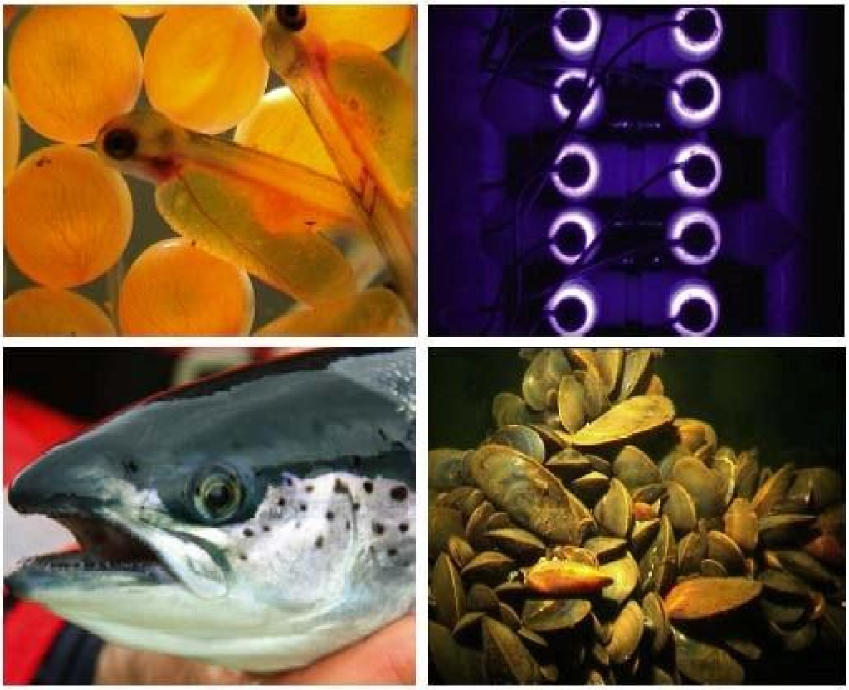
SARF106 - A Risk Benefit Analysis of Mariculture as a means to Reduce the Impacts of Terrestrial Production of Food and Energy



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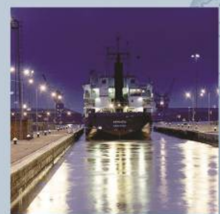
A Risk Benefit Analysis of Mariculture as a Means to Reduce the Impacts of Terrestrial Production of Food and Energy

Report R.2359

December 2015

Creating sustainable solutions for the marine environment





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Executive Summary

The world's population has been predicted to rise to over nine billion by 2050 (e.g. FAO, 2009a; Lutz and Samir, 2010), with most of this increase predicted to occur in low and middle income (developing) countries (Alexandratos and Bruinsma, 2012; Government Office for Science, 2011; Lutz and Samir, 2010). The proportion of the population living in urban areas and income levels are also expected to rise (with at least 3 billion people entering the global middle classes) which is likely to increase demand for more nutritious and higher quality foods (i.e. more resource-intensive foods such as meat and vegetable oils; Searchinger *et al*., 2013 and references therein).

The question of how to achieve such increases in food production to feed this larger, increasingly affluent population, whilst ensuring sufficient food calories to adequately feed the entire global population, in a sustainable manner (i.e. that ensures food production that contributes to inclusive social and economic development whilst reducing environmental impacts and pressures on limited resources), is the subject of current discussion and research (e.g. Searchinger *et al*., 2013; Alexandratos and Bruinsma, 2012; The Government Office for Science, 2011). An increased global population will also necessarily have greater energy requirements.

The Scottish Aquaculture Research Forum (SARF) and WWF-UK commissioned this study to investigate whether the pressure on land and freshwater for future food and energy resources, and impacts on the climate, related to greenhouse gas (GHG) emissions, may be reduced through expansion of global mariculture. The study has undertaken a high level assessment of the 'environmental footprint' of global mariculture and terrestrial-based food and energy production systems through the collation and assessment of available Life Cycle Assessments (LCA) for key food products (beef, pork, chicken, freshwater finfish, marine finfish, shellfish and crustacean species) and biomass (terrestrial and algal) for energy production. The outputs of the footprint comparison were then used to assess the risks and benefits of increasing global mariculture, through the development of projected future scenarios in which mariculture contributes differing proportions of projected future food requirements. The analysis also qualitatively considered the socio-economic and wider environmental risks and benefits (e.g. in relation to ecosystem services) of global mariculture expansion, where expansion may occur geographically and whether future technological developments may help mitigate against identified impacts.

The study identifies the key uncertainties and limitations of the risk/benefit analysis and makes prioritised recommendations on how these limitations can be addressed and the analysis developed for more regional or site-specific assessments.

Review of Global Fish and Shellfish Mariculture

The production of fish and shellfish through aquaculture has increased at an average of 5.5% per annum between 2004 and 2013 to reach 69.7 million tonnes. Currently the majority of this production is from freshwater aquaculture (62%). Marine finfish production is dominated by salmon, while mollusc production comprised mainly of clams, cockles and arkshells, oysters, scallops and mussels. Crustacean farming is dominated by shrimp and prawn production. Although the mariculture sector displays steady growth, production can vary in relation to commercial and environmental pressures including disease.

Key drivers of future mariculture production include increasing population growth and prosperity, however there is a large variation in seafood consumption per capita globally. Some projections of future demand for seafood products from wild capture fisheries and aquaculture in 2020 and 2030 were already exceeded in 2012 and future aquaculture production may have to increase by 200% compared to 2012 levels to meet some projections for 2050. For example, Wijkström, (2003) projected the demand for fisheries and aquaculture products to be 271 million tonnes (mt) seafood in 2050 (compared to 136.2mt in 2012 which comprised 69.6mt from capture fisheries and 66.6mt from aquaculture). Other key influences on future mariculture production include: opportunities and barriers to market development for the products (which include distribution networks and trade), competition for space (e.g. coastal land and marine and coastal waters with other marine sector activities) and natural resources (e.g. for feed); environmental factors (e.g. productivity and carrying capacity, disease etc.); and the impacts of climate change and technological advances (e.g. related to reproductive control, nutrition, health and welfare, equipment and engineering etc.).

Review of Global Algal Mariculture

A variety of products and commodities are derived from farmed algae (macroalgae and microalgae). These products include food (for direct human consumption or thickening agents such as carrageenan), fertiliser and for inclusion in animal feed and medicinal products, with the majority of production being for human consumption (directly or indirectly).

The global seaweed industry is estimated to be worth approximately US$7 billion per year and production has been increasing on a global scale over the last two decades reaching 26mt in 2013, (this includes macroalgae grown in marine or brackish waters and microalgae grown in seawater, brackish water or freshwater). Production is dominated by a few countries in Asia with over half of production in 2013 being attributed to China and a rapid increase in production occurring in Indonesia.

The demand for cultivated algae for food (direct consumption) is likely to continue to grow, although there is relatively limited data relating to such trends. Markets for seaweed, for example, in sushi have been growing in countries such as Australia and the UK and there is substantial growth in market potential in Europe and America. However, with regard to food security, it is anticipated that seaweed is likely to remain more of a 'garnish' than a staple food item as even in top consuming countries (e.g. Japan and Korea) seaweed constitutes 10-15% of a typical diet.

There is a high level of interest in the use of cultivated algae for use as feedstock in biofuel production (described in further detail in Section 5). Other uses for farmed seaweed that are areas of interest and research include the viability of its inclusion in livestock and aquaculture feed as a replacement for fishmeal and fish oil and in farming seaweed in integrated multitrophic aquaculture systems (IMTAs) to reduce the environmental impacts of other farming methods (e.g. finfish farming) through bioremediation. However, further research is required into both of these potential uses.

Review of Processes for Producing Energy from Algal Biomass - Efficiencies and Comparisons with other Methods

The LCA analysis indicated that production of biofuel from microalgae is currently an inefficient process. The energy balance and global warming potential (GWP) associated with the use of macroalgae for the production of energy is comparable to land crops with the benefit of negligible land use requirements. However, the feasibility of using algal biomass as a source for biofuel production is faced with substantial economic and some technical and logistical uncertainties, and considerable challenges must be overcome for the successful production and marketing of algal biofuels.

Challenges to the different biofuel production routes include components of algal biomass that are inhibitory to conversion. Other such problems may arise throughout the scaling up of conversion technology. A variety of feasible solutions to such problems might be found with appropriate research effort.

There are also challenges that relate to all algal biofuel production. Obtaining sufficiently high biomass productivity is crucial for efficient conversion to fuels, and this productivity has natural limits. High productivity is needed to generate sufficient quantities of biomass, but (notably in the case of microalgae) higher productivity may be correlated with decreased production of those algal components that are the target of production. For both macro and microalgae, wet biomass has a high transport cost and low energy content. Many of the possible conversion routes require dry biomass, necessitating drying processes that will likely be energetically and financially expensive. Drying, in addition to other steps of the fuel production chain, result in a cumulative energy demand that may approach, or exceed the energy content of the final fuel. Previous assessments have shown that the financial cost of obtaining algal biomass will likely be prohibitively high given the considered market value of the fuels produced. Some authors suggest that the combined production of biofuel and higher-value products may present an opportunity for commercial feasibility (e.g. Williams & Laurens, 2010), or that algae biomass may be combined with other feedstocks to result in financially viable alternatives (Lewis *et al*., 2011). However, these are largely hypothetical scenarios and more secure conclusions would be needed to attract the financial investment required for further development.

Technology for the production of various micro- and macroalgae algal biomass has been developed and there are examples of commercial operation, although these are for non-biofuel purposes. In contrast, data describing the conversion of algal sources for fuel production is only available from laboratory or small-scale systems. This makes it impossible to assess the potential for production of algal biofuels without large uncertainties.

Comparison of Impacts From Mariculture and Terrestrial-based Food Production Systems

The outputs of the LCA analysis for different meat and fish products showed that the worst performer for GWP, land and water use is beef. The results also show that despite being grown in marine water, some mariculture species still have a heavy dependence on freshwater and land for the provision of feeds. As many other LCAs have stated, it is the efficient use of feed which directly determines the overall efficiency of fed species and this should be the focus of improving the environmental performance of all such species. Although fishmeal/oil was associated with low GWP, land and water use impacts, there are serious concerns over the long-term sustainability of marine ingredients for the production of fishmeal and oil and any expansion in fishmeal/oil supply should focus on the full utilisation of by-products from fisheries and aquaculture processing operations. Some terrestrially-derived feed ingredients which are considered to be viable replacements for fishmeal in feed, such as gluten from wheat and maize, are very energy intensive, while others such as sunflower are water intensive and there are major concerns regarding production of soy and palm oil in relation to habitat loss. Hence the environmental benefits of replacing fishmeal with vegetable ingredients should not be taken for granted as there are many trade offs with respect to the global footprint of food production. More synergistic solutions are required between the arable, livestock and aquaculture sectors to conserve resources.

With regard to shellfish, the situation is more complicated. Although they are not fed species, they often require a lot of energy for their servicing, particularly in areas of poor water quality where more depuration is required. Unfortunately, these areas are the ones where growth has been largest and where demand is likely to increase further such as in East Asia. Apart from impacts from processing, which this report has not included, the requirement for freshwater and terrestrial land space for shellfish cultivation is minimal and more efficient on farm energy use and depuration could reduce the GHG emissions associated with shellfish production.

It is vital that these results are interpreted in the light of the methodological and data limitations including that a full weighted study combining LCAs of global systems was not possible because of lack of data and incompatibility of data in some cases. However, the results presented are in broad agreement with other similar studies such as by Nijdam *et al* (2012).

Risks and Benefits of Increasing Global Mariculture

The hypothesis that increasing mariculture can reduce the global footprint of food production (in terms of GHG emissions, land and water use) in 2050 was tested by using the quantitative LCA outputs to assess the impact of five theoretical future food production scenarios:

- Scenario 1, Business as Usual (BAU). Global meat and fish production was projected to increase from 2012 to 2050, based on recent historical production trends (million tonnes/per annum calculated between 2003 and 2012).
- Scenario 2: Increased production of low impact mariculture species. The production of shellfish species and salmon in 2050 was increased by 300% and 100% respectively compared to the BAU scenario 1 (freshwater fish production held constant at BAU Scenario 1 levels; meat production decreased to keep total global edible yield constant).
- Scenario 3: Increased production of marine and freshwater aquaculture. Production of all marine and freshwater aquaculture species in 2050 is doubled compared to the BAU scenario 1 (meat production reduced to keep total global edible yield constant).
- Scenario 4 (Visionary scenario). 50% of the total projected protein (meat and fish) demand in 2050 is provided by oysters and mussels (freshwater fish production held constant at BAU Scenario 1 levels; meat production decreased to keep total global edible yield constant).
- Scenario 5 (Visionary scenario). Global per capita fish supply in 2050 is increased to 70 kg/person for a population of 9 billion people, through increasing mariculture production, requiring 630mt of mariculture products (produced in the same relative proportions as those in the BAU Scenario 1; freshwater fish production was held constant at BAU Scenario 1 levels and meat production was decreased to keep total global edible yield constant).

The results suggest that increasing the proportion of food production from mariculture would contribute to an overall reduction in GHG emissions, land and water use, although making substantial changes to the impacts of future global food production will likely require strategies to expand freshwater as well as marine production, in addition to substantial changes in other sectors such as renewable energy. This is due in part to the heavy dependence on freshwater and land for the provision of aquaculture feeds and also because mariculture currently provides only a small proportion of overall protein consumption and thus even large percentage increases in mariculture production have only a small impact on global totals.

A key limitation of this analysis was the lack of availability of LCA data for marine and freshwater aquaculture species. The farmed species for which adequate data were available (salmon, tilapia, shrimp, oyster, mussel, trout, seabass and milkfish) only comprised about 26% of total global farmed production in 2012, with carp and other fish collectively comprising the other 74% of production. It is also important to note that the results do not account for any differences in the nutritional value of edible yield produced in any of the scenarios.

The scenarios also assume there are no constraints to the expansion of mariculture, for example, with respect to available marine space, technology, feed availability etc. Estimates of the increases in sea area required for the levels of mariculture production projected in 2050 ranged from 171% in the BAU Scenario 1 to 5,855% in Scenario 5 (see Section 7). However due to the highly variable intensity of production methods used globally, it is acknowledged that these are only crude estimates and the absolute measure of sea area cannot be calculated with any level of robustness in the current study. Further studies focussing on specific regions/areas could address this aspect more rigorously.

Key opportunities to maximise the benefits of increasing mariculture production could include the following, although further assessment of the feasibility and likely benefits would need to be made:

- Reduce the impact from formulated feed - primarily through reducing the amount of feed used in production systems but also through replacing some crop-based feed inclusions with more efficient ingredients and improving the efficiency of the feed production process. This will require continued research into the development of alternative protein and oil sources for livestock and aquaculture feeds (for example, from insect larvae, algae) and into maintaining the nutritional attributes of farmed seafood as feed composition changes. Improve Feed Conversion Ratios (FCRs) to reduce the impacts associated with feed production for fed marine and freshwater aquaculture species to further reduce the footprint of farming aquatic fish species;
- Increase both mariculture and freshwater aquaculture, a scenario which is more likely based on the fact that freshwater culture currently dominates production and is the area of largest growth;
- Improve the efficiency of on-farm energy use and depuration (where required) to reduce the GHG emissions associated with shellfish (oyster, mussel) production, which have minimal land and freshwater requirements. Increase the production of shellfish species (oyster, mussel) in areas of good water quality to reduce the requirement for depuration and hence the associated GWP impact. The ability to do this would depend on the availability of space in coastal or marine areas with good water quality (see Table S1), the economic viability of production in such areas and the ability to transport the product to consumers without negating the GWP impact reductions achieved;
- Substantially reduce the proportion of beef production and increase the proportion of pork and chicken production which had a relatively similar magnitude of impact as fish in this study;

- Increase the production of freshwater species with relatively high saline tolerance (e.g. tilapia) to brackish water where competition for water is lower (i.e. to further decrease associated water use impacts of this production). Such areas may include higher coastal ground (as opposed to coastal habitats such as mangrove forests) to which brackish water can be supplied;
- Potential for development of brackish water production in coastal fringes where saline intrusion occurs (as this land is not suitable for crops).

The wider environmental impacts of mariculture on habitats and associated biological communities depend on the species being farmed, the production system and intensity, the local physical conditions, the ecological carrying capacity of the water body, the sensitivity of the biological communities in the vicinity of farms, other marine activities activity occurring in the area and sources of pollution relating to other marine activities or land use. Therefore the wider environmental risks of expanding mariculture can only be assessed on a more regional or site by site basis. With regards to benefits, macroalgae and shellfish can provide the beneficial ecosystem services of water purification and hence there is the potential for the use of extractive species to provide bioremediation services whilst providing additional biomass for food consumption or other uses.

With respect to social impacts, mariculture provides positive social impacts through consumption and employment throughout mariculture value chains. In general, aquaculture has been found to beneficially impact on poorer sections of society. Increased globalisation of farmed seafood trade is ensuring social and economic impacts occur in both low and medium income countries (LMICs) and Organisation for Economic Co-operation and Development (OECD) countries[1] while significant trade is also developing at the regional scale in Asia and Africa. Transformative social and economic outcomes provided through aquaculture have been related to commercial rather than subsistence-orientated activities. Although smallholders engaged in aquaculture, particularly in LMIC, remain numerically dominant, their share of production is often falling relative to larger-scale enterprises. Comparably high entry costs, uncertainties and risks probably explain the lag in mariculture development compared to freshwater production and some of its mixed social and economic outcomes. Positive nutritional impacts of increasing aquaculture for the poorest groups, both rural and urban, are often indirect. As production grows, a focus on maintaining the nutritional attributes of farmed seafood, compared to wild-caught seafood, needs to be prioritised.

Potential opportunities for technology to mitigate against impacts of increasing global mariculture production include the following:

- Future improvements in feed technology to reduce the reliance of formulated feed on land-based crops (and hence lower the land and water impacts of feed production) and minimise waste through the inclusion of all agricultural, fisheries and aquaculture by-products;
- Further development of IMTA, with the use of extractive species (macroalgae, shellfish) to reduce the impact of production of higher trophic species with the subsequent production of additional products for the food production system (e.g. for feed even if not for human consumption);

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[1] OECD countries comprise 34 Member countries which span the globe, from North and South America to Europe and Asia-Pacific. They include many of the world's most advanced countries but also emerging countries like Mexico, Chile and Turkey.

- Advances in biotechnology, for example selective breeding of finfish species to increase growth (yields), disease resistance and tolerance to a wider range of dietary ingredients (to optimise feed ingredients and minimise impacts as above);
- Land based recirculating aquaculture systems (RAS) could reduce potential impacts on the marine environment and the nutrient rich effluent can be further used in the food production system, for example, for aquaponics (integrated systems in which fish and plants are grown together with the fish waste providing an organic food source for the plants). However, economic analysis currently indicates this technology is uncompetitive and liable to fail commercially unless the product is a high value and/or niche species. In addition such systems also require high capital costs and energy requirements. However, such systems may offer more potential opportunity with any future technological advancements in energy production. Offshore self-contained systems also have potential and may have significant advantages over both RAS and conventional and off-shore cage systems.

In addition to the LCA methodology and data limitations already described, a further limitation of this study relates to the 'regional' influences which are not accounted for in the global assessment. For example:

- Environmental impacts which may be site-specific need a zonal approach to assessing carrying capacity and managing impacts. The 'eutrophication potential' impact assessed in Section 6 would potentially be a better indicator of more local impacts;
- Socio-economic impacts will vary by location and region as described in Section 7.3.3;
- Consumption and culture vary greatly between regions, for example, there are areas in both Asia and Africa than have very high and very low consumption of seafood and cultural norms affect the level of waste (eaten whole, eaten as a processed product); and
- Local feed ingredients often have higher environmental impacts than those sourced from global markets.

For this reason it is extremely difficult to assign a relative ranking to the constraints, risks and benefits of increasing global mariculture and it is recommended that a similar approach to that presented in the study could be applied to more region/site specific assessments. However, relative rankings of the key constraints to, and the risks and benefits of, global mariculture expansion have been suggested below, based on the judgement of the project team.

Table S1. Summary of key constraints, risks and benefits of global mariculture expansion and suggested rankings

Summary of Key Constraints, Risk and Benefits		
Constraint	Relative Constraint Level	Further Comment
Coastal and marine space	Medium - High	High e.g. UK/Europe where there is a high level of competition for space. In these areas it is essential that future space requirements for industry development are considered within marine spatial planning for example through spatial models to assess areas of 'aquaculture potential' (e.g. MMO, 2013). However, the benefits to the industry of inclusion in marine plans are yet to be tested in the UK. Integration of mariculture with infrastructure associated with other offshore marine sectors (e.g. renewables) provides a good opportunity for maximising efficient use of available space, although incentives and/or legislation are likely to be required for such co-location. Further constraints may arise in relation to the social and political acceptability of increasing the size

Summary of Key Constraints, Risk and Benefits		
		and/or density of mariculture facilities in coastal/marine areas in the UK, Europe or North America, for example, in relation to landscape and visual impacts and subsequent effects on amenity value. High – Asia where coastal space likely already being fully utilised. Medium – Africa and Latin America – possible potential for further development in coastal waters
Technology – offshore mariculture	High	Competition for space is likely to be reduced offshore, however, the technical and economic feasibility of large scale mariculture production offshore is yet to be proven.
Technology – feed	High	The production of feed ingredients is the key driver of GHG emissions, land and water use for fed aquaculture species. The reliance on land-based crops for feed ingredients needs to be reduced, primarily through reducing the amount of feed used in production systems but also through replacing some crop-based feed inclusions with more efficient ingredients and improving the efficiency of the feed production process. This will require continued research into the development of alternative protein and oil sources for livestock and aquaculture feeds (for example, from insect larvae, algae) and into maintaining the nutritional attributes of farmed seafood as feed composition changes. Improve FCRs to reduce the impacts associated with feed production for fed marine and freshwater aquaculture species to further reduce the footprint of farming aquatic fish species Fishmeal and fish oil availability and cost have been highlighted as potential constraints to future expansion of mariculture, despite the potential for increased input from fisheries and aquaculture processing by-products.
Market demand	High	Demand is a function of market price. Aquaculture competes against other food products, often in global markets. Expansion of aquaculture to more costly locations (e.g. more remote or more marginal areas) may therefore not be profitable if there is insufficient demand at that price
Pollution (water quality) - shellfish	Medium - High (e.g. Europe)	Water quality can influence economic viability in countries with food safety legislation for protection of public health. In 2014, 56% of food alerts for bivalve shellfish in Europe related to pathogen contamination (e.g. norovirus) and 35% were related to biotoxins from harmful algal blooms (HABs). The frequency and intensity of HABs have increased worldwide (e.g. Fu *et al*., 2012), although risks can be reduced through biotoxin monitoring.
Lack of social licence to operate	Medium	Some countries (e.g. Europe, USA) - perceived and/or real environmental impacts relating to some forms of mariculture (predominately finfish culture) can result in general opposition from the public. Other objections can relate to visual impacts (and hence loss of amenity value) even though there does not appear to be any direct evidence for the latter.
Consumption patterns	Medium	Regional differences in culture and consumption make this extremely difficult to assign a ranking to. Marketing and education may have some influence on consumer choice in some regions.
Risk	**Relative Risk Level**	**Further Comment**
Disease	Medium - High	Expansion of mariculture has the potential to introduce and/or spread disease to wild populations (impacts on biodiversity) and also poses a potential risk to the economic viability of aquaculture initiatives.

Summary of Key Constraints, Risk and Benefits		
Impacts on biodiversity	Low-High	Dependent on species cultured, method and location. Technological advances (e.g. land-based RAS, offshore production, biological parasite control etc.) may help to mitigate impacts as production is expanded. Risks relating to the introduction and spread of invasive non-native species (INNS) and disease may be harder to mitigate, especially in relation to climate change induced sea temperature changes (although advances in biotechnology e.g. in relation to disease resistance or biological containment through induced sterility may help to mitigate impacts). The general integration of the ecosystem approach in fisheries and aquaculture management may further reduce potential impacts through more effective management at least in some regions.
Impacts on ecosystem services	Low - High	Any impacts of mariculture on marine habitats, flora and fauna, if of a sufficient magnitude, could potentially impact on the beneficial ecosystem processes and services provided by those features. The magnitude of this impact will depend on the type of marine or brackish aquaculture undertaken, the location, the method and the intensity.
Impact on livelihoods	Low-High	Development of aquaculture could impose price pressures on fisheries products which would undermine fishing-related livelihoods, which may be locally highly significant. However, in general the contrary is true i.e. the lower cost basis of fishing undermines the potential for aquaculture unless the catch per unit effort (CPUE) of the fishery falls to the point where aquaculture can be an economically viable substitute. In some regions, aquaculture may provide a diversification opportunity for fishermen. Access to capital to establish aquaculture initiatives is very variable between countries and regions. Co-operatives, associations, unions and agricultural banks may provide a source of capital in some countries/regions with a relatively low level of risk of loss compared to that presented by loans from other financial institutions.
Impacts on animals welfare	Medium	Increasing intensive production of animals, including marine species, may pose a risk (real and/or perceived) to animal welfare. Increasing awareness of provenance and sustainability amongst consumers and within supply chains may help mitigate this risk to some degree in some parts of the world.
Benefits	Relative Benefit Level	Further Comment
Socio-economic – employment	Medium-High	Positive impacts occur through employment throughout mariculture value chains. Employment opportunities have had a significant impact on poorer sections of society in both low and medium income countries (LMICs) and Organisation for Economic Co-operation and Development (OECD) countries, although exploitative practices remain within the sector.
Socio-economic – health	Medium	Access to and affordability of fish has generally increased as aquaculture has become established, with likely dietary benefits (although the comparative dietary value of cultured and wild fish has become an issue of concern to some in relation to changes in feed formulation).
Climate change (related to GHG emissions)_	Low-High	The current study suggests that increasing mariculture production may contribute to a reduction in the footprint of global food production, although it has highlighted that there are currently intrinsic links between terrestrial and aquatic food production systems which influence the level of benefit which may be achieved. Future technological advances in feed technology and energy production (i.e. with reduced GHG emissions) would maximise the benefits of increasing mariculture production.
Land use	Low-High	This study indicates that increasing the proportion of mariculture products in total global food production will help to reduce pressure on land resources. However, with respect to land use, the impacts of fed marine aquaculture

Summary of Key Constraints, Risk and Benefits		
		species are intrinsically linked to feed production and proportional to feed conversion ratio (FCR) in intensive and semi-intensive aquaculture systems. Hence the level of benefit achieved will relate to future advances and efficiencies in feed production and nutrition.
Water use	Low-High	This study indicates that increasing the proportion of mariculture products in total global food production will help to reduce pressure on freshwater resources. However, with respect to water use, the impacts of fed marine aquaculture species are intrinsically linked to feed production. Hence the level of benefit achieved will relate to future advances and efficiencies in feed production and nutrition.
Environmental – beneficial ecosystem services	Low-High	Food provision - mariculture provides a means of food provision which may help to reduce GHG emissions, land and water impacts. However, further assessment of this potential needs to be made when additional more robust data are available, and at a more regional level to help further quantify the potential benefits. Water purification and bioremediation - potential for these beneficial ecosystem services from shellfish and macroalgae culture e.g. in IMTA systems. However, the majority of IMTA systems have arisen through coincidence as mariculture has expanded in coastal regions and the feasibility and economic viability of IMTA needs further exploration.

