energy, mainly because of its reduced competition for land. However the impact assessment and the energy balance show that algal biodiesel suffers from several drawbacks at the current level of maturity of the technology. In comparison to conventional energetic crops, high photosynthetic yields of microalgae significantly reduce land and pesticide use but not fertilizer needs. Moreover, production, harvesting, and oil extraction induce high energy consumption, which can jeopardize the overall energetic balance. It appears that even if the algal biodiesel is not really environmentally competitive under current feasibility assumptions, there are several improvement tracks which could contribute to reduce most of its impacts. A large-scale production can be seriously considered under the achievement of the following improvements: the choice of microalgal species maintaining high lipid and low protein contents with sustained growth rates (e.g., low-N culture, strain selection, or modification), the setup of an energetically efficient extraction method, and the recovery of energy and nutrients contained in the oilcake. More generally, LCA appears as a relevant tool to evaluate new technologies for energy production. Even when dealing with young and immature technologies, this tool identifies the technological bottlenecks and therefore supports the ecodesign of an efficient and sustainable production chain.	[235]
GreenFuel Technologies (www.greenfuelonline.com/) has recently generated positive publicity for their technology, which converts CO2-containing emissions from power plants into valuable bio-fuels using proprietary algal photobioreactors (PBRs). This report shows that GreenFuel’s method will not be economically feasible, even if the company achieves spectacular progress in development of its technology. Fundamental thermodynamic constrains make it impossible for such approach to be commercially viable for fuel prices below **\$800/bbl,** even if flawless technological implementation is assumed. Since other technologies offer alternative options at substantially lower costs, GreenFuel’s approach cannot be expected to have a significant place in our future energy supply or carbon mitigation strategy	[236]
To determine whether algae are a viable source for renewable diesel, three questions that must be answered are (1) how much renewable diesel can be produced from algae, (2) what is the financial cost of production, and (3) what is the energy ratio of production? To help accurately answer these questions, we propose an analytical framework and associated nomenclature system for characterizing renewable diesel production from algae. The three production pathways discussed in this study are the transesterification of extracted algal lipids, thermochemical conversion of algal	[237]

[233] http://www.dotyenergy.com/Markets/Microalgae.htm
[234] http://pubs.rsc.org/en/Content/ArticleLanding/2010/EE/b924978h
[235] http://pubs.acs.org/doi/pdfplus/10.1021/es900705j
[236] http://www.nanostring.net/Algae/CaseStudy.pdf
[237] http://bucky-central.me.utexas.edu/RuoffsPDFs/239

biomass, and conversion of secreted algal oils. The nomenclature system is initially presented from a top-level perspective that is applicable to all production pathways for renewable diesel from algae. Then, the nomenclature is expanded to characterize the production of renewable diesel (specifically, biodiesel) from extracted algal lipids in detail (cf. Appendix 2). The analytical framework uses the presented nomenclature system and includes three main principles: using appropriate reporting metrics, using symbolic notation to represent unknown values, and presenting results that are specific to algal species, growth conditions, and product composition	
The costs of harvesting microalgal biomass can be a major component of production, accounting for up to 20–30% of the total cost (Molina Grima et al. 2003).	238
Even with optimistic assumptions about CO2 credits and how far productivity could be improved, estimated fuel costs were determined to range from $1.40 to $4.40 per gallon in 1995 (Sheehan et al., 1998). While costs for the technology were deemed as never being competitive with the projected cost of petroleum diesel, the landscape has clearly changed in the intervening decade.	239
Presently the lowest cost for biomass production of the widely used algae type Dunaliella salina in open pond systems is £2-3 kg-1 of biomass (Brennan and Owende 2009).	240
The market price of EPA (95% pure) in bulk quantities was approximately $650/kg in 2000. A	241
Synthesized β-carotene is sold for a minimum of US$ 300 per kg β-carotene, and at higher process depending on the formulation. 'Natural' β-carotene commands higher prices, with the highest price attainable for the nutritional supplement application. At present the market demand exceeds supply. If a price range for formulations of β-carotene of US$ 500–1000 is assumed, and β-carotene represents 10% of D. salina biomass, production costs should not exceed US$ 50–100 per kg. In fact, costs must be significantly lower, to account for losses at each processing step, capital expense, marketing, packaging and distribution costs.	242
Based on a UNH research project, (8) Briggs then estimates the total cost of producing 140.8 billion gallons of oil (unrefined) for biodiesel at $46.2 billion—substantially less than the $100150 billion that the US currently spends to purchase foreign crude oil. Thus the large-scale algae farms envisioned by NREL would generate many jobs and substantially reduce the US trade deficit.	243
capital, operations and maintenance costs for large-scale algae systems have been a barrier to adoption for algae-based fuels processing, according to Diversified. The Simgae approach promises 1/2 – 1/16th the capital cost, profitable oil production costs at $0.08 – $0.12/pound, and low operations and maintenance requirements. Under an exclusive worldwide license, Diversified Energy will provide systems engineering and project management to commercialize the technology. he Simgae design is expected to provide an annual algae yield of 100 – 200 dry tons per acre. Capital costs are expected to be approximately $45,000 – $60,000 (a 2 – 16 times improvement over competing systems) and profitable oil production costs are estimated at only $0.08 – $0.12/pound. These oil costs compare to recent market prices of feedstock oils anywhere from $0.25 – $0.44/pound.	244
collected and processed," said Hans van de Ven, president of BioKing. "With our fast growing algae and our advanced photo-bioreactor, it only takes four days to be in full production and to collect the first algae. And the cost of biodiesel feedstock will only be 5-10 cents a litre." 0.1 US$ per L 100 US$ per tonne	245
20 US$ per barrel 126 US$ per tonne	246
Algae Bio-fuels Skeptics Emphasize Need for Realistic Outlook and Business Discipline	247
Heading the list of losers is photosynthetic algae--technology that would use algae to convert sunlight into fuel. Jim Matheson, a general partner at Flagship Ventures, said "we just don't believe the economics." Although the venture capital firm invests heavily in bio-energy technology, "we just haven't gotten very comfortable that algae is going to come down the cost curve." BP also doesn't like photosynthetic algae. "We don't think that [technology] will ever reach the kind of cost or supply that we think people are prepared to pay," said David Eyton, the head of research and technology at BP. His statement was a direct challenge to a main BP competitor, Exxon-Mobil, which recently announced an investment of $600 million in photosynthetic algae.	248