Conclusions and Recommendations

Increasing global mariculture production has the potential to reduce impacts on land and water resources and GHG emissions, compared to terrestrial production of livestock. However, there are a number of uncertainties and constraints to doing so, and therefore this study has highlighted the following recommendations:

- Development of the model to explore regional characteristics and differences, such as consumer preferences and consumption patterns, magnitude of environmental impacts in different regions, type and source of feed ingredients, and socio-economic impacts;
- Further investigate optimal proportions of terrestrial meat, marine and freshwater fish species production at a more regional or site specific level to minimise risks and maximise benefits of expanding mariculture. The model presented in this study could be used to undertake such assessments as more robust LCA data becomes available;
- Research to improve LCA data availability for a greater range of farmed aquatic species, and catalyse general improvements in LCA methodology (see below) to enable a more accurate assessment of impacts of mariculture and freshwater aquaculture in the future;
- Exploration of the optimal production systems for mariculture species which currently have a highly variable impact (related to the variety of systems used), to minimise the environmental footprint, where practically or economically viable;
- Encourage efficient use of feed from all sources should be focussed on as this provides the key to reducing impacts in almost all categories. Efficiency improvements can be made across all sectors of feed provision including ingredient supply, feed delivery (on farm) and animal nutrition;
- Development of aquaculture feed technology to reduce reliance on land-based crops and wild fisheries, reduce the footprint of feed production and incorporate alternative protein and oil

sources into livestock and aquaculture feed (e.g. from insect larvae, algae). Improvements in feed technology will provide the additional benefit of more land-based crop production being available for direct human consumption;

- Direct appropriate feed resources to the most efficient industries/species for those ingredients, based on the nutritional requirements of the farmed species. For example, reduce high quality fishmeal inputs to tilapia diets and direct them instead to marine species;
- Prioritise research into maintaining the nutritional attributes of farmed seafood as production continues to increase and feed composition changes;
- Research into macroalgae production, including the production of biofuel from the by-products of macroalgae for human consumption and phycocolloid production in an integrated waste management system, and research into the nutritional (micronutrient) value of macroalgae and its potential role in future global food security and poverty alleviation;
- Encourage more synergistic solutions between the arable, livestock and aquaculture sectors to conserve resources. Use legislative and regulatory tools to drive the better use of resources;
- Use legislative and regulatory tools to encourage co-location of mariculture with other offshore marine sector activities where appropriate, for example, offshore renewables and/or disused oil rigs, to facilitate development of larger-scale offshore production; and
- Although expansion of mariculture to the levels explored may not be economically viable (see limitations), cost/benefit analysis could inform judgement as to whether increasing global mariculture is a desirable and socially beneficial solution to the issue of future food security.

Acknowledgements

We would like to thank the following individuals for contributing information to this project:

- Richard Slaski, SARF;
- Piers Hart, WWF-UK;
- Richard Perkins, WWF-UK; and
- Duncan Williamson, WWF-UK.

Abbreviations

ABP	Associated British Ports
ABPmer	ABP Marine Environmental Research Ltd
AP	Acidification Potential
ASC	Aquaculture Stewardship Council
BAU	Business as Usual
BOD	Biological Oxygen Demand
BRC	British Retail Consortium
BRU	Biotic Resource Use
BSE	Bovine Spongiform Encephalopathy
CAPEX	Capital Expenditures
CEU	Cumulative Energy Use
CHP	Combined Heat Power
CO	Carbon Monoxide
CO2	Carbon Dioxide
COD	Chemical Oxygen Demand
CSR	Corporate Social Responsibility
DDGS	Distiller's Dried Grains with Solubles
DECC	Department of Energy & Climate Change
DESA	Department of Economic and Social Affairs
DHA	Docosahexaenoic Acid
EC	European Commission
EIA	Environmental Impact Assessment
EJ	Exajoule
EN	Européen de Normalisation (or European Standards)
EP	Eutrophication Potential
EPA	Eicosapentaenoic Acid
EROI	Energy Returns on Energy Invested
ESA	European Space Agency
EU	European Union
FAME	Fatty Acid Methyl Ester
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FCR	Feed Conversion Ratio
FIEYO	Fish In to Edible Yield Out Ratio
FIFO	Fish In/Fish Out
FU	Functional Unit
FW	Fresh Water
GHG	Greenhouse Gas
GM	Genetically Modified
GMO	Genetically Modified Organisms
GOS	Government Office for Science
GVA	Gross Value Added
GWP	Global Warming Potential
H2	Hydrogen
HCl	Hydrochloric Acid

HUFA	Highly Unsaturated Fatty Acid
IFFO	International Fishmeal & Fish Oil Organisation
IFFO RS	International Fishmeal & Fish Oil Organisation Responsibly Supplied
IMTA	Integrated Multi-Trophic Aquaculture
INNS	Introduction of Invasive Non-Native Species
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ISSCAAP	International Standard Statistical Classification of Aquatic Animals and Plants
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LMIC	Low and Medium Income Countries
LU	Land Use
LUC	Land Use Change
LULUC	Land Use/ Land Use Change
MBM	Meat and Bonemeal
MJ	Mega Joule
N2	Nitrogen
NASA	National Aeronautics and Space Administration
NOx	Nitrous Oxides
NPP	Net Primary Production
NPV	Nett Present Value
OECD	The Organization for Economic Cooperation and Development
OEDC	Organisation for Economic Co-operation and Development
PBR	Photobioreactor
RAS	Recirculated Aquaculture Systems
SARF	Scottish Aquaculture Research Forum
SC	Super Critical
SE	South East
SI	Système Internationale
SME	Small to Medium Enterprise
TOC	Total Organic Composition
TTIP	Transatlantic Trade Investment Partnership
UK	United Kingdom
UN	United Nations
US	United States
USA	United States of America
UV	Ultra Violet
VS	Volatile Solid
WTA	Withdrawal to Availability Ratio
WTO	World Trade Organisation
WWF	World Wide Fund for Nature
yFCR	Feed Conversion Ration per Edible Yield

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

A Risk Benefit Analysis of Mariculture as a Means to Reduce the Impacts of Terrestrial Production of Food and Energy

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1. Introduction

1.1 Project Background

The world's population has been predicted to rise to over nine billion by 2050 (e.g. FAO, 2009; Lutz and Samir, 2010), with most of this increase predicted to occur in low and middle income (developing) countries (Alexandratos and Bruinsma, 2012; Government Office for Science, 2011; Lutz and Samir, 2010). The proportion of the population living in 'urban' areas and income levels are also expected to rise (with at least 3 billion people entering the global middle classes) which is likely to increase demand for more nutritious and higher quality foods (i.e. more resource-intensive foods such as meat and vegetable oils; Searchinger *et al*., 2013 and references therein).

It has been estimated, under Business as Usual scenarios, that in order to meet the growing demand for such food products in 2050, food production must increase by about 60% (excluding increases required for crops used for biofuels). Annual cereal production (for both human consumption and animal feed) will need to increase by about 0.9 billion tonnes and annual meat production by over 200 million tonnes compared to 2005/07 levels. While 90% of the crop production is expected to come from increasing crop intensity and yield, the remainder would come from expansion of arable land (approximately 70 million hectares), although this may only be achievable if crop technology advances and fertilisers are available for such expansion (Alexandratos and Bruinsma, 2012; FAO, 2009).

The question of how to achieve such increases in food production to feed this larger, increasingly affluent population, whilst ensuring sufficient food calories to adequately feed the entire global population, in a sustainable manner (i.e. that ensures food production that contributes to inclusive social and economic development whilst reducing environmental impacts and pressures on limited resources), is the subject of current discussion and research (e.g. Searchinger *et al*., 2013; Alexandratos and Bruinsma, 2012; The Government Office for Science, 2011).

The increasing global demand for food and energy, places increasing pressure on already limited land and freshwater resources for crop and livestock production, and on the climate through greenhouse gas (GHG) emissions from agricultural production (emissions from livestock, fertiliser production/use and land use change) and through the use of fossil fuels. For example, in a working paper reviewing the issue of how to create a 'sustainable food future', Searchinger *et al*. (2013 and reference therein) stated that agricultural food production uses nearly 50% of the world's land mass (if Antarctica, deserts, permanent ice and inland water bodies are excluded), 70% of all freshwater abstracted from rivers, lakes and aquifers (80-90% of which is consumed and hence not returned) and accounted for approximately 24% of GHG emissions in 2010. Furthermore, agricultural expansion is a dominant driver of tropical deforestation, the conversion of carbon-rich peatlands and associated impacts on ecosystem services and biodiversity.

A report by the Government Office for Science (GOS; 2011a) states that while substantial additional land could in principle be suitable for food production, in practice there will be competing pressures for these resources resulting in land being lost to urbanisation, desertification, salinization and sea level rise. The same report estimates that the demand for water for agriculture and global energy demand could both potentially double by 2050.

The advent of biofuels[2] has the potential to further increase the requirement for future crop production and hence potentially further increase pressure on limited land and freshwater resources. For example, in 2010, bioenergy (energy produced from biofuels) use was about 50 exajoules (EJ)/year, equivalent to about 10% of human primary energy supply. It was recently estimated that the maximum physical potential of the world's land area (outside cropland, infrastructure wilderness and dense forest) to deliver bio-energy is about 190 EJ/yr (Harbel *et al*. 2013), however, the authors highlighted that such a high level of bioenergy supply would roughly double the human harvest of plant biomass with far reaching effects on biodiversity, ecosystems and food supply (Harbel *et al*. 2013, 2010).

Increasing marine aquaculture (mariculture) has been suggested as a potential solution to the food, energy, water and land nexus through reducing pressure on land and freshwater resources (e.g. Diana *et al*., 2013; Duarte *et al*. 2009; Verdegem and Verreth, 2006; Marra, 2005) and potentially reducing GHG emissions, for example relative to emissions from increased terrestrial animal protein production and/or through the use of marine biofuels (e.g. Hughes *et al*., 2012).

Increasing global mariculture has the potential to provide socio-economic benefits, for example, creating employment (particularly within the downstream supply chain), reducing poverty (in both urban and rural areas), advancing rural development and increasing access to, and affordability of, seafood products with associated dietary and nutritional benefits (e.g. Waite *et al*. 2014).

Furthermore, there is the potential for mariculture to provide beneficial ecosystem processes and services beyond food provision. For example, naturally occurring oyster beds and reefs (e.g. *Crassostrea* spp.) provide beneficial ecosystem processes such as erosion control and water purification (see Herbert *et al*. 2012 and references therein), whilst research has indicated that oyster cultivation can be integrated with finfish aquaculture to act as a 'biofilter' to improve effluent water quality (e.g. Shpigel and Blaylock, 1991; Lefebvre *et al*. 2000). Bioremediation of nutrient emissions from finfish, and to a lesser degree shellfish, through the culture of seaweed (i.e. through integrated multi-trophic aquaculture (IMTA)) has also been a focus of recent research (e.g. Zhou *et al*. 2006; Buschmann *et al*. 2008;Nobre *et al*. 2010; Al-Hafedh *et al*. 2012).

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2 Hydrocarbon fuel that is produced from organic matter (living or once living material) in a short period of time (days, weeks, or even months) in contrast to fossil fuels, which take millions of years to form and with other types of fuel which are not based on hydrocarbons (e.g. nuclear fission).

Figure 1.1 Oyster farming in France (Source © John Bostock)

However, intensification and/or expansion of global mariculture may also increase the risk of causing increased environmental impacts. The environmental impact of aquaculture depends on the species cultured, the production system (and volumes produced) and site-specific conditions (e.g. the physical environment and other flora and fauna present). In general, environmental impacts arising from aquaculture are considered to relate to particulate discharges (e.g. food, faeces), pollution (nutrient loading, chemical contaminants), introduction or transfer of disease/parasites, impact of escapes on genetic diversity of wild populations, introduction of invasive non-native species (INNS) and the subsequent effects of such pressures on marine habitats and biodiversity. Other impacts arising from aquaculture may include the disturbance of predators (e.g. birds and seals) of mariculture species through scaring devices and loss of, or damage to, coastal habitats cleared for mariculture.

The Scottish Aquaculture Research Forum (SARF) and WWF-UK commissioned this study to investigate whether the pressure on land and freshwater for future food and energy resources, and impacts on the climate, related to GHG emissions, may be reduced through expansion of global mariculture. The study has undertaken a high level assessment of the ‘environmental footprint’ of global mariculture and terrestrial-based food and energy production systems through the collation and assessment of available Life Cycle Assessments (LCAs) for key food products (beef, pork, chicken, freshwater and marine fish and shellfish species) and biomass (terrestrial and algal) for energy production. The outputs of the footprint comparison was then used to assess the risks and benefits of increasing global mariculture, through the development of projected future scenarios in which mariculture contributes differing proportions of projected future food requirements. The analysis also qualitatively considered the socio-economic and wider environmental risks and benefits (e.g. in relation to ecosystem services) of global mariculture expansion, where expansion may occur geographically and whether future technological developments may help mitigate against identified impacts.

The study makes recommendations regarding the key uncertainties and limitations of the risk/benefit analysis and makes recommendations on how these limitations can be addressed and the analysis developed for more regional or site-specific assessments.

1.2 Project Aims and Scope

The aim of the project was to review the existing evidence relating to the footprint of global mariculture (particularly with respect to GHG emissions from, and freshwater and land use for, terrestrial-based production systems), the potential for mariculture to contribute to future food and energy requirements, the spatial and technological requirements for such an expansion of mariculture and the environmental and socio-economic risks and benefits of doing so.

The project aim was achieved through providing:

- An overview of global mariculture production of both fish and shellfish for food, covering techniques, systems and production trends;
- An overview of global algal mariculture for biomass, covering existing techniques, products and production trends as well as the processes for producing energy from algal biomass and efficiencies and comparisons with other methods of energy production (focussing on energy production from terrestrially-derived biomass);
- A comparison of the footprint of both terrestrial and mariculture food and energy production, in terms of GHG emissions, freshwater and land use in order to compare the impacts of mariculture with land-based livestock and energy production. Interpretation and discussion of the outputs in the context of wider socio-economic and environmental impacts;
- An assessment of the potential for mariculture to contribute to future food and energy requirements and the risks and benefits of doing so, including consideration of where production may take place and how future technology improvements may help mitigate against impacts identified;
- A presentation of the limitations of the study and recommendations on how these limitations can be addressed through further research.

Aquaculture has been defined as follows (Edwards & Demaine, 1998):

> *"Aquaculture is the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated. For [FAO] statistical purposes, aquatic organisms which are harvested by an individual or corporate body which has owned them throughout their rearing period contribute to aquaculture, while aquatic organisms which are exploitable by the public as a common property resources, with or without appropriate licences, are the harvest of fisheries".*

The focus of the study was on mariculture (i.e. the production of aquatic organisms in the marine environment). However, it should be noted that it is hard to define mariculture precisely because the marine environment is extremely varied in its range of salinities and many aquatic species can tolerate a wide range of salinities and may be farmed in fully saline or brackish waters. For the purpose of this study, mariculture was considered to include the culture of aquatic organisms in fully saline and brackish water based on the premise that, unlike freshwater, brackish water is generally unsuitable for crops or terrestrial animal production and because production of aquatic species in these environments can be a valuable economic activity or source of livelihood.

Although the study does not specifically address the global footprint of freshwater aquaculture, it is important to note that the major growth of global aquaculture production in recent decades has occurred inland in freshwater environments.

As per the project specification, the study considered the impacts and potential risks and benefits of expanding mariculture at a global level. As such the study assessed the impacts of mariculture and terrestrial food and energy production systems using LCA which is a tool for assessing environmental impacts of products at a broad global level. However, it is recognised that the resources required for, and the environmental and socio-economic impacts of, mariculture will differ between global regions (i.e. Africa, Asia, Oceania, Europe and the Americas) and between locations and sites within these regions The study has sought to qualitatively contextualise the outputs of the study (i.e. consider regional issues) as far as is possible within the study scope and has made recommendations regarding how such issues can be considered further in future work.

The quantitative comparison of the footprint of global mariculture and terrestrial food and energy production systems was possible through critical review and analysis of available LCA studies, albeit subject to significant data limitations described further in Section 6. However, the LCA methodology has numerous limitations, for example, not adequately addressing impacts on biodiversity and sensitive habitats or the social and economic impacts on surrounding communities. Whilst some indicators of social impacts may be captured at a national level, for example, through Gross Value Added (GVA), the total number of businesses and/or people employed, other social impacts (such as poverty alleviation, health impacts etc.) do not easily lend themselves to quantitative analysis. Similarly, whilst methods of valuing beneficial ecosystem services provided by marine systems have been developed (e.g. Defra, 2014; Eftec, 2014), there is little quantitative evidence relating to the impacts of specific industries (including aquaculture) on ecosystem services.

Due to the relative paucity of quantitative data relating to wider social and economic issues, the risks and benefits of expanding mariculture on these issues were considered qualitatively within this study. Furthermore, as noted above, it is also recognised that these issues are also likely to be region or site-specific (particularly with regard to environmental impacts) and the report will highlight what information/knowledge gaps need to be considered for more regional/national/local level assessments.

1.3 Report Structure

This report contains the following sections:

Section 1: Introduction (this section);
Section 2: Approach;
Section 3: Global review of fish and shellfish mariculture – providing an overview of global production systems, historical and potential future production trends and drivers;

Section 4:	Global review of algal mariculture - providing an overview of global production systems, products and historical and potential future production trends and drivers;
Section 5:	Review of processes for producing energy from algal biomass and current constraints to economically viable energy production using these methods;
Section 6:	Comparison of impacts from mariculture and terrestrial-based food and energy production systems;
Section 7:	Assessment of the potential for mariculture to contribute to future food production and the associated risks and benefits; and
Section 8	Conclusions and recommendations.

2. Approach

2.1 Review of Global Mariculture Production Systems and Trends

Information for the overviews of global mariculture of fish, shellfish and algae (including cultivation systems, production trends and energy extraction processes from algae; see Sections 3 to 5) was sourced from literature searches using academic databases, Google Scholar and general internet searches to ensure that relevant peer-reviewed and grey literature were incorporated. Given that the scope of the study was to provide 'brief summaries', published reviews were used as a main source of information. Additional information was provided by WWF-UK and SARF and through expert knowledge of global aquaculture systems within the project team.

2.2 Comparison of Impacts from Mariculture and Terrestrial Based-Food and Energy Production Systems

As noted in Section 1.2, a comparison of the impacts of mariculture and terrestrial food and energy production systems was made using LCA, an environmental accounting tool which measures the environmental impacts of products at a broad global level.

Although LCA has been used extensively for terrestrial products, the methodology has only been applied relatively recently to assess the impact of different freshwater and marine aquaculture species. As such, the analysis could only be undertaken for a limited number of cultured species or species groups which included:

- Atlantic salmon, Penaeid shrimp, seabass, milkfish, oyster and mussel – as representative mariculture species (farmed in marine or brackish water) for which data were available; and
- Tilapia, rainbow trout and carp – as representative freshwater aquaculture species (included due to the dominance of freshwater culture production at a global level).

The LCA outputs for these indicative marine and freshwater species were compared to the GHG emission, water and land use impacts from the production of beef, pork and chicken, which comprise the majority of global meat production from land-based livestock. As the majority of impacts of both terrestrial and mariculture/freshwater aquaculture production of the above species relate to the production of the feed for the above animal products the LCA tool was also used to assess the GHG emission, land and water use arising from the production of crops which are key animal feed ingredients:

- Sunflower oil;
- Rapeseed oil;
- Maize;
- Wheat;
- Soybean meal; and
- Fishmeal.

Finally, the LCA tool was also used to compare the impacts of energy production from the following land and marine-based biomass products used for (or with the potential for use for in the case of algae) energy production:

- Microalgae;
- Macroalgae;
- Maize;
- Wheat;
- Rapeseed oil; and
- Soybean meal.

Data for all of the LCA comparison were sourced through literature searches. A detailed methodology of the LCA comparisons, including data limitations and underlying assumptions, is presented in Section 6.

2.3 Assessment of the Potential for Mariculture to Contribute to Future Food and Energy Production and the Associated Risks and Benefits

Section 7 presents an analysis of the risks and benefits of expanding global mariculture for food production to help meet projected global demand in 2050. Theoretical indicative projected scenarios of future mariculture production were developed around a Business as Usual scenario, calculated from the growth rates of specific aquaculture products over the last ten years. Alternative scenarios, for example, in which global shellfish mariculture was doubled in comparison to the BAU scenario were then developed to enable the relative risks and benefits of adopting different strategies in relation to future mariculture production. The outputs of the LCA analysis (specifically the impacts in relation to GHG emissions, land and freshwater use) in Section 6 were fed into the scenarios to provide an indicative quantitative footprint associated with each scenario. Wider environmental and socio-economic impacts of mariculture, which are not accounted for in LCA, were then considered qualitatively to further inform the relative risks and benefits of the different scenario strategies, which also considered the potential marine area requirements and technological developments which may help to mitigate against identified impacts. A detailed methodology of the risk benefit analysis is presented in Section 7.

3. Global Review of Fish and Shellfish Mariculture

3.1 Introduction

This section considers only fish, crustaceans and molluscs, with aquatic plants (mainly seaweeds) considered in the following section. Crustaceans and molluscs are often grouped together as "shellfish" so that convention is followed here except where it is appropriate to consider each group separately. Unless otherwise stated, all graphs presented in this section are based on analysis of Fishstat 2015 data.

The production of fish and shellfish through aquaculture has increased at an average of 5.5% per annum between 2004 and 2013 to reach 69.7 million tonnes. Of this production, 29% is recorded as farmed in the marine environment, 62% in freshwater and 9% in brackish water (Figure 3.1).

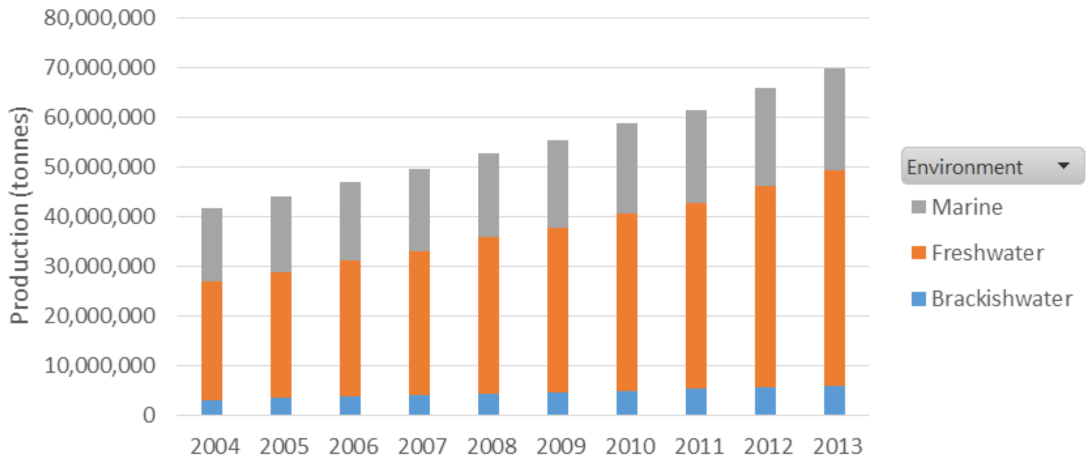
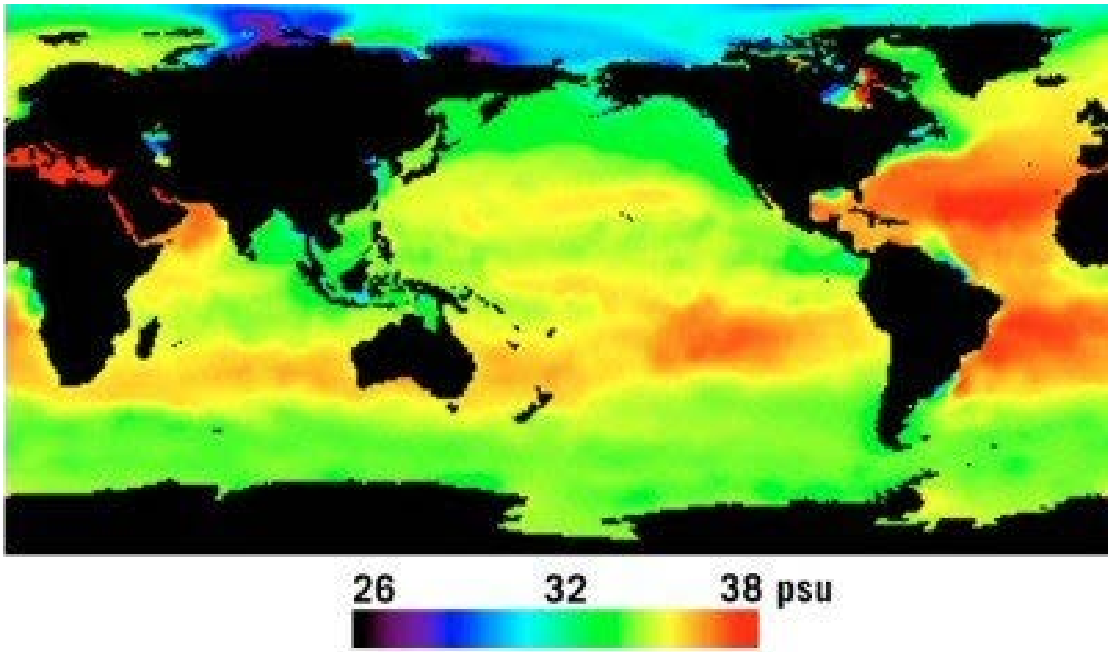


Figure 3.1 Global aquaculture production of fish and shellfish by environment

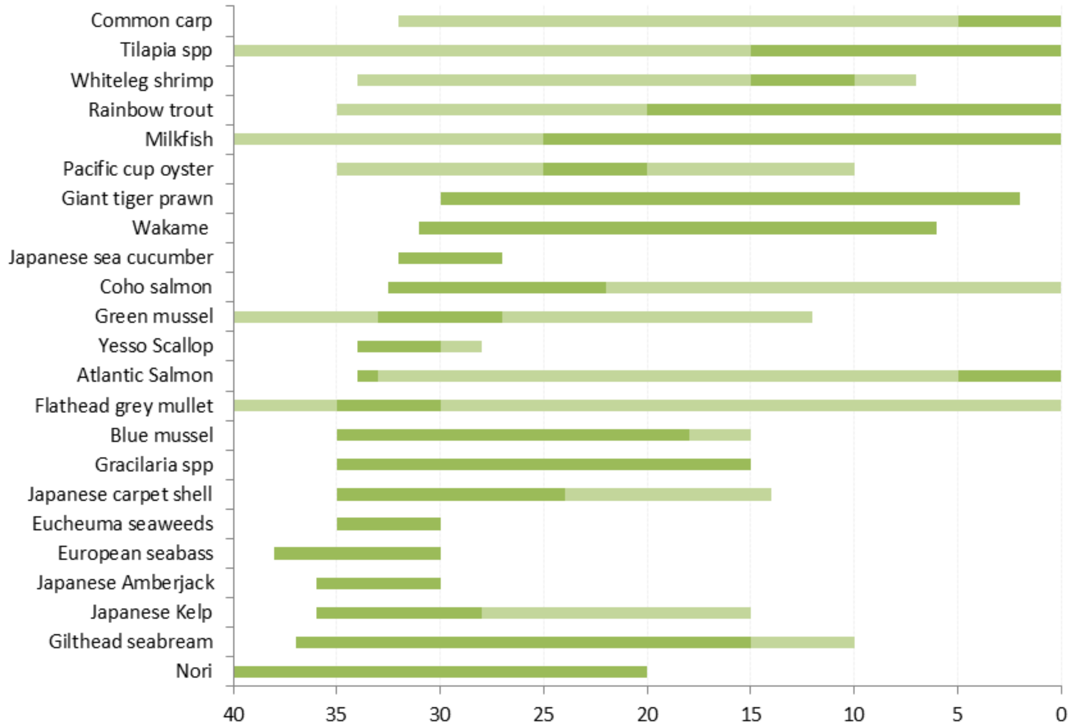
The distinction between marine and brackish water aquaculture however is not always clearly made or understood and this has implications for the current study which was tasked with focussing on mariculture. Mariculture is generally defined as the culture of animals or plants in the marine environment. However, this is quite simplistic as the marine environment is extremely varied in its range of salinities. Full strength sea water is on average, around 35ppt, however, the Baltic Sea, for example, ranges from 4ppt in the north to 33ppt in the Danish straights (Jaspers *et al* 2011). Salinity is locally affected by influences such as freshwater run-off and river inputs which lower the salinity, and high levels of evaporation, especially in tropical latitudes, which elevate salinity. These influences may be seasonal due to rainy seasons or higher levels of evaporation in certain months and the strength of these influences will then be determined by the level of mixing which occurs, from very high in exposed areas, to low in sheltered areas such as the Baltic Sea. Figure 3.2 shows the salinity gradient of the major oceans and water bodies of the world.



(Source: ESA, 2014)

Figure 3.2 Salinity gradient of the world's oceans and major water bodies

The factors controlling salinity have had an effect on the evolution of aquatic species in different areas globally, which again has had implications for the species and culture methods examined in more detail in this study. Some species may have evolved to tolerate a high range of salinities, such as those living in estuarine habitats, migratory species or those which live in waters subject to seasonal variations due to either evaporation and/or freshwater pulses. Salmons, which are some of the most commonly cultured mariculture fin-fish species, have evolved to have two separate life stages, with breeding and early development occurring in essentially fresh-water and the main grow out stages occurring in fully marine water in many cases. Other salmonids such as trout may be regarded as predominantly fresh water species, but it is possible to culture them in marine water, once they have grown sufficiently to be able to osmo-regulate in these conditions. Similarly, carps which are regarded as freshwater species are the most highly cultured fin-fish species in the world, can tolerate salinities as high as 10-15ppt with no loss in performance and can commonly be found wild in the Baltic Sea as far south as the Stockholm archipelago, which has a salinity of around 6ppt. Tilapia species which are also cultured extensively are considered a fresh-water species but are commonly cultured in polycultures with shrimp species in brackish water ponds, in Asia. Some species such as the Mozambique tilapia, *Oreochromis mozambicus* have evolved in areas subject to high evaporation and can tolerate hyper-saline waters. However, although this is true of many species, they are often sensitive to sudden changes in salinity, especially during early life stages and therefore must be acclimatised gradually to these conditions if severe stress and mortality is not to occur. Figure 3.3 shows the optimum salinity and tolerance ranges to culture selected mariculture species and others, based on their importance in levels of production according to FAO Fishstat (2015).



(Sources: FAO, 2015; Pavlidis and Mylonas 2011; Crone and bond 1976; Echave *et al* 2012; Peteiro and Sánchez 2012; Martinez *et al* 2006; Maghsoudloo *et al* 2012; Nugon 2003; Boyd and Tucker 1998; Bartsh *et al* 2008; http://www.sms.si.edu/irlspec/Perna_viridis.htm, accessed 26/11/2014)

Figure 3.3 Optimum salinity (dark green) and tolerance (light green) ranges, where available, for selected mariculture species

The definition of mariculture is important in the context of this study as depending on where the line is drawn, assessment of land use and dependence on freshwater for instance will vary considerably. However, to give the broadest analysis, aquaculture in both marine and brackish water environments are included in the analysis as brackish water is generally unsuitable for crops or terrestrial animal production and brackish water aquaculture can be a valuable economic or livelihood activity. There is also something of a continuum when considering the way in which aquaculture utilises coastal ecosystem services or impacts on coastal land use etc. However, the distinction between marine and brackish water environments is worth maintaining for some aspects of the analysis, particularly as the latter is dominated by shrimp farming.

Using FAO categories, fish and shellfish aquaculture in the marine environment (mariculture) exceeded 20 million tonnes in 2013 (see Figure 3.4) and this was dominated by molluscs (74% by live weight equivalent). Diadromous fish which include Pacific and Atlantic salmon comprised 12.7% in 2013 with marine fish adding a further 8.8%. However, as discussed later, the quantities produced do not reflect the comparative economic values of the different sectors.

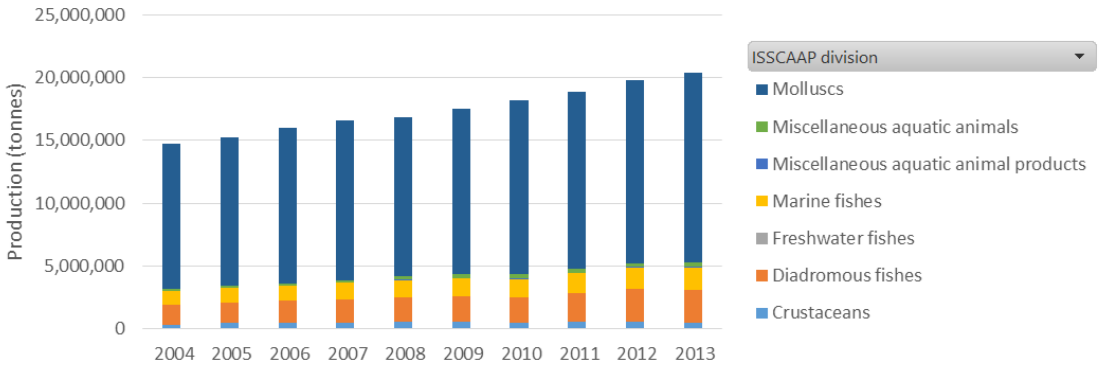


Figure 3.4 Global fish and shellfish mariculture production by species group (ISSCAAP division[2])

There is substantial overlap in terms of species groups between aquaculture in marine and brackish water environments. However, the latter is dominated by crustacean farming (61% of total production), which is mainly tropical shrimp and crab (see Figure 3.5).

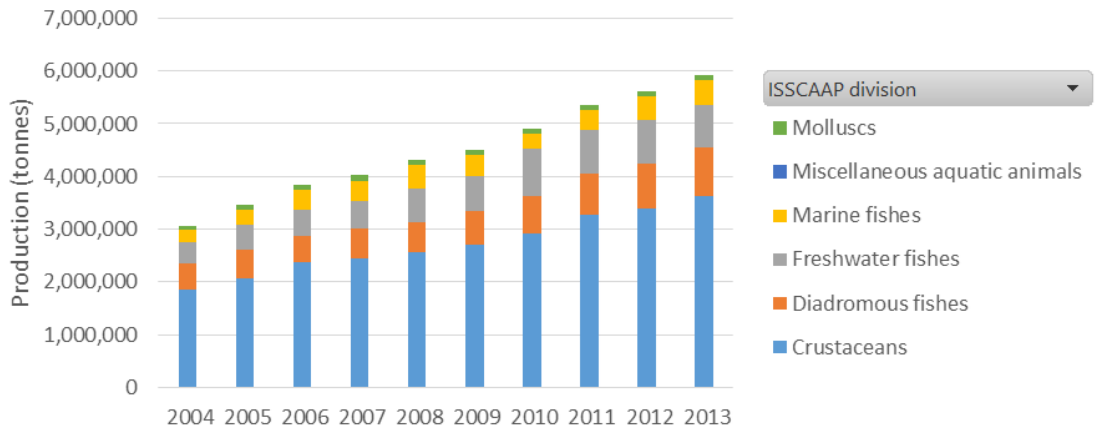


Figure 3.5 Global brackish water fish and shellfish aquaculture production by species group (ISSCAAP division)

3.2 Production Techniques and Systems

Fish and shellfish aquaculture systems can be classified according to environment, type of containment (or attachment) technology, by whether nutrients or feed are supplied, and the intensity of culture (production per unit area or volume). A typical classification by type of containment technology is shown in Figure 3.6.

[3] Note: The FAO International Standard Statistical Classification for Aquatic Animals and Plants (ISSCAAP) classifies biological entities according to their commercial value. FAO Statistics allow analysis by ISSCAAP Division (of which there are 9) or ISSCAAP Group (of which there are 50) (FAO, 2003).

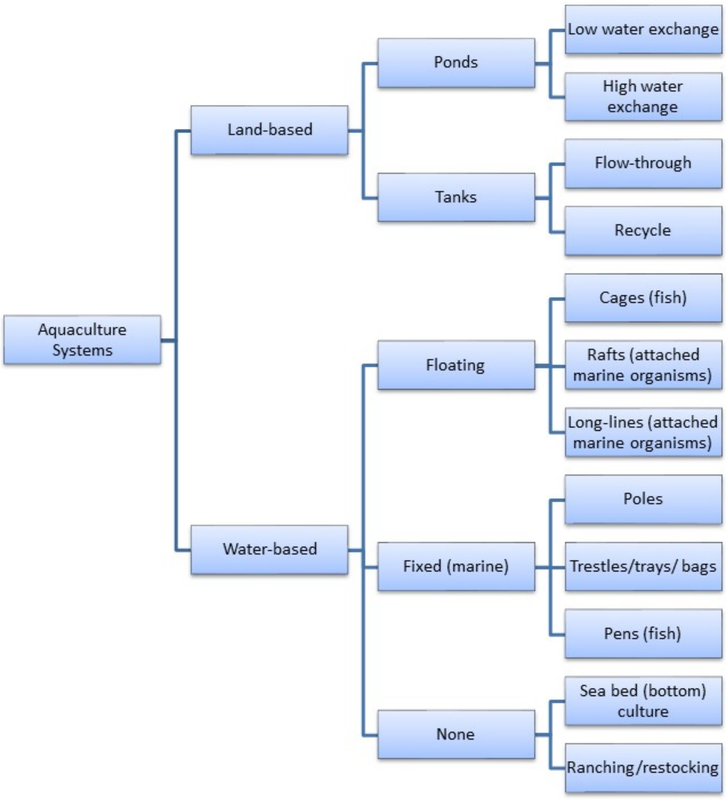


Figure 3.6 Classification of mariculture systems by containment technology

Mariculture systems can broadly be classified as land or water-based. Land-based systems include ponds and tanks which are supplied with seawater whilst water-based systems are placed within the sea or water body. This may be as a floating structure, as is the case with fish cages and mollusc rafts, or fixed structures in the tidal zone such as poles or trestles for shellfish farming. In general, tank and cage (pen) systems are generally used for fish which are fed fully formulated diets. Ponds may be managed as extensive, semi-intensive or intensive production systems for fish or crustaceans. Intensive management implies both higher quality feeds and additional power input for water pumping and aeration to supplement oxygen supply.

Shellfish are mostly produced in suspended or fixed water-based systems where they can feed on natural phytoplankton and other nutrients naturally present in the water. An exception to this is abalone culture which requires seaweed-based feeds and is often carried out in tanks.

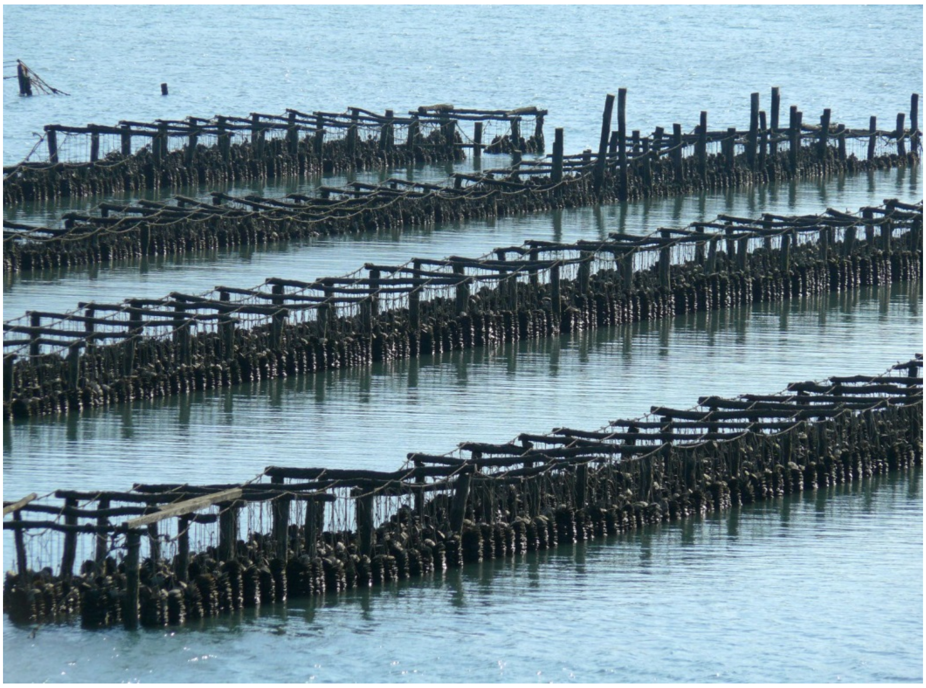


Figure 3.7 Oyster spat collectors, South Korea (Source: © John Bostock)

Some shellfish culture requires no structures and just involves management and perhaps some manipulation of the natural environment – e.g. the culture of cockles, clams and mussels in intertidal or shallow subtidal sands.

Mariculture system characteristics, including typical species produced and the scale and intensity of production systems are summarised in Table 3.1.

Table 3.1 Mariculture system characteristics

System	Typical species	Nutrition	Scale	Intensity*
Ponds	Shrimp, crab, sea bream, sea bass, milkfish	Inorganic and organic fertilizers to stimulate plankton growth, supplementary or formulated feeds	Ponds are usually between 0.25 and 10 ha in size with sites up to several hundred ha	From 0.5 to >10 t/ha/yr
Tanks	Flatfish, sea bass, grouper, abalone	Fully formulated feeds	Tanks between 5 and 250 m^3	From 10-100 kg/m^3/yr
Floating cages (sometimes referred to as "pens" although these are usually defined as net enclosures attached to the substrate without a net base)	Salmon, sea bream, sea bass, tuna	Fully formulated feeds	Cages from 250 to over 50,000 m^3	From 5-20 kg/m^3/yr

System	Typical species	Nutrition	Scale	Intensity*
Rafts	Mussels	Natural feed	Typically 20x20m, six per ha	50-500 t/ha/yr
Longlines	Mussels	Natural feed	Farms from tens to thousands of tonnes per year	50-450 t/ha/yr
Poles	Mussels	Natural feed	Mostly smaller-scale operators	10-50 t/ha/yr
Trestles and bags	Oyster, scallops	Natural feed	From one to hundreds of ha	10-20 t/ha/yr
Sea bed	Mussels, cockles, scallops	Natural feed	Tens to hundreds of hectares	From 50 kg to 30 t/ha/yr

* Tanks and cages are given in kg/m³ as depths are very variable, especially in cage systems, but as an example a tank system producing 50 kg/m³/yr in depths of 2m would be equivalent to 100 kg/m² or 1000 t/ha whilst a cage system of 20m depth producing 10 kg/m³/yr would be equivalent to 200 kg/m² or 2000 t/ha.

Whilst numerically, most aquaculture operations are relatively small scale with production between 10 and 500 tonnes per year, some sectors have seen greater corporate investment and industrialisation. The salmon sector leads this trend in fish aquaculture with leading companies operating in several countries over two or three continents with production per site up to 5000 tonnes p.a. and total production reaching 300-400 thousand tonnes p.a. Modern salmon farms are highly mechanised and employ specialist service vessels and automated feed systems. In the shrimp sector, the National Aquaculture Group in Saudi Arabia operates a pond site of 250 km² which produced 15,000 tonnes in 2012-2013 (National Aquaculture Group, 2014) and has a production capacity of 35,000 tonnes p.a. (Shrimp News International, 2014).

3.3 Historic Production Trends

Global aquaculture production of fish and shellfish from marine environments has increased at an average growth rate of 5% per year over the last 20 years. Most of this growth has been in Asia which in 2013 accounted for 80% of global fish and shellfish mariculture. Europe accounted for 11% (Figure 3.8).

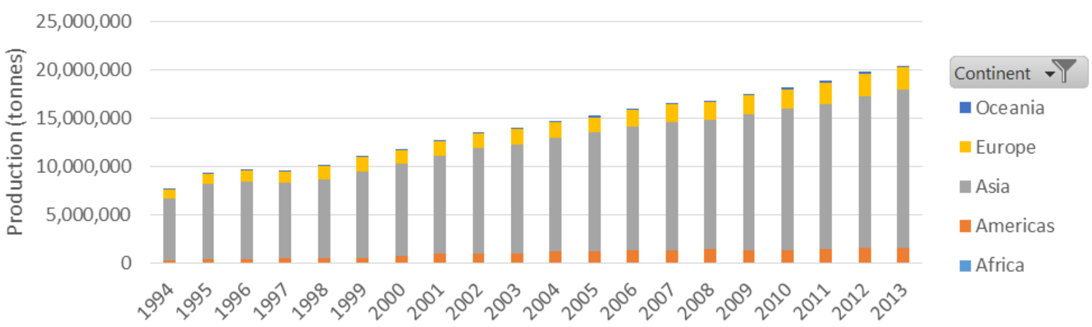


Figure 3.8 Aquaculture production of fish and shellfish in marine environments (by continent)

Marine fish culture has developed at a relatively fast rate of 7.9% per annum (20 year average), to over 4 million tonnes (Figure 3.9), although year-on-year growth has been somewhat inconsistent. The sector is dominated by salmonids, which accounted for 57% of marine fish production in 2013.

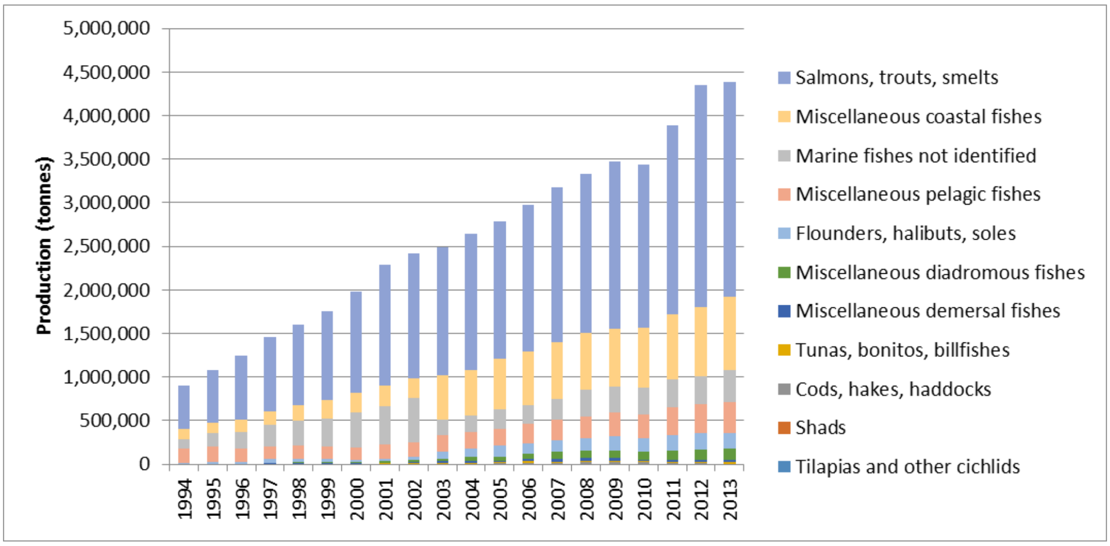


Figure 3.9 Development of fish aquaculture in marine environments (by ISSCAAP group)

Mollusc farming has increased at an average of 4.2% per annum between 1994 and 2013 to over 15 million tonnes (Figure 3.10). The major production groups are clams, cockles and arkshells (33.4% in 2013) and oysters (32.6%), followed by scallops (12%) and mussels (11.6%). High value abalone and pearl oyster account for just 2.4% of total mollusc production by weight.

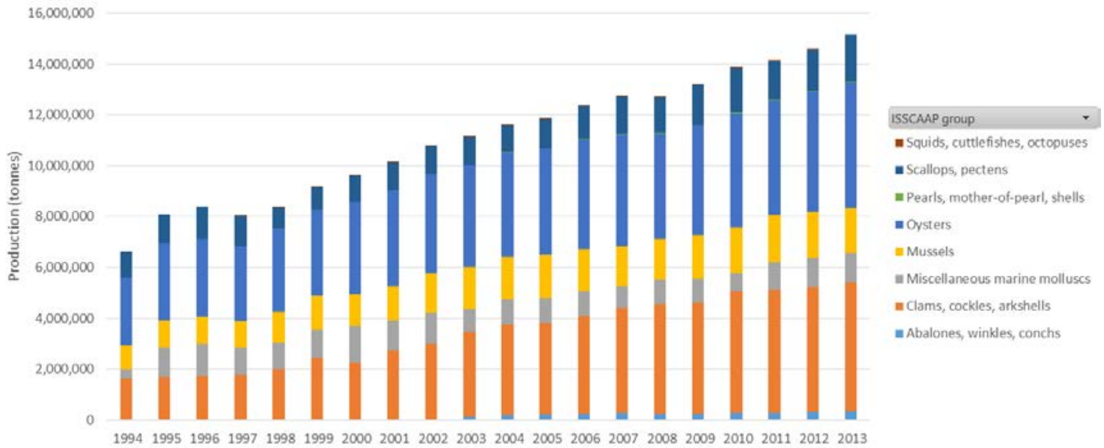


Figure 3.10 Development of mollusc farming in marine environments (by ISSCAAP group)

Crustacean farming has increased at an average rate of 7.66% per year since 1994 to over 4 million tonnes (Figure 3.11) and is dominated by shrimp and prawn production (92.7% in 2013) particularly tropical shrimp from the family Penaeidae.

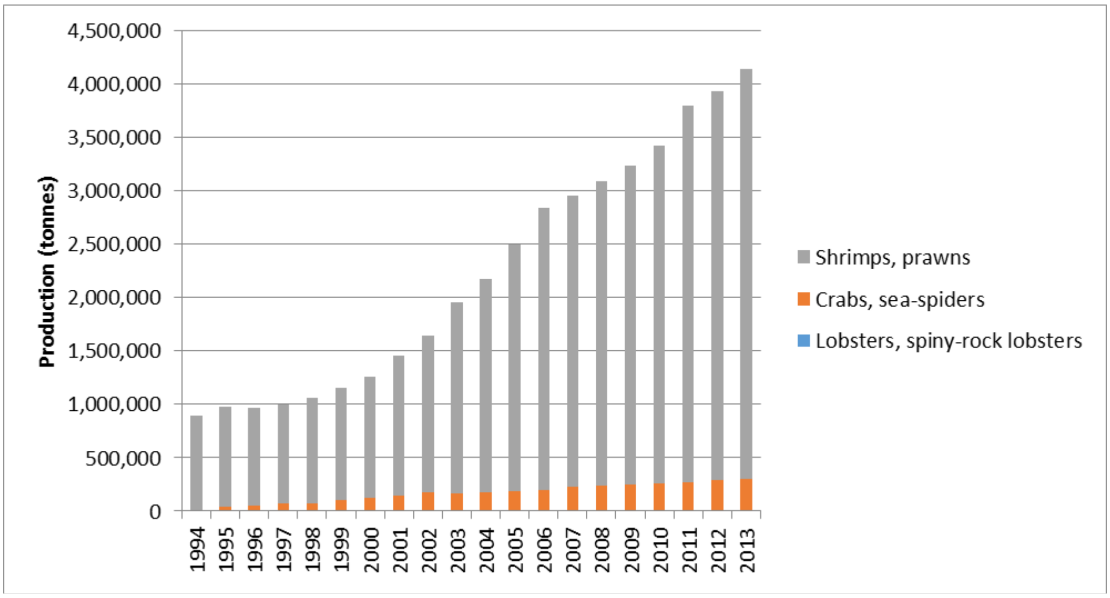


Figure 3.11 Development of crustacean farming in marine and brackish water environments (by ISSCAAP group)

Although the overall trend is for steady growth, for individual categories growth can be cyclical due to both commercial pressures and the effects of disease or other environmental pressures. Improvements in technology and continued commercial investment also play a role. Figure 3.12 shows the variability and trends by major category over the past 20 years.