238 http://rsif.royalsocietypublishing.org/content/7/46/703.full#ref-103
239 http://onlinelibrary.wiley.com/doi/10.1111/j.1365-313X.2008.03492.x/full
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248 http://www.technologyreview.com/blog/emtech/24165/

Eyton noted that BP is investing in algae--just not the photosynthetic kind. Some companies are developing technology that use algae to convert sugar, instead of sunlight, into fuel and other products. That's easier to scale up, since the algae can be far more concentrated.	
Nobody so far has been able to produce algae cost competitively in large quantities, and – in spite of all the promising ideas — it's still unclear whether that will happen. Matt Horton, CEO of Propel and a principal at @Ventures, said his view of algae hasn't changed in the last few years. "It's one of the most promising opportunities in the liquid fuels arena, but the timelines for true commercialization are still years down the road," he said. It's tough for a company like Propel to work with algae companies at this point because it's difficult to predict – with any certainty – when algae-based fuels might realistically be delivered. When a technology like algae fuel gets as much attention as it has this summer — with politicians visiting algae fuel start-ups on a weekly basis — it becomes an easy target for the sceptics. What the industry needs right now is less hype and more proof that the pond scum can really come down in cost to reach mass commercialization.	[249]
One can grow algae but it doesn't mean it's free. Although algae is believed to be one of the chief feedstocks for biodiesel, growing large amounts of algae and then converting the single-celled creatures remains expensive. Algae bio-fuel start-up Solix, for instance, can produce bio-fuel from algae right now, but it costs about $32.81 a gallon. The production cost is high because of the energy required to circulate gases and other materials inside the photo -bioreactors where the algae grow. It also takes energy to dry out the biomass, and Solix uses far less water than other companies. But it said the production cost can be brought down to $5.50 a gallon, by exploiting waste heat at adjacent utilities. It's only in phase II of Solix's business plan that it will be able to drop production costs to $3.30 to $1.57 a gallon, or around $60 to $80 a barrel. Solix has set a goal of cutting the cost of making algae by 90 percent.	[250]
Oil production is estimated at $84/bbl if no further improvements are made. We suggest enhancements that could reduce cost to $50/bbl or less.	[251]
We're hoping to be to be at parity with fossil fuel-based petroleum in the year 2017 or 2018, with the idea that we will be at several billions of gallons," Rosenthal told SolveClimate News in a phone interview. Dan Simon, president and CEO of Heliae, an algae technology company based in Arizona, thinks industry could deliver commercial algae at the price of oil after about three years. However, he acknowledged it may take longer — perhaps as long as a decade. The current cost of a barrel of algae bio-fuel ranges from $140 a barrel to $900 per barrel. "Algae oil production will be neither quick nor plentiful — ten years is a reasonable projection for the R&D to allow a conclusion about the ability to achieve relatively low-cost algae biomass and oil production, at least for specific locations," the authors, Nigel Quinn and Tryg Lundquist of the Lawrence Berkeley National Laboratory, wrote.	[252]
RAND report: very cautious. Many years.	[253]

[249] http://gigaom.com/cleantech/the-algae-fuel-backlash-here-come-the-skeptics/
[250] http://www.oilgae.com/blog/2009/02/phycal-harvests-oil-from-algae-without.html
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