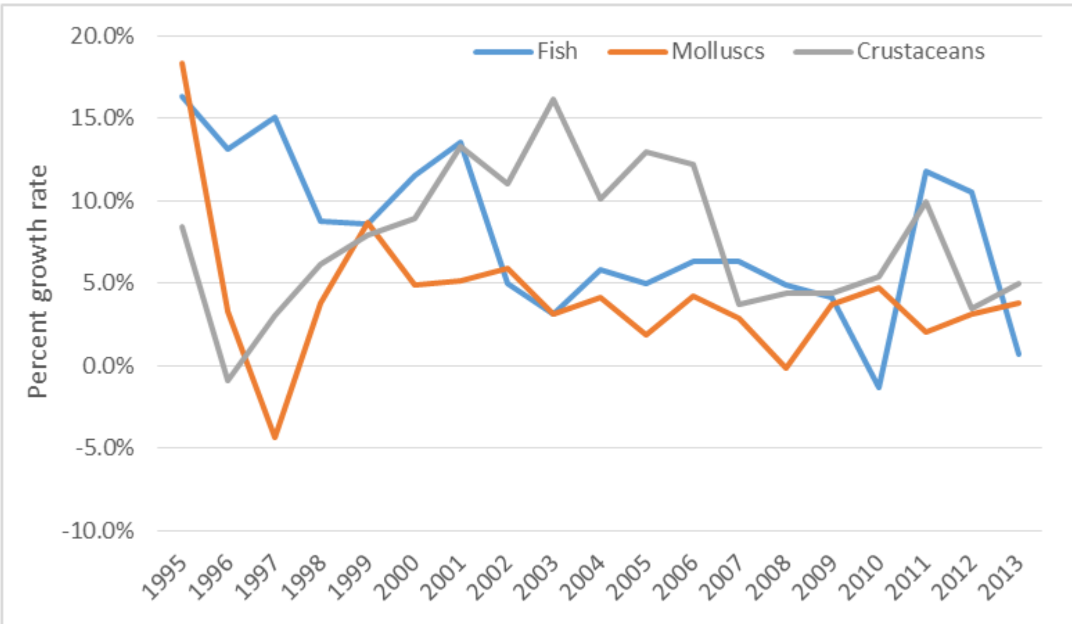
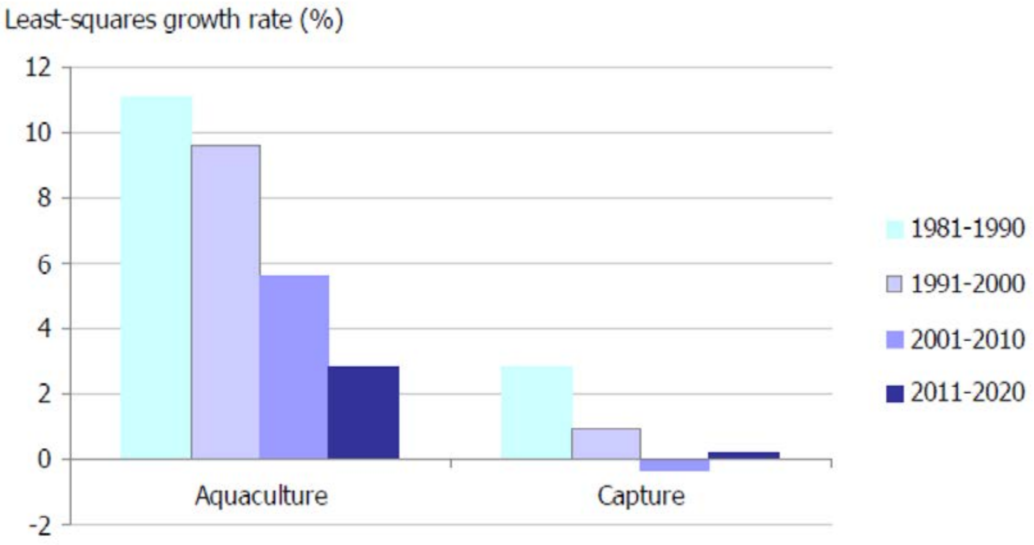


Figure 3.12 Annual percent growth rate for fish and molluscs in marine waters and crustacean farming in marine and brackish waters

However, the long term trend for aquaculture (and fisheries) is that of a declining growth rate (Figure 3.13 – which presents the data using the least squares regression method to minimise the impact of randomly high or low values at the start or end of the time series). This is partly due to reaching physical constraints (i.e. land or water area), or possibly market limits (at economically viable prices given prevailing costs of production) However, it will also be the case that as production increases single percentage points represent ever larger actual quantities. A consistent (linear) annual increase in terms of tonnage would therefore show up as a declining growth rate when measured in percentage terms.



(Source: OECD-FAO, 2011)

Figure 3.13 Growth rate of fish production by decades

3.4 Future Trends and Drivers

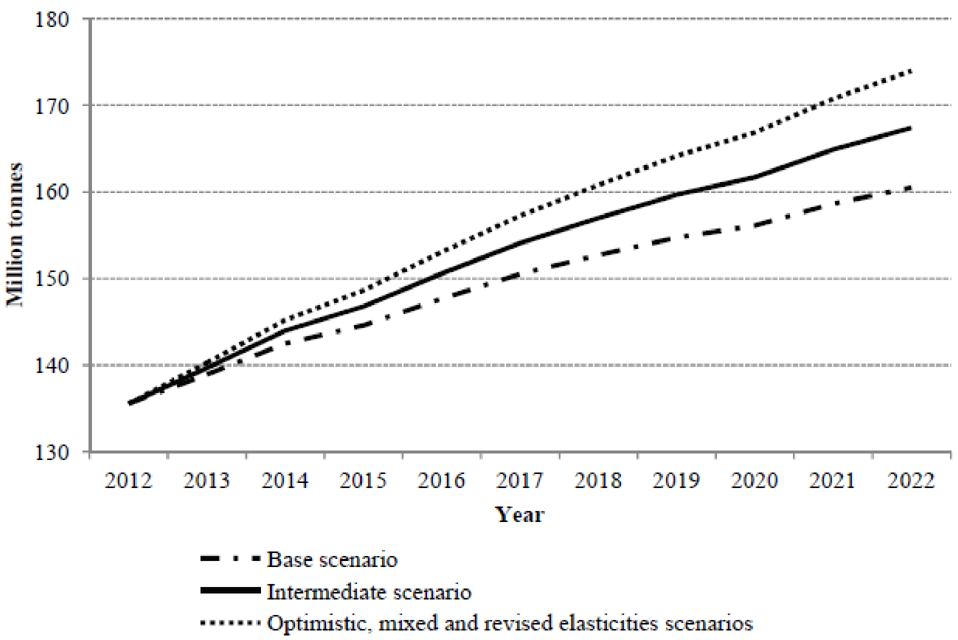
3.4.1 Consumption and Demand

The main drivers of demand are generally taken as population growth (increasing overall food demand) and prosperity (increasing the proportion of animal and fish protein in the average diet – often linked with urbanisation) (Bostock *et al*, 2010), although other factors such as the price of seafood in relation to other foods, geographically influenced cultural traditions and consumer trends will also be important. Forward projections for demand have been made by several authors as shown in the Table 3.2. The approaches vary in the assumptions made and in the detail of the underlying analysis. Most either assume constant per capita consumption, or constant relevant pricing, although use is also made of multiple scenarios. Current trends in production growth have also been extrapolated forward. Only one study provides projections for more than one date in the future (World Bank 2014) and there are significant differences in expected global production levels between the estimates. However the lower predictions of Delgado *et al* (2003) for 2020 and Ye (1999) for 2030 were already exceeded in 2012 and the World Bank (2014) projection for 2020 has probably already been passed.

Table 3.2 Forward projections of fisheries and aquaculture product demand for food (million tonnes)

Source	Baseline year	2020	2030	2050
Delgado *et al*. 2003	1997	130 (108 – 145)		
OECD-FAO, 2011	2010	164		
Lem *et al*, 2014	2012	181 (base prediction for 2022. Scenarios between 181 and 194.8)		
Ye, 1999	1996		126.5 – 183	
World Bank, 2014	2006	138	152	
Wijkström, 2003	2000			270.9
Note: Fisheries and aquaculture product supply for human food was estimated to be 136.2 million tonnes in 2012 (FAO, 2014)				

As little additional supply is likely to come from the capture fisheries sector, most of the projected growth is likely to be from aquaculture. In 2012, 136.2 million tonnes of fish and shellfish was utilised for human consumption, of which 69.6 million tonnes came from capture fisheries and 66.6 million tonnes from aquaculture. Aquaculture production would therefore need to increase by 23.7% on 2012 data to reach the World Bank projection for 2030 and by 70% to reach the upper projection of Ye (1999) for the same year (or indeed that of Lem *et al* (2014) for 2020; see Figure 3.14). On the same basis aquaculture output would need to be increased by 200% on 2012 data to meet the projection of Wijström (2003) for 2050.



(Source: Lem et. al. 2014)

Figure 3.14 Projected world fish consumed as food, live weight, 2012 - 2022

Global per capita fish supply in 2012 was 19.2 kg/person (live weight equivalent), a substantial increase from the 9.6 kg/person reported in the 1960s (FAO, 2014). This average masks substantial variations from below 1 kg/person in Ethiopia to over 70 kg/person in Hong Kong[4]. Although not strictly comparable in terms of measured units, this compares with a global per capita meat consumption of 42.8 kg/person (22% bovine, 35% poultry, 37% pig & 4% ovine and 2% other meat) or 75.5 kg for developed countries (118 kg for USA) (FAO, 2014a). This is discussed further in Section 7.

Conventional supply and demand economics apply to fish and shellfish, although greatly affected by regional characteristics. A study by Dey *et al* (2008) of nine Asian countries found fish comprised between 5 (China) and 20 (Bangladesh) percent of household expenditure on food. Perhaps as a consequence, the own-price elasticity of demand[5] for fish (an indicator of consumer sensitivity to price) is greater in Bangladesh, especially for higher value fish products and for lower-income social groups. The study found the average elasticity of demand for fish to be 0.94 (slightly inelastic) reflecting its importance as a staple food item in most cultures. This supports earlier work by Asche & Bjorndal (1999) who developed a model predicting own-price elasticities of demand for food fish would be in the range of –0.8 to –1.5.

Examining first sales prices for aquaculture products show that almost 50% of production was sold at below US$4/kg in 2013, 75% was sold below $7/kg and almost 95% was sold below $10/kg (Figure 3.15 below; see also Table 3.3). This places pressure on producers to minimise production costs and limits opportunities for expansion in higher unit value species.

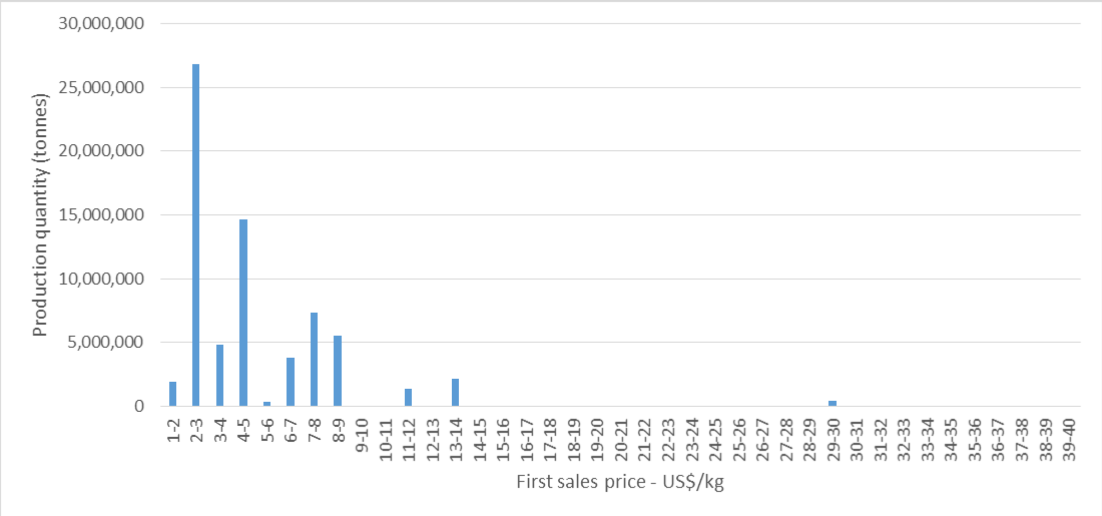


Figure 3.15 Volume of aquaculture produce by price category

4 http://www.st.nmfs.noaa.gov/Assets/commercial/fus/fus12/08_percapita2012.pdf

5 A measure of the responsiveness of demand (quantity) in relation to a change in price. This is usually a negative relationship with demand falling when prices rise. An elasticity below 1 suggests a relatively inelastic relationship where percentage changes in demand are lower than a percent change in price that affects the demand. Elasticities above 1 indicate a more elastic relationship where percent changes in demand are greater than the percent change in price. See https://stats.oecd.org/glossary/detail.asp?ID=3206.

The closest substitutes for aquaculture products are products from the capture fishery. Due to cross-price elasticity of demand[6] this means aquaculture product prices have often been affected by changes in supply of similar products from the capture fishery. However, this is gradually reducing in product categories where aquaculture dominates, such as salmonids.

Table 3.3 Indicative first sale prices by species group

First Sale Price per kg (US$)	Example Species Groups (From Aquaculture)
<2	Freshwater molluscs, **mussels**
2-4	Carps, tilapia, some catfish
4-6	Other freshwater fish, oysters, **cod, some pelagic fish**
6-8	Some marine fish, salmon, trout, **crabs, clams, cockles, arkshells & scallops**
8-10	**Sea bass, sea bream, shrimp, prawn, other marine fish**
10-12	**Flounders, halibuts, soles, some marine molluscs**
12-14	Eel, freshwater crustaceans
14-20	**Tuna**
20-30	**Lobster, abalone**
30-40	Sturgeons
Note: Products from mariculture in **bold**	

(Source: FAO Fishstat database 2015)

3.4.2 Market Development

Carlucci *et al*. (2015) performed an international meta-analysis of studies on consumer purchasing behaviour in relation to fish and shellfish. They identified a range of drivers and barriers affecting the basic type and quantity of fish purchased and a further list of attributes that affected the specific product purchased. These help to identify potential strategies for expanding the market for fish and shellfish, particularly in regions with traditionally lower per capita consumption, whilst taking into consideration specific regional, national or local characteristics.

In many developing countries the most effective strategy is probably improvement of distribution networks, particularly facilities for maintaining cold-chains[7] from harvest to retail. This greatly reduces food spoilage and wastage and getting a fresher and higher quality product to the market improves prices and increases the number of potential customers that can be supplied (Asmah 2008). At greater geographic scales facilitation of international trade can have substantial impacts on consumption in importing countries and provides economic development opportunities for exporting countries. This is already very evident for fisheries and aquaculture produce as these now constitute the most highly traded food commodity internationally (Asche and Smith, 2010). However, potential exporters have to overcome a range of barriers to achieve market access (Table 3.4). Some of these are deliberately imposed by countries to protect domestic producers whilst others are a consequence of more demanding and complex consumer protection legislation and administrative procedures.

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6 Cross price elasticity of demand refers to changes in demand for a certain product due to changes in price of another related (substitute) product. See https://stats.oecd.org/glossary/detail.asp?ID=3185.

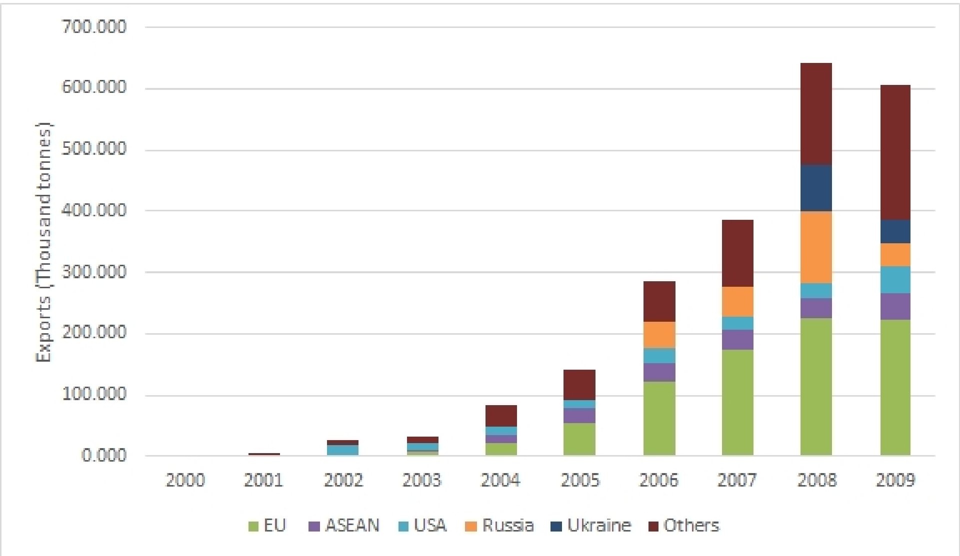
7 A temperature-controlled supply chain used to help extend and ensure the shelf life of products.

Table 3.4 Example tariff and non-tariff barriers

Tariff Barriers	Non-Tariff Barriers
Specific duty	Quota
Ad Valorem duty	Foreign exchange regulations
Anti-dumping duty	Technical and administrative regulations
Counteracting/countervailing duty	Consular formalities
Alternative duty	State trading and government procurement
Compound duty	Preferential arrangements
Seasonal duty	Import license
Transit duty	Trading blocs
Single column and multicolumn duty	Canalisation of trade
Other charges	Economic and political wars
	Prior import deposits
	Customs regulations
	Sanitary and phytosanitary regulations and certification

(Source: Compiled from several sources)

For instance, exporters to the EU, which is the largest import market for fish and shellfish produce (farmed and wild capture), require approval of all production and processing facilities and official authorisation to export. This requires a competent authority to be in place in the country concerned which has been duly recognised by the EU. Individual consignments require a health certificate and other documentation to comply with traceability rules. The USA has similar arrangements. There may then be additional voluntary standards that have to be applied, e.g. GlobalGap or BRC (British Retail Consortium) Global Standards for sales into major retail chains. It is particularly challenging to meet these requirements and overcome other trade barriers if the production sector is highly fragmented. Some consolidation, especially at processing level, has been necessary to make feasible substantive exports. However, once these barriers have been overcome, the opportunities can be substantial. Clear examples are the Thai shrimp industry or Vietnamese pangasius catfish industry which expanded rapidly on the basis of export sales (Figure 3.16).



(Source: VASEP, 2010)

Figure 3.16 Development of Vietnamese pangasius exports

Barriers to trade are generally addressed through bilateral or multilateral agreements, the latter particularly through the World Trade Organisation (WTO). The WTO has been working on a global reform of the international trading system through the "Doha Round[8]" which started in 2001. This has so far failed to reach a comprehensive settlement, so bilateral and regional agreements have had more impact. Most attention has been given recently to the EU-US Transatlantic Trade Investment Partnership (TTIP)[9] which is aiming to reduce barriers to trade between these two economic regions through closer alignment of regulatory requirements.

A second strategy is product diversification and value addition. Markets can be expanded through offering a greater range of food products and particularly products that offer greater convenience and add variety (Birch et. al. 2012; Gonçalves & Kaiser 2011). Convenience foods (both fresh and frozen) have been an increasingly important format for fish sales particularly in Northern Europe and the USA. In Southern Europe and much of Africa and Asia, whole fish are still preferred, especially for family meals and when dining out, although value added products are also increasing in popularity in most markets (Carlucci *et al*. 2015). One reason for the success of salmon aquaculture is its relatively high fillet yields (over 60%) which makes them a more economic prospect for value added products. For comparison, the fillet yields of most fish including cod and seabream are often between 30 and 40% (FAO, 1989).

Packaging has been less well studied, but has generally been found to have less importance than other product attributes (Carlucci *et al* 2015; Loose et. al. 2012). However, in a recent USA survey of retailers (Major & Chanil 2015) the most cited driver of increased sales was the availability of smaller pack sizes, which was most likely linked with pack price targets.

Ethical and quality assurance attributes are seen as key drivers for future development. For instance Lappo *et al* (2013) in foresight to 2030 identified five important consumer trends and purchase drivers (Table 3.5).

Table 3.5 Anticipated trends in purchase drivers

Trends	Impact on Food Demand
Food safety and health benefits	▪ Increased demand for food that is eco-labelled and certified by the authorised body ▪ Increasing popularity of organic food ▪ Decreased consumption of fast food
Corporate social responsibility	▪ Increased preference of consumers to buy "socially responsible" products ▪ More informed consumer choice about food products ▪ Increased demand for products from reliable brands/producers ▪ Affinity with "honest" brands/producers
Production systems and innovations	▪ Further adaptation to new foods, though slow in cases when genetic modification, nanotechnology, aquaculture and convenience applies ▪ Growth in relevant certification and ecolabelling
Sustainability	▪ Increase production and demand for products that are produced sustainably and certified
Country and region of origin	▪ Choice of local foods over exported by consumers if products prices are competitive

(Adapted from: Lappo et. al., 2013)

8 https://www.wto.org/english/tratop_e/dda_e/dda_e.htm
9 http://ec.europa.eu/trade/policy/in-focus/ttip/

In this respect, the growth of both government and voluntary standards schemes and the certification of products and producers is increasingly important although it can also lead to consumer confusion (Retail Forum for Sustainability, 2012). However, good provenance does not necessarily increase sales, but can help to retain consumers who might otherwise seek alternative products. Research in the UK for the retailer Sainsbury's found that health was the greatest driver for increased consumption whereas rising prices was the major reason for reducing consumption. Concerns over sustainability discouraged 18% of surveyed consumers and it is these who might be encouraged to maintain consumption through well publicised certification schemes (The Future Foundation 2012).

3.4.3 Competition for Resources

Aquaculture operations can be directly or indirectly dependent on a range of natural resources and ecosystem services (see Table 3.6). These resources are generally finite and subjected to competing interests. Most pressing for mariculture has been coastal space, especially for finfish cages in EU countries and North America. With some localised exceptions, aquaculture production has been largely stagnant in these regions since the early 2000s with obstacles to the development of new sites identified as a major cause (EC, 2013).

Table 3.6 Key resource dependencies for different aquaculture systems

Aquaculture System	Spatial and Water Resource Requirements	Nutritional Resource Requirements	Loading on Ecosystem Services
Coastal ponds – fish and shrimp	Coastal land and water	Inorganic and organic fertilizers, feeds with cereals and fishmeal or substitutes	Organic suspended solids; dissolved organic and inorganic nutrients
Flow-through tanks – fish	Some coastal land and water	Feeds with cereals and fishmeal/fish oil or substitutes	Organic suspended solids; dissolved organic and inorganic nutrients
Recirculated tanks – fish	Some coastal land and water	Feeds with cereals and fishmeal/fish oil or substitutes	Controlled outputs so limited demands on immediate ecosystem
Cages – fish	Coastal water area	Feeds with cereals and fishmeal/fish oil or substitutes	Organic suspended solids; dissolved organic and inorganic nutrients
Shellfish - suspended	Coastal water area	Natural feed	Organic suspended solids*
Shellfish – intertidal	Intertidal land	Natural feed	Organic suspended solids*

* Shellfish systems are generally considered to be abstractive as they remove more suspended solids and nutrients than they discharge however, there can be enhanced sedimentation and biodeposition below cultured bivalves due to faeces/pseudofaeces production and discharge

Competing interests in the coastal zone include navigation, hydrocarbon extraction, inshore fisheries, visual and recreational amenity. Substantial public scrutiny is now given to projects that are proposed in some western/developed countries that are seen to exploit natural resources for commercial profit and that are perceived as adversely affecting the natural environment including the quality of scenery. The scale of coastal aquaculture operations seen in China and other parts of Asia would be socially unacceptable elsewhere.

A crude measure of coastal resource use is production per kilometre of coastline. This shows China well ahead of all other countries on coastal resource use with an average production of 946 t/km in 2013. Most of this is comprised of seaweed (449 t/km) and molluscs (424 t/km) with 37 t/km for marine fish and 36 t/km for brackish water culture (crustaceans, fish, turtles etc). For comparison, the same calculation shows the aquaculture production intensity in the UK to be less than 1% that of China at 9.3 t/km[10].

Other countries with relatively high production of marine fish per kilometre include Norway (23), Malta (20), Turkey and Singapore (around 13.5 each). The highest intensity of brackish water production is Egypt (135 t/km) due to the nature of the Nile Delta. Other countries with high intensity of brackish water systems include Ecuador (66), Vietnam (55), Thailand and Bangladesh (around 50 each). The highest intensities of mollusc farming (other than China) are found in Taiwan, Thailand, Netherlands, Korea, France, Spain and Peru whilst seaweed production intensity is relatively high in Indonesia, Korea and Philippines (see also Section 4). Table 3.7 shows the nominal mariculture production intensity per km of coastline for all aquaculture producing countries.

Table 3.7 Nominal production intensity per kilometre of coastline

Country	Marine Fish t/km	Brackish Water Fish and Crustaceans t/km	Molluscs t/km	Seaweed t/km	Total t/km
China	37.43	36.02	424.03	449.06	946.54
Egypt	0.00	134.61	0.00	0.00	134.61
Korea, Republic of	5.85	0.00	23.32	90.66	119.84
Indonesia	0.20	14.04	0.31	97.69	112.24
Taiwan	1.33	52.46	42.34	1.61	97.74
Thailand	0.00	49.46	30.78	0.00	80.24
Viet Nam	0.45	55.55	15.70	7.65	79.35
Ecuador	0.00	66.13	0.00	0.00	66.13
Philippines	3.65	9.66	1.33	45.97	60.61
Bangladesh	0.00	48.95	0.00	0.00	48.95
Malaysia	0.00	9.22	4.50	28.90	42.62
Japan	8.37	0.00	11.46	14.42	34.24
Netherlands	0.01	0.09	29.68	0.00	29.78
Spain	5.66	0.18	22.70	0.00	28.54
Honduras	0.00	26.32	0.00	0.00	26.32
Norway	23.41	0.00	0.04	0.00	23.45
India	0.00	22.18	0.76	0.26	23.20
France	0.86	0.00	21.42	0.05	22.33
Peru	0.00	0.00	20.14	0.01	20.15
Malta	19.89	0.00	0.00	0.00	19.89
Israel	12.34	4.12	0.00	0.00	16.46

10 This is predominantly due to the salmon farming industry in Scotland. However, the calculation for Scotland alone may not give a substantially higher result as the World Resources Institute data for the UK gives a coastline length of 19,717 km whereas the British Cartographic Society quote a length of 18,588 km for Scotland and associated islands - http://www.cartography.org.uk/default.asp?contentID=749).

Country	Marine Fish t/km	Brackish Water Fish and Crustaceans t/km	Molluscs t/km	Seaweed t/km	Total t/km
Singapore	13.57	0.32	1.71	0.00	15.60
Nicaragua	0.00	13.77	0.00	0.00	13.77
Turkey	13.62	0.00	0.00	0.00	13.62
Italy	0.70	0.73	11.99	0.00	13.41
Chile	9.37	0.00	3.21	0.16	12.75
Denmark	2.04	0.00	0.11	7.52	9.67
Greece	8.17	0.07	1.16	0.00	9.39
United Kingdom	7.92	0.00	1.38	0.00	9.30
Cyprus	7.85	0.00	0.00	0.00	7.85
Bosnia and Herzegovina	4.74	0.00	2.17	0.00	6.91
Tunisia	0.33	5.42	0.06	0.00	5.80
New Zealand	0.66	0.00	4.95	0.00	5.61
Ireland	1.45	0.00	3.74	0.01	5.19
Belize	0.00	3.55	0.00	0.01	3.55
Mexico	0.29	2.54	0.21	0.00	3.04
Cambodia	0.49	0.14	2.40	0.00	3.03
Brunei Darussalam	0.00	3.01	0.00	0.00	3.01
Portugal	1.34	0.01	1.32	0.00	2.67
Iran (Islamic Rep. of)	0.00	2.16	0.00	0.00	2.16
Tanzania, United Rep. of	0.00	0.14	0.00	1.93	2.07
Solomon Islands	0.00	0.00	0.00	1.69	1.69
Sri Lanka	0.00	1.57	0.00	0.01	1.59
Croatia	1.20	0.00	0.35	0.00	1.55
Germany	0.00	0.01	1.41	0.00	1.42
Panama	0.17	1.23	0.00	0.00	1.41
Costa Rica	0.00	1.40	0.01	0.00	1.41
United States of America	0.16	0.00	1.20	0.00	1.36
Kiribati	0.00	0.01	0.00	1.15	1.15
South Africa	0.01	0.00	0.59	0.53	1.13
Australia	0.71	0.11	0.25	0.00	1.07
El Salvador	0.00	1.02	0.02	0.00	1.04
Côte d'Ivoire	0.00	1.03	0.00	0.00	1.03
Mauritius	0.81	0.00	0.01	0.00	0.82
Iceland	0.06	0.73	0.02	0.00	0.82
Canada	0.46	0.00	0.16	0.00	0.62
Brazil	0.00	0.00	0.58	0.02	0.60
French Polynesia	0.00	0.00	0.45	0.00	0.45
Algeria	0.00	0.40	0.00	0.00	0.41
Saudi Arabia	0.26	0.04	0.00	0.00	0.30
Senegal	0.00	0.14	0.14	0.00	0.29
Madagascar	0.00	0.00	0.00	0.28	0.28
Namibia	0.00	0.00	0.20	0.07	0.27
Myanmar	0.02	0.12	0.00	0.11	0.24
Dominican Republic	0.22	0.02	0.00	0.00	0.24
Mozambique	0.02	0.00	0.00	0.00	0.02
New Caledonia	0.00	0.00	0.01	0.00	0.01

(Source: Calculated from FAO Aquaculture Production data 2013 and Coastline length from the World Resources Institute as given on Wikipedia: http://en.wikipedia.org/wiki/List_of_countries_by_length_of_coastline)

Achievable production intensities will vary substantially by locality and system type and in relation to the choices made with respect to allowable environmental change and the interests of other users of the resource (including impacts on wild fisheries and amenity). There will also be technical constraints, for instance relating to the density of aquaculture which can be sustained without economically unacceptable adverse effects on production, e.g. through deterioration in water quality or the prevalence and transfer of fish diseases.

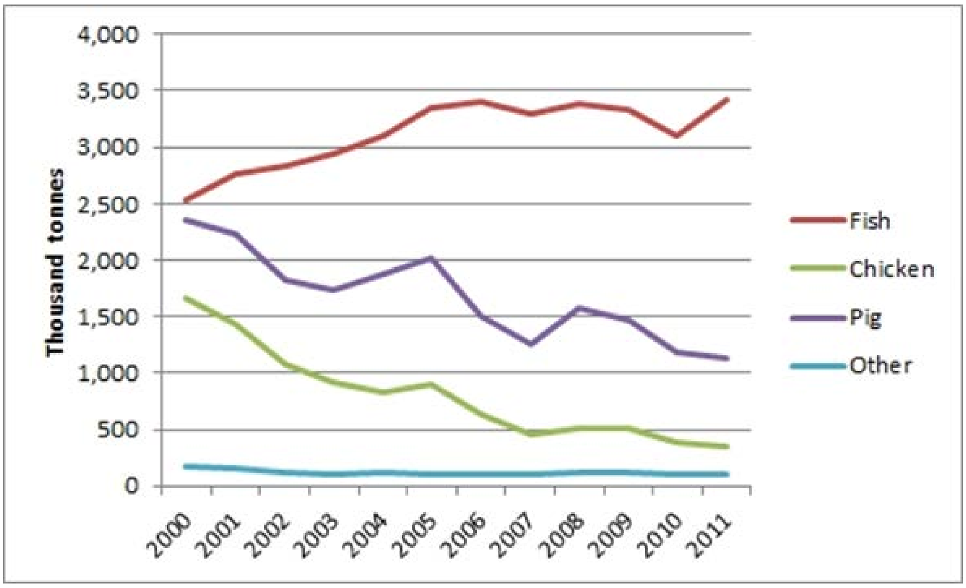
The shrimp sector has been particularly affected by environmental and disease problems following expansion in production. In the case of shrimp farming in Thailand, environmental and disease problems in brackish water farms prompted a move to lower salinity inland sites using an introduced species (*Litopenaeus vannamei*) which displaced rice farms and caused temporary salinization of inland soils (Braaten & Flaherty 2000). This underlines the fact that production systems are relatively plastic and develop in optimum configurations according to the opportunities and constraints that the industry faces (see Belton and Little, 2007). In particular production intensity is likely to be lower where land and water are relatively available but infrastructure and power is poor or expensive. Direct land and water inputs can be reduced for equivalent production through increased investment in equipment and expenditure on power and higher quality feeds as illustrated in Table 3.8.

Table 3.8 Brackish water pond intensity implications

Pond Type	Intervention Required	Approximate Shrimp Yield (t/ha/cycle)	Approximate Fish Yield (t/ha/yr)	Power Input Required Per Tonne Produced (MWhr)
Extensive ponds based on natural or minimal feed	Minimal feeding with grains, farm and home residues	0.1 – 0.5	>2	0
Extensive fed pond	Feeding by complete diet pellets	0.5-2.5	2-4	<5
Semi- intensive ponds with night-time and supplemental aeration	Night-time or emergency aerators, ~1-5 hp/ha	1.5-8.0	4-10	8-15
Intensive, fully aerated ponds	24-hour aeration under 20 hp/ha (pure oxygen, if needed), completely mixed	8-20	20-100	20-100

Whist the siting type and scale of mariculture activities depends largely on economic factors, existing operators increasingly understand that for sustainability and further expansion they need a “social licence to operate” – i.e. regulatory and community approval for the farm locations and activities. This requires good dialogue with stakeholders and engagement with community concerns.

One of the most discussed issues affecting aquaculture development is the use of fishmeal and fish oil in fish (and to a lesser extent) shrimp diets (Kristofersson & Anderson 2006; Naylor *et al* 2009; Oksen & Hasan 2012). Aquaculture has utilised an increasing share of global total supplies (Figure 3.17) suggesting availability could become a limiting factor for production, and that rising demand could encourage overfishing (although efficiency of use in feed has been improved – see below).



(Source: IFFO, 2013)

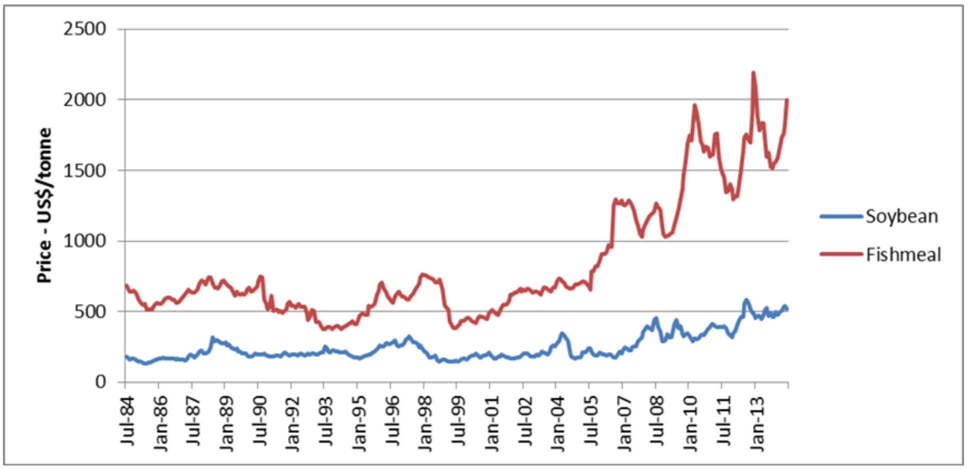
Figure 3.17 Global utilisation of fishmeal

In recent years, some of the additional demand has been met from by-products from fish processing, including salmon (Figure 3.18). This has increased supplies by around 25% (IFFO, 2013).

(Source: IFFO, 2015)

Figure 3.18 Global production of fishmeal and fish oil

Increased demand for fishmeal and oil has also led to substantial price increases (Figure 3.19), which in turn have driven research and development towards more efficient utilisation and wherever possible the use of plant-based alternatives. For protein, the use of soy concentrate (which has higher protein content and much reduced anti-nutritional factors[11]) combined if necessary with direct amino acid supplementation has been found to provide equivalent growth performance (e.g. Hart & Brown 2008; Salze *et al* 2010). Fish oil can also largely be substituted with vegetable oil, but at the cost of reducing omega three fatty acid content in the final product (considered to be a health benefit of eating oily fish). A potential solution to this using genetically modified canola seed oil has been tested with preliminary success (Betancor 2015), but this would need to gain commercial acceptance. The use of oils from microalgae would also be feasible (Qiao *et al* 2014), but unlikely to be economic in the foreseeable future.



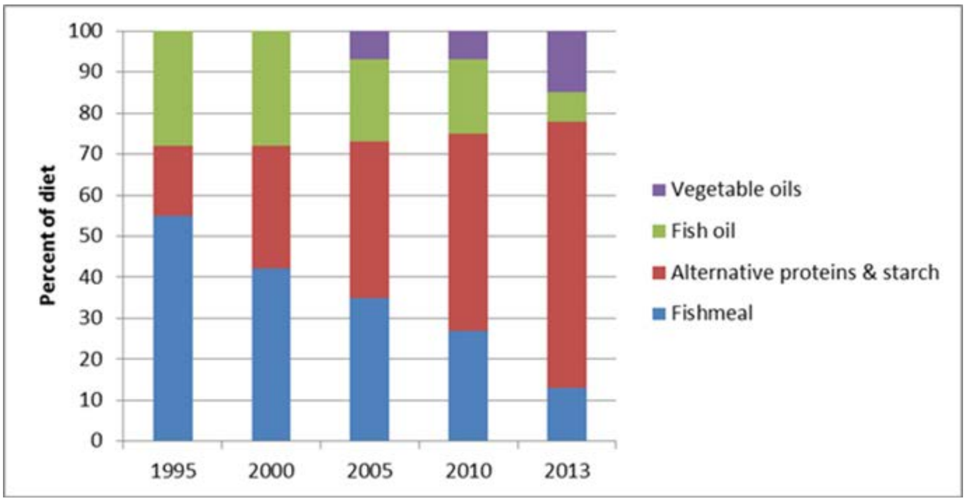
(Source: Index Mundi, 2015)

Figure 3.19 Fishmeal and soy commodity price trends

Economic pressures have already forced the aquaculture sector to improve efficiency of fishmeal and fish oil use and percentage inclusion rates in typical salmon diets for instance have declined markedly (IFFO, 2013) (Figure 3.20).

However, the implications of greater use of soybean and other seed meals and oils for aquaculture feeds are greater land use for crop cultivation, use of freshwater resources and industrial fertilizers. An alternative source of protein for aquafeeds is processed animal proteins (PAPs). These were banned in Europe following the BSE crisis in the 1990s, but non-ruminant proteins were re-authorised by the EU in 2013. Porcine blood meal for instance is in good supply and would have nutritional value in aquaculture diets being a good source of histidine which is lacking in plant proteins (Hatlen et. al. 2013). However, such products would be unacceptable for halal and kosher markets and for other consumers who might be concerned about this development. Experimental work is also ongoing to explore the potential for insect protein (Čičkováa *et al*. 2015; Barroso *et al*. 2014) or worms (Guerrero & Guerrero 2014) cultured on organic waste from other production processes.

11 Substances that when present in animal feed or water reduce the availability of one or more nutrients



(Source: IFFO, 2013)

Figure 3.20 Changing composition of salmon feeds over time with substitution of fishmeal and fish oil

3.4.4 Climate Change

With high levels of uncertainty concerning the degree, impacts and timescale of climate change, only a selection of potential issues can be considered here. The actual impact in terms of food production or economics will depend substantially on any actions that are taken to mitigate climate change, or the strategies that are developed for adaptation (Shelton, 2014). According to FAO (2009b) "Climate change will have potentially significant impacts on the four dimensions of food security: availability of aquatic foods will vary through changes in habitats, stocks and species distribution; stability of supply will be impacted by changes in seasonality, increased variance in ecosystem productivity and increased supply variability and risks; access to aquatic foods will be affected by changes in livelihoods and catching or farming opportunities; utilization of aquatic products will also be impacted and, for example, some societies and communities will need to adjust to species not traditionally consumed". Some of the key mechanisms are summarised briefly here:

3.4.4.1 Temperature rise

Increases in seawater temperatures are already being recorded and are predicted to continue (Clemmesen *et al* 2007). This will mean that farms that currently operate with optimum temperature regimes will find they are increasingly having to operate with sub-optimum regimes. Higher temperatures usually bring increased risk of diseases (and can encourage the emergence of new diseases), and can lead to alterations in reproductive cycles. Ultimately, sites which are currently viable, may become unviable for farming specific species. The converse may also be true however, and that sites that are currently sub-optimal may become more optimal (Lorentzen & Hannesson 2006). This could lead to farms switching to a different species where this is economically viable. For cold water species it may encourage development in areas closer to the Arctic and Antarctic circles to maintain production capacity.

3.4.4.2 Sea level rise

Whilst this will increase marine surface area it will reduce land area and coastline. It is more likely to lead to a reduction in usable area for mariculture due to higher competition for coastal area and the inundation of areas that have no history of mariculture practices, although new opportunities might open up closer to the poles (Shelton, 2014). Existing coastal pond systems however are likely to be particularly hit.

3.4.4.3 Acidification

Rising levels of carbon dioxide (CO_2) in the atmosphere also increase levels in seawater, which in turn can lead to a lowering of pH and reduced buffering capacity (decline in carbonate ion concentrations). This may benefit some species, especially seaweeds, but has been associated with reproductive failures and other problems in molluscs and crustacean which could impact on shellfish production (Barton *et al* 2012).

3.4.4.4 Extreme weather events

Climate change is expected to lead to an increase in the frequency of extreme weather events such as cyclones, tornados, flooding and blizzards (Clemmesen *et al*, 2007). These can cause major financial losses for farms and increased frequency could lead to operations becoming financially unviable. For instance the farming of marine fish in Taiwan has been severely impacted by more frequent typhoon damage (Su & Su 2010). Increased rainfall and flooding could lead to higher runoff and sediment loads which could adversely affect shellfish and other systems (Callaway *et al* 2012).

3.4.4.5 Ecological change

It seems likely that climate change could also lead to alterations in ecosystem structure and function, particularly as there is increasing loss of biodiversity. A possible example of this is the increasing frequency of harmful algal blooms in coastal waters around the world (Hallegraeff 2010) which pose a direct risk to fish and shellfish mariculture through factors such as deoxygenation of the water, direct toxicity to the cultured organisms, or contamination of cultured species with toxic compounds. A related problem has been increases in jellyfish blooms (Callaway *et al*, 2012), which have caused substantial losses at cage fish farms in Western Canada, Chile, Ireland and Scotland.

Overall, climate change will increase the challenges facing the mariculture sector with respect to sustaining and increasing output.

3.4.5 Technology Advances

The development of aquaculture has required scientific and technical advances across a range of discipline areas. This will need to continue for aquaculture to simultaneously increase output whilst adapting to changes in physical and economic environments and responding to evolving markets and social contexts. Key areas for innovation include:

3.4.5.1 Reproduction control

Whilst aquaculture dates back millennia, fish and shrimp mariculture is a comparatively recent development based on closing the reproductive cycle of marine species. The major challenges were understanding the hormonal cycles determining spawning and finding manipulations for these using a mix of environmental queues and/or hormonal injections. The second issue was the development of larval rearing techniques, especially the use of live feeds and the enrichment of zooplankton with additional lipids and micronutrients. Research and development continue to add to the list of marine species that can be economically produced in hatcheries. One of the most challenging in this respect however, has been blue fin tuna. The high prices paid for this species in Japan and the fragile nature of existing wild stocks has made this a natural target for development. Although significant progress has been made, commercial viability requires further breakthroughs.

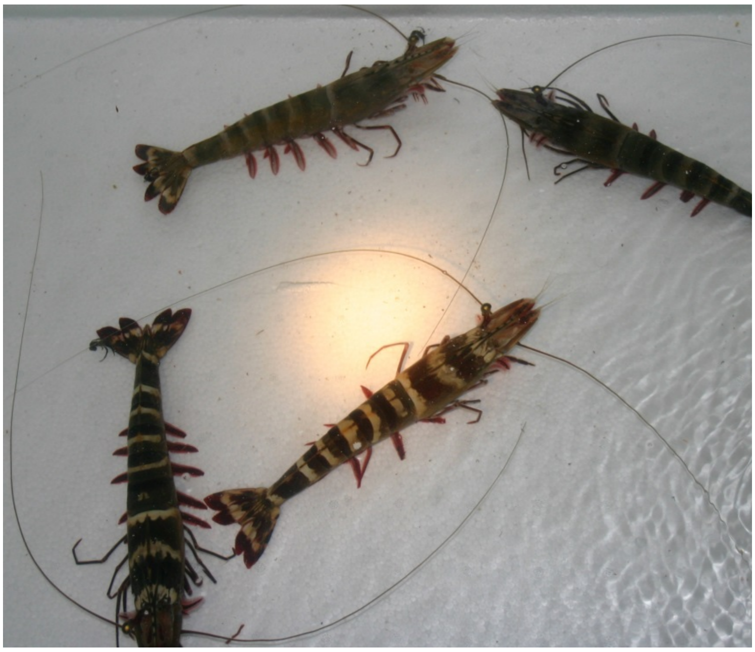


Figure 3.21 Black tiger shrimp broodstock (Source © Richard Newton)

3.4.5.2 Nutrition

The intensification of mariculture has relied on the development of nutritionally complete artificial diets. "Trash" or "bait fish[12]" are still used in some systems, but in terms of volume, the majority of the industry is based on formulated feeds, either nutritionally complete, or partially complete and used to supplement natural pond productivity. Good quality processing, handling and storage of raw materials has proved very important, and for many fish species the use of extruded diets which float or have relatively neutral buoyancy is also a major consideration. Processing is particularly important with respect to many plant ingredients which contain anti-

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12 Marine fish having little value as human food but used directly as feed for some fish and animal production. The fish are usually small species caught as bycatch in commercial fishing but may be specifically targeted in shallow inshore areas.

nutritional factors, some of which can be reduced through heat or pressure treatment. The production of quality feeds requires significant infrastructure and investment, so this has arguably been one of the leading constraints to intensive aquaculture development in much of Africa. As the largest single component of most farm operating costs, the cost of quality feed will remain a key determinant of future scope for industry development, as will any advances that improve feed utilisation efficiency.

3.4.5.3 Health and welfare

The intensification of many aquaculture systems has been accompanied by greater problems with disease which have led to either poor profitability or complete financial collapse for many operators. The worst examples include white spot syndrome in shrimp, which has caused major losses in many shrimp farming countries (Flegal & Fegan, 2002), and infectious salmon anaemia which has affected most salmon producing countries, but caused the greatest losses in Chile. Both of these diseases are caused by viruses of which there are several other examples affecting most intensively farmed aquatic species including molluscs. There are also bacterial and fungal pathogens as well as parasites that have also been responsible for both chronic and acute losses.

A number of significant bacterial disease problems in fish have been successfully addressed through the development of vaccines, e.g. for furunculosis and vibriosis in salmonids. Some viral disease problems have also been reduced through this approach and research is ongoing on vaccines for parasite problems. Viral diseases have also been tackled through selective breeding programmes (see below) and the use of immunostimulants and probiotics. Parasites have largely been controlled through the use of chemical baths or in-feed therapeutants although resistance problems have emerged most notably in the case of sealice affecting salmon. The use of biological control methods (co-culture of species of wrasse and lumpsucker) are currently being commercialised as a further approach. Greater attention is also being given to management approaches that focus on the promotion of health through attention to fish welfare issues (Kadri & Steiropoulos 2013). This is important not only for business viability, but also through consideration of impacts that aquaculture can have on natural populations. Although diseases spread initially from the wild to farmed populations, these can then act as a reservoir and a source of infection back to wild populations. This has been a particular issue affecting relations between salmon farming and angling interests. The creation of area management agreements to coordinate stocking, treatment and fallowing patterns has gone some way to address this.

As new diseases frequently emerge, it is likely that health will remain a key factor in the development of future aquaculture systems and the operation and performance of the industry.

Some concerns regarding the welfare of fish farmed in intensive systems (e.g. in relation to stressors such as handling, crowding, transport etc) has led to the establishment of quality assurance and food labelling schemes. For example, in the UK, the RSPCA Freedom Food mark and Soil Association organic mark, set welfare standards for farm-reared fish above typical/standard UK production standards.

3.4.5.4 Selective breeding

Aquaculture is well behind terrestrial livestock production in terms of domestication, however progress is being made with salmon and increasingly other leading species. The production time for Atlantic salmon was halved in around six generations with other improvements to disease resistance and early maturation (Bostock *et al* 2010). Similar work is ongoing with European sea bass and shrimp. These can be expected to yield further improvements in production efficiency including with respect to growth, feed conversion rates, acceptance of higher stocking densities and disease resistance. One downside of this development is increased potential risk of disruption to natural populations and their genetic composition if there are substantial escapes of farm stocks, which is leading to greater attention on ensuring containment security (Liu *et al*. 2013).

3.4.5.5 Engineering

Larger-scale mariculture, especially in more exposed environments has been facilitated through the development of specialised equipment. This has borrowed from allied sectors such as fishing, offshore energy and naval architecture. For marine fish, floating net cages (pens) have become the preferred system. Most commonly these are suspended from floating collars made of high density polythene pipe (originally developed for the gas industry) which are moored in groups using specialised spade anchors and grids constructed of rope and chain with customised link components, surface and sub-surface buoys. The salmon farming sector is predominantly servicing these from feed barges that are moored adjacent to the cage group and supply feed through pipes driven by air blowers. It also makes extensive use of specialised well boats for transporting fish to and from the cages, and performing grading and disease treatment operations. The future expansion of the aquaculture industry to more offshore sites will depend on further increases in scale and suitability of equipment for such harsh environments.

Much of the shellfish sector is based on more traditional technologies although specialist equipment has been developed for larger scale floating systems (rafts and long lines) and for tasks such as stocking lines, grading and harvesting. Such innovations have extended the range of sites that can be utilised and have increased labour productivity. Shellfish that are produced in areas with risk of pollution need to be depurated prior to sale which adds to production costs. Further optimisation and commoditization of these systems will help extend the areas that can be used for shellfish cultivation.

A further area of system design that has been important for mariculture development is the adaptation of potable and waste water treatment technologies for use in hatcheries, nurseries and occasionally for grow-out. Recirculated aquaculture systems (RAS) can provide high levels of environmental control, enhancing biosecurity and reducing any impacts on the wider environment. This approach has been advocated by environmental campaign groups as a means of removing aquaculture from the natural environment. However, there are significant economic barriers to this and at current levels of technological development, the commercial risk levels are higher. The potential licensing of genetically modified salmon in the USA suggests there may be a way forward with the combination of GMO and RAS technologies if the former prove acceptable to consumers.

3.4.5.6 Information technology

Little work has been done to document the gain in productivity achieved through the use of information technology. In part this may be due to the incremental nature of its implementation. Data is captured throughout the production process through a mix of manual and automated procedures. This can be analysed and used to develop improved models for production planning. Specific developments for aquaculture have included fish and larval counting systems based on infrared imaging and analysis and biomass estimation using stereo camera systems to estimate fish size. Information technology systems are also needed to fulfil legal and industry traceability and food standard requirements. It is likely that data collection and analysis will become an increasingly important factor for industry competitiveness.

3.5 Summary

The production of fish and shellfish through aquaculture has increased at an average of 5.5% per annum between 2004 and 2013 to reach 69.7 million tonnes. Of this production, 29% was farmed in the marine environment, 62% in freshwater and 9% in brackish water (marine and brackish water farming has been considered to comprise mariculture in the present study). Most aquaculture growth over the last 20 years has occurred in Asia which accounts for 80% of total global fish and shellfish mariculture.

Marine finfish production is dominated by salmon (57% of total marine fish production in 2013). Mollusc production in 2013 comprised mainly of clams, cockles and arkshells (33% total), oysters (33%), scallops (12%) and mussels (12%). Crustacean farming is dominated by shrimp and prawn production (93% in 2013). Although the mariculture sector displays steady growth, production can vary in relation to commercial and environmental pressures including disease.

Key drivers of future mariculture production include increasing population growth and prosperity, fuelling demand for an increasing proportion of animal and fish protein in the average diet, although there is a large variation in seafood consumption per capita globally, ranging from 1kg/person in Ethiopia to over 70kg/person in Hong Kong in 2012. Some studies of future demand for seafood products from wild capture fisheries and aquaculture in 2020 and 2030 were exceeded in 2012 when 136.2 million tonnes of seafood were utilised for human consumption (69.6mt from fisheries and 66.6mt from aquaculture). Future aquaculture production may have to increase by 200% compared to 2012 levels to meet some projections for 2050 (271mt seafood). Other key influences on future mariculture production include opportunities and barriers to market development for the products (which include distribution networks and trade amongst other factors), competition for space (e.g. coastal land and marine and coastal waters) with other marine sector activities and natural resources (e.g. for feed), environmental factors (e.g. productivity and carrying capacity, disease etc), the impacts of climate change and technological advances (e.g. related to reproductive control, nutrition, health and welfare, equipment and engineering etc). Trade offs will need to be made (e.g. between increased land/water area use or increased energy consumption) which suggests the optimum solution may vary depending on local and regional circumstances and priorities.

4. Global Review of Algal Mariculture

This section reviews the culture of marine algae (macro-and microalgae), the products derived from algae (Section 4.2), production techniques (Section 4.3), historic production trends (Section 4.4) and future influences and drivers of global algal mariculture (Section 4.5). The processes via which macro- and microalgae are used for energy production are described in Section 5 and a comparison of the footprint of energy production from algal biomass compared to terrestrially-derived biomass (i.e. crops) is presented in Section 6.

4.1 Introduction

Algae are a diverse group of eukaryotes, most of which are autotrophic meaning they obtain energy either from light in a process commonly known as photosynthesis or inorganic chemical reactions through chemosynthesis. Algae function at the bottom of the food chain and, therefore, their productivity is fundamental to the survival of higher trophic level organisms.

Algae are largely categorised by their colour, typically red, brown or green. Brown algae (*Phaeophyta*) are brown, olive or yellowish-brown in colour and contain chlorophyll a and c as well as a pigment called fucoxanthin. Red algae (*Rhodophyta*) contain the pigment phycoerythrin which leads to their red colouration and enables photosynthesis at greater depths due to increased light harvesting (absorbs blue light which penetrates deeper into the water column than other wavelengths/colours of light). Green algae (*Chlorophyta*) are green in colour due to high chlorophyll a and b abundance, found at similar levels in cells compared to higher plants. Cyanobacteria (*Cyanophyta*) are also often described as a type of blue-green algae (Lee, 2008), although this has been disputed as they are bacteria (prokaryotic).

Algae can grow in a range of aquatic environments, including brackish (estuarine), freshwater (riverine) and marine (sea) waters. In addition, the distribution of algae is dependent on other factors, such as light intensity, nutrient availability and exposure (e.g. sheltered bays or rough seas). For the purpose of this study, we have defined algal mariculture as a specific type of aquaculture, referring to the cultivation of marine algal material. This includes marine macroalgae and microalgae cultivated in the marine environment or under marine conditions (e.g. marine ponds), but does not include aquatic plant material farmed in freshwater environments.

Microalgae are microscopic, often single-celled organisms which function independently of one another. Macroalgae or “seaweeds” are larger multicellular organisms (groups of cells), which are visually similar to terrestrial plants, but they can possess a holdfast, stipe and fronds as opposed to roots, stem and leaves (true plants), respectively. As they do not possess a root system, nutrients are absorbed by the entire organism from the surrounding aquatic environment.

This section provides a brief review of global algal mariculture trends, including the type of goods produced, species harvested, production techniques used, locations of current infrastructure and past/present production volumes. It also provides a summary of potential future trends and drivers for the industry and areas currently undergoing (or in need of) further investigation.

4.2 Products Derived from Algae

4.2.1 Macroalgae

Currently, over 100 species of macroalgae are used for food, medicine, fertiliser and the processing of colloid (a substance in which microscopically dispersed insoluble particles are suspended throughout another substance) and other chemical products (Santelices, 2007; cited in Hughes *et al*. 2012). As at 2012, the number of algal species and species groups (including microalgae and freshwater species) registered in FAO statistics was 37 (FAO, 2014).

4.2.1.1 Food

The majority of cultivated macroalgae (seaweed) is intended for human consumption. Seaweeds can provide a direct edible food product, either fresh (e.g. *Caulerpa*, *Porphyra*, *Ulva*) or dried (e.g. *Enteromorpha*, *Fucus*, *Saccharina*, *Sargassum*, *Undaria*), or can be used for the extraction of agar, carrageenan and alginate which are indirectly consumed through their use as hydrocolloids (e.g. *Gelidium*, *Gracilaria*, *Chondrus*, *Eucheuma*, *Kappaphycus*, *Macrocystis*). Hydrocolloids are used to form colloid systems, evenly dispersing particles specifically in water based products.

Farmed *Undaria* (wakame) and *Porphyra* seaweeds are almost entirely destined for direct human consumption. Dried Japanese kelp (*Saccharina japonica*) is used directly as a source of food, but also for alginate, mannitol and iodine extraction (Lucas and Southgate, 2012). A substantial proportion of seaweed culture (e.g. *Gracilaria*) is used as feed for other aquaculture industries, such as abalone and sea cucumber culture (FAO, 2014).

The FAO have produced online fact sheets for numerous cultured aquatic species, including various marine macroalgae such as *Eucheuma* spp., *Gracilaria* spp. and *Saccharina japonica*. Other than dried seaweed, *Eucheuma* products related to the extraction of carrageenan are exported to the international market (FAO, 2015). Carrageenan is typically used as a gelling or thickening agent in many food products. Industrial applications of agar, the principle product of *Gracilaria* spp., are subject to three quality grades, namely sugar reactive agar, standard agar and food-grade agar, with their designation depending on sugar concentration, temperature, consistency and structure among other features (FAO, 2015). Agar is used as an ingredient in many food products, but is also commonly used in microbiological studies as a culture medium (e.g. culturing bacteria).

4.2.1.2 Fertiliser

The use of seaweed extracts as a fertiliser/growth stimulant for terrestrial plant production has been well studied over the last decade (e.g. Zhang *et al*. 2003; Smit, 2004; Estefanía *et al*. 2014; Anisimov *et al*. 2013; Briceño-Domínguez *et al*. 2014), particularly in India (e.g. Zodape, 2001; Dhargalkar and Pereira, 2005; Christobel, 2008; Jothinayagi and Anbazhagan, 2009; Sridhar and Rengasamy, 2010; Rajarajan *et al*. 2014). This includes the use of extracts from *Sargassum*, *Ulva*, *Macrocystis* and *Gracilaria* seaweed genera. In addition, seaweed production can be enhanced through the use of fertilisers, including the use of other seaweed extracts. A study by Robertson-Andersson *et al*. (2006) indicated that the hormonal content of the seaweed extract, particularly cytokinin, is thought to increase crop production as opposed to the provision of increased essential nutrients.

4.2.1.3 Other products

Another application of cultivated seaweeds is for medicinal purposes, cited for use in treatments for muscle-related problems (*Ascophyllum*), neutraceuticals (nutritional products) (*Undaria*), iodine deficiency (*Saccharina*), blood anticoagulants (*Chondrus*) and antibacterial/antifungal prescriptions (*Asparagopsis*, *Caulerpa*, *Dictyota*) (Lucas and Southgate, 2012). A small portion (less than 20%) of Japanese kelp produced in China is used for iodine and alginate extraction (FAO, 2014).

There is also interest and research into the potential to use macroalgae in animal feed and to provide biomass feedstock for energy production (see Section 4.2.2.3, Section 4.5 and Section 5).

4.2.2 Microalgae

4.2.2.1 Aquaculture feed

Microalgae are predominantly cultivated for use as a feed resource for other aquaculture industries, used either directly for larval nutrition (e.g. molluscs and penaeid shrimp) or indirectly to prey species (e.g. *Rotifera* spp.) fed to small fish larvae (Muller-Feuga, 2000; cited in Hemaiswarya *et al*. 2011). Microalgae species commonly used by other aquaculture industries include the genera *Chlorella*, *Tetraselmis*, *Isochrysis*, *Pavlova*, *Phaeodactylum*, *Chaetoceros*, *Nannochloropsis*, *Skeletonema* and *Thalassiosira* (Hemaiswarya *et al*. 2011). For example, areas of application for *Chlorella* spp. are as rotifer live prey and formulated feed ingredients. *Tetraselmis* spp., *Chaetoceros* spp. and *Thalassiosira* spp. are used to feed bivalve molluscs (larvae/postlarvae/broodstock) and crustacean larvae while *Nannochloropsis* spp. are used as feed for finfish larvae (Shields and Lupatsch, 2012).

4.2.2.2 Human consumption

Microalgae are known to contain high levels of the nutritionally important omega 3 polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Human health benefits attributed to omega 3 include a reduced risk of cardiac diseases such as arrhythmia, stroke and high blood pressure, whilst also offering beneficial effects to depression, rheumatoid arthritis and asthma (Simopoulos, 1991; Covington, 2004; Adarme-Vega *et al*. 2012). *Spirulina* spp. have been suggested to provide various health benefits, including clinical trials suggesting *Spirulina* can cure a variety of diseases and improve immune system function (reviewed by Habib *et al*. 2008).

4.2.2.3 Feedstock for biofuel (macro-and microalgae)

In addition to products suitable for human consumption, both cultivated macroalgae and microalgae also have the potential to provide an aquatic energy crop for the production of biofuel (gas, ethanol, methanol, butanol, oil, etc). This is due to the low concentration of cellulose, lack of lignin and easily biodegradable sugars in seaweeds. Feasibility studies have been conducted on numerous marine algal species, such as *Laminaria*, *Sargassum*, *Macrocystis*, *Gracilaria*, *Ulva* and, more recently, microalgal strains, suggesting potential for development of this industry (Vanegas and Bartlett, 2013). A review of the processes for producing energy from algal biomass and the current status of this technology is reviewed in Section 5.

4.3 Production Techniques and Systems

The general concept of algal growth is relatively straightforward, with cells only requiring light (or another form of energy, e.g. sugars), CO_2, water and several inorganic nutrients to grow. Algal production can be very high if conditions are optimal, whilst also providing the added environmental service of converting carbon dioxide to oxygen (e.g. Chung *et al*. 2011; Sahoo *et al*. 2012); however, it should also be noted that products subsequently burnt for energy generation will lead to the re-release of CO_2 into the atmosphere, making the process carbon neutral as opposed to a carbon sink. The techniques used to cultivate marine algae vary significantly, depending on the species grown, geographical location and target market.

4.3.1 Macroalgae

Seaweeds can be harvested from naturally grown resources, but the vast majority of seaweed products are produced from cultivated seaweed using a variety of techniques. Long-line systems are routinely used for the cultivation of seaweed (90% of global production; Lucas and Southgate, 2012), whereby seedlings are affixed (seeded) to culture ropes suspended in the water column and, thus, provided with substrate for growth. Horizontal and vertical long-line systems are used, depending on the conditions. Vertical culture methods are more suited to shallow water, but plants can become intertwined as a result of strong currents and storm conditions. The horizontal culture method can be used in slightly deeper water, making good use of space to enable currents to flow between the plants. However, shading can occur where plants at lower positions on the rope do not receive enough light and, subsequently, do not grow sufficiently. Rope farming techniques are used for *Eucheuma* spp., *Gracilaria* spp. and *Saccharina japonica* (FAO, 2015) as well as *Macrocystis* spp.

Bottom stocking is a relatively simple, but labour intensive, method of transferring viable specimens to areas where growth is desired. *Gracilaria* spp. are moved either still attached to rocks or by carefully removing the major branches. In order to ensure successful growth in the new location, thalli (new growth shoots) can be attached to new rocks using rubber bands or pushed into the sediment. However, planted materials can be dislodged during harvesting or periods of significant water movement and, due to the high labour intensity, the process is only economically viable when labour costs are low (FAO, 2015).

For *Eucheuma* spp., which can be grown using this method, the total grow-out period varies from 2-3 months after planting. Experimental evaluation of bottom stocking of *Gracilaria* spp. has suggested potential yields of about 21 tonnes (dry weight) per hectare for a 6 months growing period (FAO 2015). Selective breeding of seaweed species has enabled the enhancement of desirable characteristics in macroalgae mariculture, including increased frond length, higher iodine content and lower water content (Hughes *et al*. 2012).

Figure 4.1 Seaweed longlines in China (Source: © Trevor Telfer)

Net culturing is a large and important practice in algal mariculture, particularly in China. Nets are inoculated and rotated in culture medium containing Conchocelis stage (spore releasing) *Porphyra* spp. to promote settling prior to transfer to the growing area (Blouin *et al*. 2007). Cultures are also periodically exposed to air to kill epiphytes, with the view to improving production. The nets can be designed to float on the sea surface or affixed to the seabed (FAO, 2015).

4.3.2 Microalgae

Large-scale microalgae production can be facilitated through the use of open and closed systems. The two systems differ in terms of their exposure to the environment.

In open pond systems, algae are cultivated in suspension using ponds, tanks or raceways. Normally, gas and light requirements are met through reliance upon the natural environment, although examples exist where artificial light is applied. In raceway systems, gas exchange and water mixing and flow is enhanced using paddle wheels. The supply of CO_2 can be supplemented by aerators, although the open design might lead to increased environmental emissions (Hannon *et al*, 2010).

In closed systems (referred to as photobioreactors), algae are grown suspended in water within closed containment. The reactors can be designed so as to maximise exposure to natural light, or sometimes artificial light may be used. CO_2 must be applied, and as with open-pond systems, there must be a source of nutrients (e.g. N, P and C) adequate for maximum productivity. Photobioreactors include designs using horizontal flat-plates, tubular arrangements that are positioned horizontally, vertically or inclined, and vertically placed columns.

Lower costs and ease of handling are associated with open systems, but the inability to control environmental factors (particularly temperature and CO_2 levels) and contamination with other algal species which are not the target growth species can present problems to the final yield which may comprise a significant proportion of the total biomass. The use of algal strains capable of growing in conditions (e.g. high salinity) in which non-target species cannot survive, has been explored as one solution to this problem. Closed systems are generally more expensive to operate, but they are considered to have tighter control on growth conditions and, thus, a greater potential for production (Kröger and Müller-Langer, 2012). Production rates typically range between 10 and 20 $g/m^2/day$ for open systems and between 20 and 45 $g/m^2/day$ for closed systems (Christenson and Sims, 2011). However, production rates are only one side of the story; upscaling is another issue.

Closed bioreactor systems are typically used on much smaller scales compared to open ponds and, therefore, challenges persist in terms of volume produced with links to economic sustainability. Much smaller-scale production also occurs, particularly for *Spirulina* and *Chlorella* spp., with simple, low-cost techniques (culture pots) used to cultivate wild caught algae. Furthermore, in PBR systems, fouling by dirt or algae can occur upon the external and internal surfaces of the reactor, limiting the amount of light exposed to culture.

For both system types, light availability and intensity can be an issue. Many past and existing projects have been located at lower latitudes where solar irradiance is higher and more stable across seasons. Cultivation of algae located in higher latitudes, such as those of the UK, may not have sufficient irradiance for adequate productivity. It may be possible to select algae that are adapted to grow and produce desired physiological characteristics within the light regimes of higher latitudes. If this cannot be done, the application of artificial light may be necessary. In addition, water temperature may fluctuate due to seasonal and diurnal variation, potentially reducing algal productivity.

4.3.3 Integrated Multi-trophic Aquaculture

Integrated Multi-Trophic Aquaculture (IMTA) is an approach to aquatic cultivation whereby the waste products from one species provide an input (e.g. feed or fertiliser) for another species. This approach has potential for synergistic benefits in terms of the final yield of both species, with less wastage and improved environmental and economic outputs. This practice is briefly reviewed here as it relates to the potential integration of seaweed culture with the culture of higher trophic species such as molluscs, crustaceans and fish.

A variety of studies have been conducted involving seaweed species (Chopin *et al*. 2001; Chung *et al*. 2002; Neori *et al*. 2008), including combinations of *Porphyra* spp. and salmon (Chopin *et al*. 1999), kelp and abalone (Nobre *et al*. 2010) and the red seaweed *Gracilaria lemaneiformis* and the scallop *Chlamys farreri* (Mao *et al*. 2009). In particular, opportunities for growth in IMTA have been reported for Chile (Buschmann *et al*. 2008), Australia (Winberg *et al*. 2009) and China (Mao *et al*. 2009) in recent years. Offshore aquaculture installations may also consider the use of IMTA, despite increased technical and conceptual challenges (Troell *et al*. 2009).

Bio-remediation can also be applied through IMTA in which one species is used to reduce/remove waste products or pollutants from another cultivated species or system. As nutrient emissions from finfish and, on occasion shellfish aquaculture, have raised environmental concerns, bioremediation through the culture of seaweed has been a particular focus of research. For example, the red seaweed *Gracilaria lemaneiformis* has been shown to efficiently remove high nutrient levels in waters which arise due to fish feed (Zhou *et al*. 2006). Similarly, it has been shown that *Ulva lactuca* growth can be supported by the high nutrient content of manure, providing a bio-remedial application in addition to the potential production of bioenergy and protein-feed (Nielsen *et al*. 2012). Remediation of finfish emissions of solid bound nutrients through the concomitant culture of bivalves has also been investigated. Bio-remediation is observed around the world, particularly in China where monocultures of seaweed and bivalves; seaweed and fish; and seaweed, fish and bivalves, are cultivated in close proximity, although seaweed and bivalves are sometimes grown together using shared structures. The development of these systems has often been the coincidence of parallel wide-scale mariculture expansion, although it has occasionally been deliberate. The potential for the provision of beneficial ecosystem services, such as bioremediation, is discussed further in Section 7.

4.4 Historic Production Trends

The harvesting of natural seaweed crops is primarily carried out in China, Chile and Norway (66% of the global total), equating to approximately 1 million tonnes per year (Lewis *et al*. 2011). However, production volumes of cultivated seaweed are an order of magnitude greater, highlighting the importance of algal mariculture in the trade of macroalgae. It is estimated that the global seaweed industry is worth approximately US$7billion per year (Lewis *et al*. 2011).

Algal mariculture has increased on a global scale over the last two decades, with production of aquatic plants (including freshwater species) rising from 3.8 million tonnes in 1990 to 26.1 million tonnes in 2013 (FAO, 2014). Between 2000 and 2007, this corresponded to a 6.6% yearly increase in value (Lucas and Southgate, 2012). Production is dominated by a few countries in Asia, particularly East Asia (see Table 4.1). More than half of the total was attributed to China in both 2012 (54%; 12.8 million tonnes) and 2013 (52%; 13.5 million tonnes), although it should be noted that these statistics include macroalgae grown in marine or brackish waters and microalgae grown in seawater, brackish water or freshwater (FAO, 2014).

Indonesia has shown huge growth in algal mariculture over the last decade; it was the second largest producer in 2012 with a reported production of 6.5 million tonnes (FAO, 2014). In addition, the following countries have been involved in algal mariculture over the last two decades: Philippines, Republic of Korea, Democratic Republic of Korea, Viet Nam, Japan, Malaysia, Zanzibar (the United Republic of Tanzania), Solomon Islands, India, Timor-Leste, Madagascar, Fiji, Kiribati, Mozambique (ceased production due to non-technical reasons), Chile, Norway, Ireland, USA (markedly reduced production), Russia (minor contribution), France (minor contribution) and Spain (minor contribution) (FAO, 2014).

Table 4.1 Aquatic plant production trends

Country	Volume (Million Tonnes) Per Year						
	1990	1995	2000	2005	2010	2012	2013*
China	1.5	4.2	6.9	9.5	11.1	12.8	13.5
Indonesia	0.1	0.1	0.2	0.9	3.9	6.5	-
Philippines	0.3	0.6	0.7	1.3	1.8	1.8	-
Republic of Korea	0.4	0.6	0.4	0.6	0.9	1.0	-
Japan	0.6	0.6	0.5	0.5	0.4	0.4	-
Total	3.8	6.8	9.3	13.5	19.0	23.8	26.1

* Estimated based on provisional/reported information. Note, statistics include macroalgae grown in marine or brackish waters and microalgae grown in seawater, brackish water or freshwater.

(Source: FAO, 2014)

Global macroalgae production is dominated by two red seaweeds, *Kappaphycus alvarezii* and *Eucheuma* spp., with over 8 million tonnes (wet weight) produced in 2012, typically for the extraction of carrageenan. Japanese kelp (*Saccharina japonica*) was also produced in high volumes in 2012 (over 5 million tonnes wet weight), primarily used as a food sources but also for iodine and alginate extraction, followed by *Gracilaria* spp., wakame (*Undaria pinnatifida*), *Porphyra* spp. and other seaweeds/microalgae (FAO, 2014).

4.5 Future Trends and Drivers

According to Duarte *et al*. (2009), the global human population is predicted to be over 9 billion (upper estimate) by the year 2050, with the oceans and particularly mariculture expected to provide a key food resource.

With regard to global production trends, FAO (2014) states that the recent rapid development of seaweed cultivation in Indonesia described above is expected to continue in the future as the national policy is to embrace “blue growth”, and the country has vast areas suitable for culture (shallow sunlit sea) and possesses the relatively simple techniques required for reproduction and culture of *Kappaphycus alvarezii* and *Eucheuma* spp. Production is also expected to continue to grow in China, where the development of high-yield strains of major seaweed species and of warm-water tolerant strains of Japanese kelp (enabling production in the relatively warmer coastal provinces in the south of the country) have resulted in production doubling between 2000 and 2020. Seaweed farming has also long been promoted in China in areas of marine cage culture for bioextraction of nutrients in the seawater.

Currently seaweeds are eaten as whole foods by a relatively small percentage of the world population, mainly in Asia. Although there are limited data relating to future trends in macroalgae markets for direct human consumption, demand for seaweed for food is likely to continue to grow quite strongly. For example, imports to Australia grew at 27% per year in the 2000s and the market for sushi in the UK has been growing at over 20% per annum. Markets such as Europe and America also have substantial growth potential and the key to expanding such markets is good processing, packaging and marketing. However, in general, it is anticipated that macroalgae is likely to remain more of a "garnish" than a staple food item as even in top consuming countries such as Japan and Korea, seaweed only constitutes 10-15% of a typical diet, although the potential for farmed seaweed to play a potential role in the future of global food security as a staple food source has recently been reviewed by Forster and Radulovich (2015). These authors suggested that a combination of selective breeding to improve algal growth and composition traits could reduce the cost of production and increase the value of seaweed, which together with improved farm efficiencies, may result in affordable, nutritious seaweed products that might potentially become food staples.

With regard to nutrition, seaweeds can provide fibre, protein, minerals, vitamins and low fat carbohydrate content and many seaweed species are recognized as wholesome and healthy foods (e.g. Forster and Radulovich, 2015 and references therein). In Japan, the official Japanese Food Guide promotes seaweed as a nutritional foodstuff and in Asian countries research has demonstrated the health benefits derived from eating seaweeds (Cornish and Garbary, 2010 and references therein). However, their chemical composition can vary both between species and seasonally within species, hence if seaweeds are to be promoted as alternatives to land based plants to contribute to global food security, species specific research on their nutritional value and the bioavailability of specific seaweed based compounds (e.g. micronutrients) and to guarantee production of standardised products containing them will need to be undertaken (Forster and Radulovich, 2015; Cornish and Garbary, 2010 and references therein).

With respect to other drivers of future algal mariculture, in the UK, Lewis *et al*. (2011) evaluated the product options and markets for the processed outputs of commercial scale macroalgal production . The authors concluded that whilst a variety of chemicals which can be extracted from macroalgae are required within the human food and pharmaceutical industries, current market demand for such products were essentially met or there were limited commercial value in others.

Other more likely future drivers of algal mariculture relate to the potential for use of macro- and microalgae in animal feed or as feedstock for biofuel production.

Several studies have reviewed the potential for algal mariculture to contribute to formulated feed, for example for finfish cultivation, as an alternative way to address the likelihood of fishmeal and fish oil becoming a limiting factor in the expansion of fed aquaculture. For example, in a review paper, Olsen (2011) suggested that algal mariculture, along with other lower trophic level resources, could provide a vital feed product to sustain finfish aquaculture in the future. The production of finfish through aquaculture is much less efficient where long food chains are used to feed the stocks compared to direct feeding of end products using lower trophic level organisms (e.g. macroalgae). The production of fish protein is more ecologically expensive than production of plant protein due to the higher trophic level (Bostock *et al*. 2010). Olsen (2011) suggested that when carnivores are fed food from lower trophic levels (e.g. macroalgae, plants), as much as a 100 times greater yield of cultured carnivore fish species can be achieved through eliminating the energy lost through trophic transfers (i.e. from primary producers, to zooplankton, to pelagic forage fish and finally to cultured carnivore fish species) as occurs in the traditional fish meal-fish oil food chain. The author acknowledged some oversimplifications of the method, but stressed that the evidence still points to enormous benefits in employing such an approach. However, a study to specifically assess the potential for macro- and microalgae as commercially viable raw material for use in aquaculture feeds (beyond its established use as feed in the hatchery production of finfish, shellfish and invertebrate species) highlighted a number of nutritional and economic barriers to doing so (Slaski and Franklin, 2011). For example, the red and brown macroalgal species farmed in large quantities in Asia are currently unsuitable ingredients for finfish feeds due to their low protein content compared to other sources of plant material of similar cost and due to their low lipid content. Furthermore, the processing procedures applied to these species to extract hydrocolloids (the main commercial product from these species) are too harsh to produce any by-product of significant nutritional value. With regard to microalgae, the relatively low global production volumes and sale price rendered microalgae products too expensive for use in aquaculture feeds. Slaski and Franklin, (2011) concluded that, whilst algae contain the basic nutritional components for finfish species such as salmon, at that time, there were no opportunities to use algal materials as a component in aquaculture finfish diets. However, it was noted that should cost effective production systems for microalgae be developed in the future (e.g. by the biofuel sector), there was potential for cost effective production of certain microalgal species to supply high quality proteins and omega-3 highly unsaturated fatty acid (HUFA) rich lipids in formulated animal feed, including for finfish such as salmon. Similarly Shields and Lupatsch (2012) suggested the main drivers as to whether microalgal biomass will be adopted in the future as a bulk animal feedstuff or will remain only as a supplement (in terms of supplying protein and energy), will depend on biomass availability, composition and cost. They concluded that current costs are limiting the availability of algal products for use as feed, as also suggested by Hemaiswarya *et al*. (2011), but envisage that the increased interest in algal biofuels may significantly advance the field (also see Slade and Bauen, 2013). With regard to algal composition, Shields and Lupatsch (2012) suggest that even if sufficient quantities of algal biomass become available at a suitable price in the future, animal feed manufacturers will still need to take account of the potentially large variations in composition (proteins, lipids, fatty acids, minerals etc) and digestibility between different algal strains. Furthermore, to improve their digestibility, some types of algal biomass may require additional processing steps beyond those applied to conventional feedstock, which will also affect cost. These authors suggest that subject to the above constraints, microalgae is likely to provide the most suitable bulk feedstock for use in finfish diets, whereas macroalgae may be more suitable for use with terrestrial livestock and lower trophic level aquaculture species.

The potential for cultivated macro- and microalgal biomass to be used as feedstock for the production of biofuels is reviewed in detail in the Section 5.

4.6 Summary

A variety of products and commodities are derived from farmed algae (macroalgae and microalgae). These products include food (for direct human consumption or thickening agents such as carrageenan), fertiliser and for inclusion in animal feed and medicinal related products, with the majority of production being for human consumption (directly or indirectly).

The global seaweed industry is estimated to be worth approximately US$7 billion per year and production has been increasing on a global scale over the last two decades reaching 26mt in 2013, (note, this tonnage includes macroalgae grown in marine or brackish waters and microalgae grown in seawater, brackish water or freshwater). Production is dominated by a few countries in Asia with over half of production in 2013 being attributed to China and a rapid increase in production occurring in Indonesia.

Although demand for cultivated seaweed for direct human consumption is likely to continue to increase, including for markets outside of Asia, it is not currently anticipated that it will become a food staple, although data related to such trends are limited. A recent review suggested that a combination of selective breeding to improve algal growth and composition traits could reduce the cost of production and increase the value of seaweed, which together with improved farm efficiencies, could result in affordable, nutritious seaweed products that could potentially become food staples. However, further species-specific research into the nutritional value and bioavailability of beneficial chemical compounds is required.

There is also a high level of interest in the use of cultivated algae for use as feedstock in biofuel production (described in further detail in Section 5). Other uses for farmed seaweed that are areas of interest and research include the viability of its inclusion in aquaculture and animal feed, as a replacement for fishmeal and fish oil (e.g. Olsen, 2011). To date, technical developments and commercial applications have focussed on algae as a micro-feed (rather than a source of gross nutrients). The potential to use microalgal biomass as a bulk feedstuff for formulated feeds is currently limited by biomass availability, composition and cost. Even if sufficient quantities become available at a suitable price in the future, the potentially large variations in composition (proteins, lipids, fatty acids, minerals etc) and digestibility between different algal strains will need to be addressed.

Finally there is increasing interest in farming seaweed in IMTAs to reduce the environmental impacts of other farming methods (e.g. finfish farming) through bioremediation. The development of IMTA systems has often been the coincidence of parallel wide-scale mariculture expansion, although it has occasionally been deliberate. The potential for the provision of beneficial ecosystem services, such as bioremediation, through algal mariculture is discussed further in Section 7.

5. Review of Processes for Producing Energy from Algal Biomass and Current Constraints to Economically Viable Energy Production Using These Methods

5.1 Introduction

Fossil fuels account for approximately 84.5 % of the UKs energy supply (DECC, 2015). The use of non-renewable fossil energy sources is considered unsustainable due to emissions, such as carbon dioxide (CO_2) and nitrous oxides (NO_X) and their impact upon the environment and because of the temporal limitations of its supply. This has prompted efforts to develop alternative, renewable forms of fuel production that lessen the impact associated with the use of traditional non-renewables. The 2008 Climate Change Act sets a legally binding target for a reduction of greenhouse gas emissions in the UK by at least 80% below 1990 levels, by 2050 (DECC, 2011). In accordance with the European Union Renewable Energy Directive (Directive 2009/28/EC), 15% of energy generation in the UK must come from renewable energy resources by 2020 (DECC, 2012). The use of energy crop biomass is considered important for achieving these targets DECC, 2011; 2012). Development of these biofuels has been categorised into three main categories: first, second and third generation biofuels. First generation biofuels are those derived from agriculture crops, whereas second generation biofuels are derived from lignocelluosic crops and biomass co-products, including those classified as wastes. The ability to replace conventional fossil fuels using first and second generation biofuel whilst improving sustainability and lessening environmental impacts, has been questioned due to a variety of reasons. Similar resources, such as fertilizers, pesticides and water for irrigation are used in the production of crops for biofuels as in the cultivation for conventional agriculture. The production and use of these are associated with a variety of environmental issues, including greenhouse gas (GHG) emissions, emissions to land and water compartments, and socio-economic impacts on food security through the diversion of crop biomass from food value chains. Consequently, there has been a focus on the development of third generation biofuels, usually derived from algae, and intended to avoid these problems. Their development has been encouraged in various policies and has resulted in a range of funded projects. Among those investigated, species of both macroalgae and microalgae from marine environments have been identified as potential feedstocks[13] for biofuel production.

The general purpose of this review is to:

- Describe the types of biofuel that can be produced from marine algae;
- Detail various energy production methods that have been developed/investigated;
- Compare efficiency of process with energy production from other sources (focussed on terrestrially derived biofuel); and
- Identify the potential production bottlenecks and barriers to development of algae for meeting renewable energy needs.

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13 Within the context of this report, feedstock refers to biomass and contents thereof, intended for conversion to biofuel.

A general review of the different production techniques for the culture of macro- and microalgae, including for the potential use as feedstock for bioenergy production has been presented in Section 4. This section (5) summarises the technologies used to extract biofuel from algal biomass (Section 5.2) and the current technological and/or economic constraints to the viability of these processes (Section 5.3).

5.2 Technologies for the Conversion of Biomass to Fuel

5.2.1 Anaerobic Digestion

Biogas can be produced through anaerobic digestion, the decomposition of biomass by bacterial action, in an environment absent in oxygen. Typically, this gas is composed mainly of methane (CH_4) and carbon dioxide (CO_2), although small amounts of other gases may also be formed, such as hydrogen (H_2), hydrogen sulphide (H_2S) and nitrogen (N). Biogas can be used to produce electricity and heat in combined heat power (CHP) processes. Biogas can also be used to supplement the supplies of natural gas, and compressed to be used as a transport fuel. To understand the process of anaerobic digestion, four main stages can be defined. These are *hydrolysis*, *acidogenesis*, *acetogenesis* and *methanogenesis*.

- Hydrolysis is the degradation of organic complexes into simpler structures. Polysaccharides are depolymerised by enzymes to produce monosaccharides and amino acids, and lipids are degraded to long-chain fatty acids.
- Products of hydrolysis are then fermented by acidogenic organisms, producing short-chain fatty acids[14] (e.g. propionic and butyric acids), alcohols, hydrogen (H_2) and carbon dioxide (CO_2).
- Further degradation of the products of acidogenesis results in the formation of acetic acid ($C_2H_4O_2$), H_2 and CO_2.
- Finally, products of the previous stages, such as H_2, CO_2 and acetate are converted to methane by archean organisms[15]. Anaerobic digestion of biomass can be performed using batch or continuously fed processes. It can take place as a single-step process, in which the stages of anaerobic digestion occur within the same reactor, and as a two step-process, whereby the hydrolytic, acidogenic and acetogenic stages take place in physical separation from methanogenesis.

Anaerobic digestion technology is well developed and has been used to produce biogas from a variety of feedstocks including sewage sludge, animal manure and lignocellulosic biomass. Biogas production from algae is not a new concept, with research focusing on microalgae beginning in the 1950s (Golueke *et al*., 1957) and macroalgae in the 1970s. However, biofuel production from algae has not developed to become a commercial enterprise, as it is not yet been demonstrated to be economically viable. Where demonstrated at pilot level it has been heavily subsidised, so does not represent the true costs.

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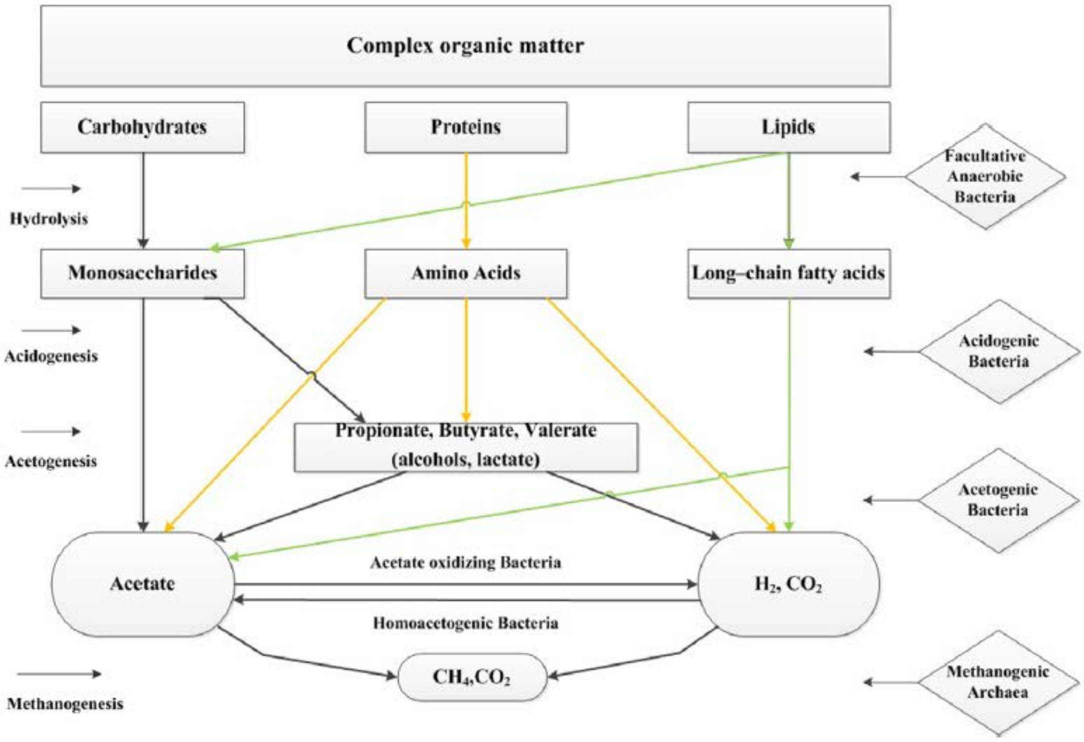
14 Commonly referred to as 'Volatile fatty acids.'

15 Bacteria like organisms which are characterised as "extremophiles" living in harsh environments.



(Reproduced from: Christy *et al*., 2014)

Figure 5.1 Anaerobic digestion of organic material, producing CH_4 and CO_2

5.2.1.1 Macroalgae as a feedstock biomass for anaerobic digestion

Original studies identified some macroalgae species as a potential feedstock for gasification (Bird and Rhyther., 1985; Bird *et al*., 1981; Fannin *et al*., 1983): *Macrocystis pyrifera* , *Gracilaria tikvahiae* and *Hypnea* sp. , and *Ulva sp*. Further work has mostly focused upon species of brown algae, such as *M.pyrifera*, *Laminaria hyperborea*, and *Ascophyllum nodosum* (Chynoweth *et al* 1987; Moen 1997), and green species such as *Ulva lactuca* (e.g. Bruhn *et al*., 2011). In the brown seaweeds, laminarin and mannitol are the structural polymers that are relatively easy to digest in comparison to the cellulose, hemicellulose and lignic complexes found in terrestrial biomass (Chynoweth *et al*., 1987., Moen, 1997), with the inhibitory effects of polyphenols and salt reduced through the addition of formaldehyde (Moen, 1997). Marine bacteria have also been investigated for the degradation of macroalgae feedstock (see Morand *et al*., 1991; Kelly and Dworjanyn., 2008). High ash, mineral, metals and volatile fatty acid content can also have inhibitory effects on the digestion process (Ross *et al*, 2008) though these can be reduced by progressively acclimatising the reactor through their gradual introduction (Morand *et al*., 1991). Other compositional factors can influence process functioning, such as levels of carbon (C), N and phosphorus (P), and total organic composition (TOC) (Chynoweth *et al*., 1987; Adams *et al*., 2011). Concentration and application rate of feedstock and mixing with digestive bacteria are also important variables which influence system function. The various microorganisms responsible for anaerobic digestion can differ in physiological requirements and sensitivity to environmental conditions. Consequently, there must be a suitable match between the microorganisms used and the processes employed.

Pre-treatments have been investigated for their potential to improve biogas/methane yield or lead to other efficiency improvements. They often influence the functioning of an early stage in the conversion process, thus affecting its outputs. The methods investigated include thermo and thermo-chemical treatments, mechanical and natural treatments, which aid in the degradation of the feed-stock. A simple mechanical treatment might increase the surface area of the feedstock by chopping the macroalgae into smaller pieces (author, personal observation), or by grinding it into a powder (Choi *et al*, 2014). Early on in the development of macroalgae biofuels, the feasibility of natural hydrolysis of *Ulva* was demonstrated, whereby storage at 4^oC for 1 month increased methane yield by 45% (Carpentier, 1986). More recently, the study of pre-treatments for biogas production have focused on thermo treatments, and the enhancement of these through additional/combined chemical treatments. Jung *et al* (2011a) exposed *Saccharina japonica* to thermo-treatments as part a fermentative hydrogen (H_2) production process. The thermo treatment enhanced the suitability of the hydrolysis process by decreasing the contents of cellulose and hemicellulose, and increasing the concentrations of glucose and xylose. H_2 production was highest when a thermo pre-treatment of 170^oC was used. However, above this temperature improvements seen during hydrolysis decreased due to the increased production of furfural, which is inhibitive to the production of gas through microbial action. Jung *et al* (2011b) applied heat and hydrochloric acid (HCl) as an alternative thermo-chemical pre-treatment for the same process. Optimisation of the H_2 yield was achieved by altering heat temperature, HCl concentration and reactor times. HCl was found to be the main influencing variable, and pre-treatment resulted in improved efficiency by increasing the rate of hydrolysis and reducing the concentration of a major by/co-product, hydroxymethylfurfural. Kwon *et al* (2012) enhanced pyrolysis during thermo-pre-treatment of the same species, by adding CO_2. In comparison to the addition of N_2, the addition of CO2 resulted in significant increase in the mass conversion to CO, and small increases in the production of methane and ethylene (C_2H_4), as end products of gasification. This benefit was supplemented by a reduction in tar (hydrocarbon) production which resulted from the enhanced efficiency of thermo-treatment through the addition of CO_2. Steam explosion is a thermo-treatment which has been successfully applied in laboratory experiments to improve biogas yields (Vivekanand *et al*., 2012). Whereas mannitol and laminarin are digested relatively easy, steam explosion may increase the digestibility of alginate, and increases of up to 20 % methane yield from *S. latissima* have been achieved (Vivekanand *et al*., 2012).

5.2.1.2 Microalgae as a feedstock biomass for anaerobic digestion

Many studies have been published regarding the anaerobic digestion of microalgae. A number of studies have focused on the use of marine microalgae, such as *Phaeodactylum tricornutum* (Zamalloa *et al*., 2012), *Dunaliella tertiolecta* (Lakaniemi *et al*., 2011) *Nannochloropsis salina* (Schwede *et al* 2013a; Schwede *et al* 2013b) and *Tetraselmis spp*. (Ward *et al*., 2015; Ward & Lewis, 2015).

In microalgae, structural complexes in the cells walls, such as cellulose and hemicellulose, can be resistant to biodegradation, reducing biogas production rate and yield. As a consequence, pre-treatment steps may be necessary to rupture algal cells and assist hydrolysis. A variety of thermal, mechanical, chemical and enzymatic treatments have been investigated (Passos *et al*, 2014). The need for pre-treatment and the effectiveness of the different options appears to vary across species as a function of their compositional characteristics. The molecular structure of

Nannochloropsis spp. limits anaerobic digestion and has shown resistance to chemical pre-treatments (Schwede *et al*., 2013a; Bohutskyi *et al*., 2014). In a comparative study, the anaerobic digestion of microalgae with cell walls constructed from glycoprotein (such as *Tetraselmis spp*.) resulted in higher yields of CH_4 than those obtained from *Nannochloropsis spp*. (Bohutskyi *et al*. 2014). For some species, pre-treatments may not be necessary if the anaerobic microbial community can effectively digest the algae. The anaerobic digestion of non-pre-treated cells[16] of *Tetraselmis* spp. resulted in similar yields (252 ml/g VS) of biogas than that obtained from pre-treated cells (248 ml/g VS) (Ward and Lewis, 2015). It is important to consider the energy cost incurred through the employment of various pre-treatment methods in relative proportion to the resulting increases (or possible lack, thereof) in biogas production. In some cases, the energy required to disrupt the algal cells may actually exceed the energy that they contain (e.g. Lee *et al*., 2013).

In relation to biochemical composition of microalgae, there may be other challenges to the efficacy of anaerobic digestion. The hydrolysis of proteins from within algal cells can lead to levels of ammonia-nitrogen that are inhibitory to acetogenic or methanogenic bacteria (Sialve *et al*., 2009). Under conditions of semi-continuous anaerobic digestion of *Nannochloropsis salina*, the levels of ammonium increased when the availability of organic substrate was enhanced through thermal pre-treatment of the feedstock (Schwede *et al*., 2013a). The presence of ammonium increased to a level considered inhibitory, coinciding with a decrease in biogas production and methane content. Volatile fatty acids and long-chain fatty acids are released through the degradation of lipids during hydrolytic and acetogenic stages. The removal of lipids for biodiesel has been suggested as a way to pre-treat microalgae by rupturing their cells and lowering the lipid content to prevent possible inhibition (Ward *et al*., 2014; Ward & Lewis, 2015).

A particular consideration when using marine-microalgae is the potential for inhibition of microbial activity due to salinity (Sialve *et al*., 2009; Ward *et al*., 2014). Occurrence of this problem might be avoided if saline tolerant microorganisms can be used and there is the possibility that some anaerobic communities may be able to adapt.

5.2.2 Ethanol Fermentation

Ethanol as a fuel can be used in transport vehicles, electricity generation etc. Ethanol and gasoline blends are available, such as 'E5' (5% ethanol, 95% gasoline) and 'E25' (25% ethanol, 75% gasoline), although some engines can use non-blended ethanol (E100). During alcoholic fermentation microbial fermentation of mono- and disaccharides (simple sugars[17]), such as glucose ($C_6H_{12}O_6$), produces ethanol (C_2H_5OH), CO_2, and often heat. Commercial ethanol-fuel production has been based upon the fermentation of sugars in sugarcane and corn. However, these crops compete with the production of food-crops and their cultivation is associated with environmental impacts. Biomass containing polysaccharides, such as starch

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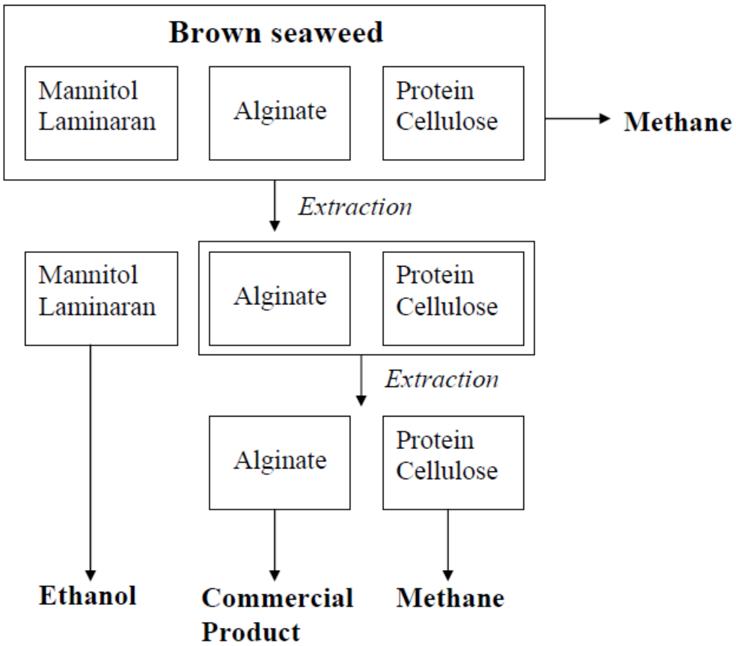
16 The samples used for the study where subjected to freezing during transportation and storage. However, the authors consider that freezing alone could not account for the yield obtained from 'non-pre-treated' algae.

17 Carbohydrates are saccharides organised into groups of different complexity: monosaccharides; disaccharides; oligosaccharides; and polysaccharides.

and cellulose ($C_6H_{10}O_5$)[18], can also be used. Terrestrial cellulosic biomass has been used as a feedstock, but structural lignin is difficult to degrade and can inhibit accessibility to cellulose whereas aquatic algae generally do not contain lignin.

5.2.2.1 Ethanol from macroalgae

Macroalgae in the class Phaeophyceae (i.e. brown algae) contain sugars in the form of alginate, mannitol and glucan (e.g. laminarin). Horn *et al* (2000b) originally described two methods for the conversion of laminarin and mannitol in *Laminaria hyperborea* to ethanol: a two-step process involving two different microorganisms (one for mannitol conversion and the other for laminarin conversion); and a single-step process using one microorganism species, which is capable of utilising both mannitol and laminarin. However, optimal ethanol yields imply maximal sugar conversion, including mannitol and glucan in addition to alginate. To this end, research has focused on developing microbial fermentation strategies of these different sugar sources. Wargarcki *et al* (2012) describe a process by which fermentation of mannitol, glucose and alginate in *Laminaria japonica* was achieved using genetically engineered *E.coli*, producing ethanol above 80% of the maximum theoretical yield. As with biogas, salt contents in seaweed biomass can be inhibitive to ethanol production (Adams *et al*., 2009). Kelly and Dwordjanyn (2008) discuss the use of marine bacteria including species found upon macroalgae that might successfully convert seaweed to ethanol without the inhibition exhibited by terrestrial microorganisms.



(Reproduced from: Horn, 2000)

Figure 5.2 Proposed routes to produce methane and ethanol from the co-products of alginate production

[18] Although both starch and cellulose are described molecularly as $C_6H_{10}O_5$, cellulose is differentiated by its stronger structure, owing to the arrangement of its constituent glucose in beta-linkages.

In the production of bioethanol, pre-treatments have been used to improve the availability of sugar through structural breakdown when producing ethanol from kelp. For example, Horn *et al* (2000a; 2000b) first milled the seaweed then applied a combined thermo-chemical pre-treatment of using water diluted to pH 2 using HCl and a temperature of 65ºC for 1 hour to release the laminarin not soluble in cold water, and to break down cellular structures. However, Adams *et al* (2009) found that variations of this treatment where counterproductive when applied to *S.latissima*.

5.2.2.2 Ethanol from microalgae

Much of the work on microalgal digestion for ethanol has focused on freshwater or terrestrial species, notably *Chlamydomonas reinhardtii* and *Chlorella vulgaris*. Although the saccharide contents of microalgae differ among species, many contain starch which is structurally similar to those found in terrestrial crops used for ethanol production. Cellulose is also found in some species. Carbohydrate content depends upon both the environmental conditions and on the specific alga grown. Manipulation of the culture environment has been investigated as a way of increasing the carbohydrate contents of algal cells whilst maintaining sufficient levels of biomass production[19]. These include limiting the culture nutrient supply, changing irradiance and temperature, and using salt-induced osmotic stress (Markou *et al*. 2012). Pre-treatments can be used to disrupt microalgae cells so to increase the accessibility of carbohydrates to hydrolytic or fermentative organisms. As applied to microalgae, these treatments have been mainly investigated using freshwater species. These methods include the use of thermal - chemical treatments, using such acids as hydrochloric acid (HCl) and sulphuric acid (H_2SO_4), or the alkaline sodium hydroxide (NaOH) (e.g. Harun & Danquah, 2011a; Harun *et al*. 2011; Hernández *et al*. 2015). Heat treatments have been used by autoclaving the algal biomass or exposing it to microwaves (e.g. Hernández *et al*. 2015). Mechanical treatments can rupture cells, such as the use of sonication - the application of sound waves (e.g. Harun & Danquah, 2011b). The use of enzymatic hydrolysis has been investigated as a method to optimise saccharification, following such cell disrupting pre-treatments. Amylolytic and cellulolytic enzymes have been used to hydrolyse starch and cellulose into fermentable monosaccharides (e.g. Harun & Danquah. 2011b; Kim *et al*. 2014; Hernández *et al*. 2015).

Ethanol fermentation of the sugars from microalgae has also been largely restricted to freshwater species, with only a small number of examples of ethanol being produced from marine-microalgae, including *Dunaliella* spp. (Nakas *et al*. 1983; Shirai *et al*. 1998).The fermentative organisms used have typically been of terrestrial origin, including strains of the frequently used yeast *Saccharomyces cerevisiae*, and strains of the bacterium *Escherichia coli*. It is important to consider that marine microalgae biomass may require desalinisation if hydrolytic enzymes or fermentative organisms cannot function well in the presence of salt (Matsumoto *et al*. 2003).

Ethanol production can occur within the cells of some microalgae when under dark, anaerobic conditions. The Embden-Meyerhof-Parnas pathway has been presented as the metabolic

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19 Manipulations of culture environmental variables, whilst sometimes leading to increased carbohydrate content, may also reduce biomass productivity. Increasing the yield of carbohydrate implies increases in cellular content as well as maintaining, or increasing the level of biomass production.

pathway in which intracellular starch is degraded to pyruvate, which is then converted to acetaldehyde by pyruvate decarboxylase and subsequently reduced to ethanol (Ueno *et al*. 1998). Dark fermentation (Hirano *et al*. 1997) has been demonstrated in a number of marine-microalgae, such as *Chlorococcum littorale* (Ueno *et al*. 1998). Using microalgae to produce ethanol in this way has been proposed as a simple ethanol production route that avoids some of the costly steps involved with conventional fermentation. However, the low yields obtained through dark fermentation imply the need for significant improvements.

5.2.3 Biodiesel

Biodiesel is a fuel characterised by a mixture of long-chain fatty acid mono-alkyl esters. It can be produced through transesterification of triglyceride lipids from plant oils or animal fats. The process consists of a sequence of reversible reactions through which triglycerides are converted to diglycerides, diglycerides into monoglyceride and monoglyceride into glycerol, with alkyl esters being produced from each conversion. Biodiesel can be blended with petroleum diesel and used in many diesel engines often requiring little or no modification. Pure biodiesel can also be used, but for this, and blends containing high percentages of biodiesel, some engine specificity may be necessary. The characteristics of fatty acid methyl ester (FAME) biodiesel that must be met for its distribution in European markets, have been standardised, for vehicles fuels by EN 14214, and for heating fuel by EN 14213. A variety of oils may be used, such as those extracted from designated fuel crops, including soyabean and rape seed (the residual cake is used for other purposes). Biodiesel production through the transesterification of lipids from algae biomass as also been investigated.

5.2.3.1 Biodiesel from macroalgae

Some investigations have focused on the thermal / thermochemical pyrolysis methods to produce viable bio-oil fuels from macroalgae (Ross *et al*., 2008; Adams *et al* 2011; Wang *et al* 2013). Bio-oil production might be possible using the co/by-products of other macroalgae based value chains. Ferrera-Lorenzo *et al.* (2014) used macroalgae meal, presented as a co-product of the agar-agar industry, as a feedstock for conventional and microwave heated pyrolysis.

The research regarding diesel from macroalgae is limited in quantity compared to the production of biogas and bioethanol, but some basic advantages and drawbacks can be identified. The products of thermochemical pyrolysis include oils, gas, aqueous solutions and chars, which may also be used as a renewable input to additional value chains. The quality and quantity of these products can be influenced by varying parameters, such as heat, in order to optimise a target-product (e.g. Wang *et al*., 2013). Pyrolysis of macroalgae is initiated at lower temperatures than that of terrestrial biomass with high cellulose content or high lignin. The characteristics of the main carbohydrates, and absence of lignin within the macroalgal material results in some characteristics of the oil which might be suitable for the production of transport fuel (Ross *et al* 2008).

However, levels of metals and potassium and sodium rich ash within the feedstock can be higher than levels at which problems such as slag production and system component fouling become noticeable (Ross *et al* 2008; Adams *et al*. 2011). This would be a severe drawback to industrial scale anhydrous thermochemical conversion. Additionally, Wang *et al* (2013) found the presence of aromatic hydrocarbons that can pose a hazard to human health in pyrolytic oil derived from *Enteromorpha clathrata* (a green macroalga) and *Sargassum natans* (brown) oil. High protein levels within the feedstock material lead to oil nitrogen contents being higher than what would usually be found in those from terrestrial biomass. The presence of nitrogen would result in nitrous oxide emissions upon combustion, suggesting that denitrogenation / nitrogen management techniques would need to be introduced.

Hydrothermal liquefaction of macroalgae is a potential means to produce bio-crude whilst avoiding the limitations of anhydrous thermochemical treatment as described above (Zhou *et al*. 2010 Anastasakis and Ross, 2011). In hydrothermal liquefaction, wet biomass can be decomposed under increased temperature and pressure to produce bio-crude, gas, char and water. Bio-crude produced from macroalgae in this way may have properties similar to those of bitumen from petroleum, although higher nitrogen and oxygen contents suggest that deoxygenation and denitrogenation may be needed (Anaskasakis and Ross, 2011).

5.2.3.2 Biodiesel from microalgae

The production of biodiesel from the lipids of microalgae was a focus of The 'Aquatic Species Program', set up in 1978 after the 1973 oil crisis, and funded by the United States Department of Energy. A summary report, released in 1998 concluded that a number of microalgal species may be suitable for use in the production of biodiesel, although the cost of this production was inhibitively expensive relative to petroleum diesel at that time (Sheehan *et al*., 1998). Since the publication of these findings, there has been no commercial production of biodiesel derived from microalgae. However, research into the use of microalgae for this purpose is ongoing and pilot projects have been initiated. High lipid content is a desirable trait as it influences oil yield and improves the efficiency of its extraction. Total lipid content of microalgal cells varies with species and the conditions in which they are cultivated. Reported values range from approximately 1 to 85% of algal dry weight, although this range may be reduced when accounting for differences between the techniques used to arrive at these values (Williams and Laurens, 2010). Frequently, higher values for cellular total lipid content have been achieved through the application of stress within the algal cultivation systems (Griffiths & Harrison, 2009). During cultivation, limiting the rate at which nitrogen is supplied, or applying a phase nitrogen deprivation following a phase of nitrogen replete conditions, have led to increased content levels of lipids of some species (references). However, it has often been observed that increases in lipid content achieved through methods of nitrogen deficiency have not translated into increased lipid productivity[20] (Sheehan *et al*., 1998). This situation can arise when reductions in the availability of nitrogen decreases biomass productivity to a level that offsets the increase in cellular lipid content. In general, lipid productivity may have a stronger correlation with biomass production than with lipid content (Griffiths & Harrison, 2009). In nutrient-replete laboratory cultures, among 30 strains assessed, the marine alga *Porphyridium cruentum* displayed the highest biomass productivity, but not the highest lipid productivity, as percentage lipid content was low (Rodolfi *et al*., 2009). Although it may not always be possible, it would seem beneficial that high levels of lipid content and high biomass productivity occur

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[20] Definition of lipid productivity.

together. Increases in both lipid productivity and lipid content were exhibited by a strain of *Nannochloropsis sp*. when cultivated outdoors using methods of nitrogen deprivation (Rodolfi *et al*., 2009). Among microalgae, the marine *Tetraselmis suecica* is a species identified as having a higher lipid production, owing to its high biomass productivity, although its percentage lipid content (~17% dry weight (dw) in nutrient replete conditions) is relatively low (Rodolfi *et al*., 2009; Griffiths & Harrison, 2009). Other marine species, *Nannochlopsis* spp., *Pavlova lutheri* and *Phaeodactylum tricornutum* have shown good growth rates and percentage lipid contents (Griffiths & Harrison, 2009).

As well as screening algae for high lipid productivity, lipid composition must also be considered, as it influences biodiesel properties (Knothe, 2011). It is important that the algal lipids consist of a high proportion of triglycerides, the lipid type most suitable for conversion to biodiesel. Some investigations have found that increases in cellular proportional lipid content gained through manipulation of the cultivation environment have largely consisted of triglycerides (Reitan *et al*., 1994). In addition to triglycerides, microalgae contain other lipids including glycolipids and phospholipids. These polar lipids have a lower energy content (Williams and Laurens, 2010) and can contain sulphur (e.g. the glycolipid sulfoquinovosyldiaacylglycerol) and phosphorous (phospholipids). As such they are unlikely to be suitable for conversion to biodiesel conforming to EU standards. Microalgae contain varying quantities of saturated, monounsaturated and polyunsaturated fatty acids and their presence has an important influence upon biodiesel quality. Increased levels of 'unsaturation' increases the susceptibility of biodiesel to oxidative degeneration although, high levels of saturation are associated with improved diesel performance at cold temperature. Comparatively, biodiesel produced from saturated fatty acids has better oxidative stability, but lower cold-temperature performance. If problematic, high levels of unsaturation might be reduced using hydrogenation technology (Chisti, 2007).

Following cultivation of an algae species with sufficiently high levels of lipid with a suitable profile, the algal oils must be extracted. Before extraction, a pre-treatment may be applied to facilitate subsequent lipid extraction. The algal biomass may be dried to eliminate water to improve lipid extraction and milled to a powder. Alternatively lipids can be extracted through cell disruption using mechanical methods, such as bead milling (Cheng *et al*., 2011), microwave heating (Ali & Watson, 2015), sonication (Cho *et al*., 2012; Pereira Neto *et al*., 2013) and high-pressure homogenisation (Cho *et al*., 2012). Chemical methods, such as the application of sodium nitrite (Bai *et al*., 2014), and chemical-thermal treatments (Lee *et al*., 2014) have also been investigated. At laboratory scales, lipids have been extracted through the addition of solvents such as hexane and chloroform (Wahlen *et al*., 2011; Teo & Idris, 2014). Solid cellular debris is then separated from the resulting solvent-lipid complex, and the solvent and any water that may be present are removed from the lipid. These process steps have been carried out using a variety of methods (e.g. Teo & Idris, 2014). Preferably, the methods employed should maximize the extraction of those lipids suitable for biodiesel production, whilst minimizing the extraction of unsuitable lipid fractions and non-lipid components. Supercritical fluid[21] extraction has been used as an alternative to organic solvent extraction methods (Supercritical fluid has the effusive properties of gas and the solvation characteristic of a liquid).

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21 A supercritical fluid is commonly defined as being a state without distinct boundaries between liquid and gas phases, and is formed by increasing temperature and pressure of the substance beyond that of its critical point.

Supercritical CO_2 (SC- CO_2) has been used as a solvent for the extraction of lipids from marine microalgae for biofuel production and other industrial applications (Crampon *et al*., 2011; Bjornsson *et al*., 2012). In general, the CO_2 is converted to its supercritical state and is applied to the algal feedstock within an extraction vessel. The lipids are extracted from the feedstock and an SC-CO_2-lipid complex is formed. This complex then enters another vessel and is decompressed so that the SC-CO_2 becomes vaporised and separated from the extracted lipids. Lipids extracted using supercritical fluid might, in some cases, be more suitable for conversion to biodiesel (Bjornsson *et al*., 2012). Unless performed in combination with a co-solvent, extraction of lipids using SC-CO_2 avoids the mixing of the residual algal biomass (and the extracted lipids) with a toxic substrate that must be removed before further processing. Extraction using SC-CO_2 may require a shorter reaction time than when using organic-solvents, although energetic and economic costs of the process may still present a potential bottleneck.

5.3 Current Constraints to Energy Production From Cultivated Algal Biomass

The successful production and commercialisation of algae based biofuels are faced by various bottlenecks, which are summarised below.

The concept of using algae biomass for a net production of energy needs to be demonstrated. Positive energy returns on energy invested (EROI)[22] are critical for the successful development of algae based biofuels, and such positive values must be as high as possible. For produced goods, the cumulative energy demand can be calculated. This is the cumulative energy that is used for the production of a good, and includes energy used in the production and supply of infrastructure / capital goods, and energy demand for operation activities and the associated production and supply of goods that this operation requires. The energy converted from algal feedstocks must be higher than the cumulative energy used in its production (positive EROI). Every technological process involved in the production chain has an energetic cost that will contribute to the cumulative energy demand. Therefore, it is important that the technologies chosen result in an increase in energy yield (i.e. an increase in energy available from the resulting biofuel product) that surpasses the alternative options. In some cases, analysis of some algal biofuel production systems have shown negative energy yields (Lardon *et al*., 2009; Sander & Murthy, 2010; Passell *et al*., 2013), highlighting the development of process methods with decreased energy requirements as being crucial for feasible production. An assessment of the efficiency of energy production from macro- and microalgae using LCA has been undertaken in Section 6.6.

Biofuels made from algae biomass must be marketable and profitable and economic success is yet to be demonstrated. The markets in which algal biofuels may operate may be variable. On global markets, the price of algal biofuels must compete with the price of conventional fossil fuels. Bio-oil products, such as biodiesel will have to compete with those alternatives from conventional crude oil. The price of fossil fuel oil is largely impacted by geopolitics, which is reflected in the fluctuations seen over past decades. Events leading to an increase in supply on world markets have led to a downturn in the price of crude oil (at time of writing). However,

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22 A positive energy return on energy invested gives a net production of energy; it is not to be confused with net energy return ratios where higher values have negative energy production.

in the event that world supply of fossil oil becomes scarce, oil prices could rise considerably and, thus algal biodiesel may be seen to be increasingly competitive. To some extent, it is possible that higher prices of algal oil could be offset if it is seen to have an improved environmental profile when compared to conventional oil. The products of anaerobic digestion of algal biomass would have to compete with the extraction of fossil gas, as well as the anaerobic digestion of low cost feedstocks. The use of algae for ethanol production will also need to compete with other candidate feedstocks. As a consequence, it is important the costs of production can be minimised. The economic success of algal biofuel production may require supporting policies such as tax credits and subsidies. Amanor-Boadu *et al*., (2014) reported that hypothetical carbon neutral production of biodiesel and ethanol from microalgae grown in open-raceways was not profitable without policy support, and some support measures did not result in profitability unless combined with other measures. Other economic analyses have also found algal fuel production systems to be currently unprofitable (e.g. Rosenberg *et al*., 2011).

The production of fuel alone may not produce a positive net-revenue. Producing algal fuels in biorefineries may be economically feasible when the production of fuel alone is not profitable (Wijiffels *et al*., 2010). Similar in concept to fossil oil refineries, biorefineries are used to maximise the utilisation of biomass by producing multiple products, such as different fuel types and value added products. Theoretically, biodiesel production using lipids from microalgae might be combined with the extraction of proteins for animal feeds, proteins and carbohydrates fractions could be used for biogas production through anaerobic digestion, ethanol could be produced from the fermentation of carbohydrates, and a proportion of the algal lipids could be sent to the production of edible oils (Wijiffels *et al*., 2010; Williams & Laurens, 2010). However, maximising production of biofuels might not be the most profitable scenario for biorefineries. A basic economic analysis of differing production scenarios displayed a general trend of decreasing revenue with increasing lipid content, due to less of the biomass being available for higher value products (Williams & Laurens, 2010).

Economic assessments of algae based biofuel production are challenged by various sources of uncertainty. There is a variety of possible process combinations that might comprise a system used to grow biomass and produce fuel. Where process technology is not fully developed, assumptions must be made. As production is not at full commercial scale, estimations of profitability must be based upon data from pilot projects or from laboratory experiments. This diversity is reflected in the range of values from the published economic studies of algal biofuels. Details of some basic economic assessments are given below.

There is little information regarding economic analysis of biofuel production from macroalgae. A report by published by The Crown Estate provides basic financial assessments for fuel and energy produced from macroalgae (Lewis *et al*., 2011). The assessments include the separate production of ethanol and butanol under different scenarios. For the two fuels, the most realistic scenarios when using only as a macroalgae feedstock (corresponding the base case scenarios in the report) are presented here (Table 5.1). It is important to note that these calculations have been based on assumptions, a situation which is inevitable given the lack of development in the proposed production technologies as applied to macroalgae. The data sources, assumptions and conclusions for each production scenario are discussed in the original report (Lewis *et al*., 2011). For both ethanol and butanol, the cost of seaweed (taken to be £240 per dry tonne) is considered to be prohibitively expensive, and shared by the financial assessments offered by

Reith *et al*. (2005). Lewis *et al*. (2011), was able to achieve a positive NPV for both products, only by assuming the seaweed feedstock is free of charge.

Table 5.1 Financial assessment detailing costs and revenues for the production of ethanol and butanol using macroalgae as a feedstock

		Ethanol	Butanol
Capacity	km³ / yr	30	30
Capital	£million / yr	45	107
Revenue	£million / yr	12.4	31
Operating + finance costs	£million / yr	35	84
Net profit	£million / yr	-22.6	-53
NPV (10% discount rate)	£million / yr	-238	-559

Lewis *et al*. (2011) also contains a financial assessment of an anaerobic digester and combined heat power plant that uses macroalgae as a feedstock and produces electricity, heat and fertiliser (digestate). Table 5.2 shows the financial assessment for two plants of different scales, using only macroalgae as a feedstock. Limitations and inhibitory factors will likely be experienced by using macroalgae as the sole feedstock and may be reduced by combining its digestion with another biomass. The financial assessments provided by Lewis *et al*. (2011) show that the combined digestion of macroalgae with other feedstocks might result in higher net present values than may be achieved using macroalgae alone. The financial assessments assume that renewable energy subsidies are available in the form of feed in tariffs for electricity and renewable heat incentives for heat (Table 5.2). The obtained NPV's (Table 5.3), although positive, are likely to be too low to secure investment. The costs of macroalgae biomass are optimistic (compared to the more realistic price of £ 240 per dry tonne) and are currently not likely to be feasible. It is also apparent that the inclusion of energy subsidies significantly affects the financial outcomes. For more a detailed description of assumptions and discussion of results, see Lewis *et al*. (2011).

Table 5.2 Financial product outputs, prices and renewable energy incentives for the two assumption scenarios

		Scenario 1	Scenario 2
Electricity output	kW energy	230	1,000
Heat output	kw thermal	220	1,200
Fertiliser output	Tonne / yr	5,000	20,000
Electricity price	p / kWh	6	
Feed in tariff	p / kWh	14	9
Heat price	p / kWh	6	
Renewable heat incentive	p / kWh	6.5	6.5
Fertiliser price	£ / tonne	5	

(Source: Lewis *et al*., 2011)

Table 5.3 Incomes, costs and net present value (NPV) for the two assumption scenarios

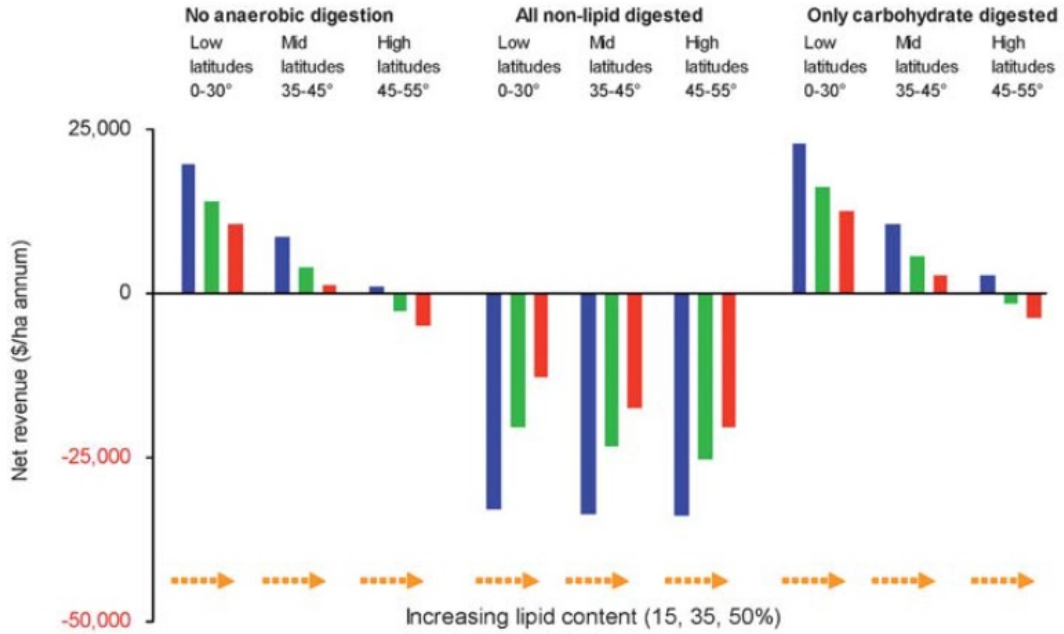
		Scenario 1	Scenario 2
Electricity income	£	350,406	1,301,500
Heat income	£	109,936	280,256
Fertiliser income	£	25,000	100,000
Seaweed cost	£ / t d.w.	80	28
CAPEX	£million	1	6.5
NPV	£million	0.23	0.01

(Source: Lewis *et al*. 2011)

Williams and Laurens (2010) provide a financial assessment of three production scenarios for biodiesel from microalgae grown in a combined photobioreactor / raceway system. The assessment explores variable algal lipid levels (15, 35 and 50% lipid per dry weight) as well as different latitudes, these being low (0-30°), mid (35-45°) and high (45-55°). For each combination of lipid and latitude variables, three different production scenarios where assessed. In the first scenario, the carbohydrate and protein fractions of the cell debris remaining after lipid extraction, are sold as animal feed. In the second scenario, all the non-lipid material, in addition to water and glycerol from oil transesterification, is anaerobically digested to produce methane for further energy conversion. The nitrogen and phosphate from digestion co-products are used for microalgae fertilisation. In the third scenario, protein from cell debris is sold, and carbohydrate, glycerol water soluble material is anaerobically digested. In this last scenario all phosphate, and only a small amount of nitrogen, is recycled. The net revenues the assessments for each scenario are represented in Figure 5.3. There is a general trend of reducing revenue as the algal lipid content increases. Given the assumptions used in this assessment, the production of biodiesel and methane is not financially possible, unless some of the cellular material is sold to increase the revenue. Production in higher latitudes does not look promising for any of the scenarios in this assessment. Williams and Laurens (2010) acknowledge the uncertain nature of the assumptions, costs and prices used in this assessment, and that values for algal production and energy yields are not necessarily obtainable. As with macroalgae, this is an inevitable situation considering the lack of technological development. For detailed description of assumptions, and discussion of results, see the original text.

To some extent, algal biofuel production is likely to be subject to economies of scale[23]. Thus, larger production systems may be able to mark*et al*gal biofuel at a lower price but to date none has been demonstrated under commercial use conditions. The cost of producing algal biomass is a major contributor to the overall cost of biofuel. Productivity of algal cultures is a key determining factor in both the profitability (e.g. Brownbridge *et al*., 2014; Davis *et al*., 2014) and energetic efficiency of algal biofuels.

23 Economies of scale describe the relationship between capital costs, operating costs, and the scale of an operation and production output. Often as, the quantity of production increases, cost of production decreases.



(Source: Williams and Laurens, 2010)

Figure 5.3 Net revenue (in US$) for the different production scenarios. The different lipid levels are represented by the colours of the bars: blue – 15%, green 35%, and red 50%

Reliance upon CO_2 from the atmosphere is a limiting factor to algal microalgal productivity in intensive cultures. If the algae cultivation requires exogenous CO_2 inputs (other than which can be provided through exposure to the atmosphere), the purchase of CO_2 can have a significant influence on production costs. Provision of CO_2 may become less costly if it can be obtained from flue gases. If an algal species is capable of heterotrophic growth, the use of organic carbon may be possible, although in addition to the necessity for a source, any residual biomass must be managed (Chisti, 2013). Technology employed for the provision of CO_2 to algal cultures from these sources represents an energetic and possible financial cost.

In land-based algal cultivation, nitrogen and phosphorous requirements may need to be met through fertilisation, and even if their use in algal cultivation is considered to be efficient, the use of conventional fertilisers will compete with agriculture, highlighting the importance of alternative low-cost, energetically efficient nutrient sources. The use of wastewater has received attention, although despite the quantities generated, the expansion of algal cultivation is limited when dependent upon its supply.

In addition to productivity, harvesting of biomass and its subsequent preparation for conversion to fuels, represent potential bottlenecks. For macroalgae species, the methods and technology for the harvesting of biomass are well established, although labour intensive methods may need mechanised alternatives. For microalgae, although harvesting technology is established for commercial production, a variety of options exist. The variation of estimated capital and operating costs for harvesting of microalgae was attributed to the variety of process options (Williams and Laurens, 2010). Both seaweed and microalgae harvest have high moisture contents (up to 90%). To increase the concentration of biomass, physical separation methods can be employed, but drying is required for conversion technologies that require higher levels of dry feedstock. Drying is energetically and financially expensive, and can account for a significant proportion of the overall energy demand of a system. This is a key driver in the development of conversion technologies that can utilise wet algal feedstocks, and efforts to develop energy efficient techniques for harvesting and dewatering. However, under some conditions ethanol fermentation of seaweeds has been negatively affected by salt concentration (Basha and Matsumura, 2014).

The development of algal biofuel production systems must be accompanied by investigation into its various environmental effects. Potential environmental impacts will be associated with the component unit processes of the production chain. The associated resource use and emissions, contribute to global-wide or large-scale impacts such as global warming, eutrophication, acidification, photochemical oxidation and human toxicity potential. To quantify these impacts, and to understand which system processes have the highest environmental burdens, it is necessary to perform life cycle assessments. Models of some production scenarios for microalgae and macroalgae biofuels have shown that some environmental impacts may actually be greater than those from petroleum production (Passell *et al*., 2013; Aitken *et al*., 2014; Mu *et al*., 2014). For seaweeds, on-land production of seeded ropes for long line cultivation (Pietrack and St.Peter 2011; Aiken *et al* 2014) and the activities associated with the cultivation and harvesting stages (Langlois *et al*., 2012; Alvarado-Morales *et al*., 2013; Aitken *et al*., 2014), appear to have a significant contribution to the impacts of the production system. Likewise, models of microalgae biofuel production suggest that process involved in the production and harvesting of the biomass have the highest contributions (Passell *et al*., 2013). Life cycle assessment (LCA) can also be used to explore opportunities for improving system environmental profiles by identifying those particular technologies that have high impacts and comparing the alternatives. In an analysis of downstream (post harvesting) processing, microalgae drying accounted for the majority of calculated impacts (O'Conell *et al*., 2013). These impacts where reduced by as much as to 91% by incorporating alternative drying methods. The published LCA studies make use of available data, and in some cases data from commercial scale algae production has been used (e.g. Passell *et al*. 2013). However, suitable data for LCAs from commercial enterprises is not usually readily accessible, and conversion technologies are often not fully operational at larger scales.

A frequently stated advantage of algal biofuels is that production of the biomass does not compete with agricultural land use. Microalgae production can take place on unproductive land, and macroalgae can be grown in coastal seawater, and possibly offshore sites. Although not fully understood, there are potential ecological impacts associated with large-scale seaweed farms. The cultivation can act as a nutrient sink. Ecological models developed by Aldridge *et al* 2012), showed a potential for nutrient depletion to have local and wide scale ecosystem impacts, depending on nutrient uptake of the seaweed as well as environmental variables. Levels of chlorophyll in phytoplankton could be reduced by these depletions, which could affect the population dynamics of species from other trophic levels, such as herbivorous species that feed upon the phytoplankton and species which use herbivorous organisms as a food source. However, in some cases the provision of a nutrient sink may confer benefits in areas via the bioremediation of high anthropogenic nutrient inputs (e.g. Chopin *et al*., 2001), though this is dependent on scale of production, species choice and management. Macroalgae cultivation might also affect the distribution of some species (such as fish) by providing new habitats.

Although not a problem inherent to algae biofuels or even terrestrial biofuel-crop production, some of the technologies being developed involve genetically modified organisms, a topic which characteristically invokes environmental concerns from consumers and environmental groups. The advanced fermentation process described by Wargacki *et al* (2012) is made possible by the engineering of *Escherichia coli* microbial strains. The use of GMO technology is controlled variously by different government bodies, and thus has implications for possible geographical limitations to the use of fuel using such technology (Benson *et al* 2014). This should be considered under the normal risk assessment process for use of GMOs.

Legislation may present barriers to production through their current levels of restriction. In other cases, legislation may also require amendments in order to be sufficiently capable of industry regulation. Benson *et al* (2014) deal specifically with the concerns surrounding the above kinds of environmental impacts in relation to EU regulatory frameworks. They conclude that although it is likely current frameworks should be sufficient, future problems are possible, with more comprehensive investigations being required to identify which elements of policy may need adjusting. The article notes that the state of research within the context of global governance is particularly lacking.

5.4 Summary

As a general conclusion, it can be said that the feasibility of using algal biomass as a source for biofuel production, is faced with large uncertainties. It seems clear that considerable challenges must be overcome for the successful production and marketing of algal biofuels.

There are specific challenges presented to the different biofuel production routes. There may be components of algal biomass that are inhibitory to conversion. For example, high ash content in macroalgae is an obstacle to its anaerobic digestion as well as conversion to biodiesel. Other such problems, not necessarily due to the composition of the algae feedstock itself, would likely become apparent throughout the scaling up of conversion technology. A variety of feasible solutions to such problems might be found with appropriate research effort.

There are also challenges that can be more generally described as relating to all algal biofuel production. Obtaining sufficiently high biomass productivity is crucial for efficient conversion to fuels, and this productivity has natural limits. High productivity is needed to generate sufficient quantities of biomass, but (notably in the case of microalgae) higher productivity may be correlated with decreased production of those algal components that are the target of production. For both macro and microalgae, wet biomass has a high transport cost and low energy content. Many of the possible conversion routes require dry biomass, necessitating drying processes that will likely be energetically and financially expensive. Drying, in addition to other steps of the fuel production chain result in a cumulative energy demand that may approach, or exceed the energy content of the final fuel. The financial assessments provided in this report show that the financial cost of obtaining algal biomass will likely be prohibitively high given the considered market value of the fuels produced. Some authors suggest that the combined production of biofuel and higher-value products may present an opportunity for commercial feasibility (e.g. Williams & Laurens, 2010), or that algae biomass may be combined with other feedstocks to result in financially viable alternatives (Lewis *et al*., 2011). However, these are largely hypothetical scenarios and more secure conclusions would be needed to attract the financial investment required for further development.

Technology for the production of various micro- and macroalgae algal biomasses has been developed and there are examples of commercial operation, although these are for non-biofuel purposes. In contrast, data describing the conversion of algal sources for fuel production is only available from laboratory or small-scale systems. This makes it impossible to assess the potential for production of algal biofuels without large uncertainties. At the current stage of algal biofuel development, there appears to be a lack of sufficient evidence to secure investment for commercial scale operation. Some projects have been launched that aim to move algal biogas and bioethanol production towards commercialisation (such as the joint UK-Irish BioMara project, and the projects of BAL biofuels in Chile). These and similar enterprises aim to operate at the scales at which technology must be demonstrated and the future of these algal biofuels may be largely dependent upon their ability to succeed.

6. Comparison of Impacts from Mariculture and Terrestrial-Based Food and Energy Production Systems

6.1 Introduction

The aim of this section is to compare the environmental impacts associated with different mariculture products for food and for fuel. The intention of this comparison is to give a broad overview of the impacts from each species production. There are a huge range of systems involved, not only in mariculture but also the service industries which support it, including feed provision (e.g. see Section 3). The variability that is evident in these geographically diverse systems and conditions cannot be completely represented within this comparison because of lack of data and resources. The most important mariculture species are assessed primarily using peer reviewed literature sources to determine their most fundamental resource requirements which are then compared with each other and against freshwater species and terrestrial products against which they compete. The comparison includes 3 major marine finfish, 2 major bivalve species and Penaeid shrimp. These are compared to 3 major freshwater finfish species, and the 3 major terrestrial food commodities; beef, pork and chicken.

6.2 Methodology

The comparison is made from Life Cycle Assessment (LCA) studies of the different species concerned as LCA is an increasingly important tool for assessing different products at a broad level. It is an ISO standardised (ISO 2006a, 2006b) environmental accounting tool which measures the impacts of a product, including all the raw materials abstraction and refining, the manufacturing of upstream products, and then the final consumption and sometimes disposal of the final products. This avoids problem shifting which has sometimes been a criticism of other environmental impact assessment tools (ISO 2006a). For example, formulated fish feeds often cause less local eutrophication around fish farms than home-made feeds but they are more energy intensive to produce and can cause other emissions elsewhere. Despite the ISO standards, there is still a certain amount of subjectivity and value loaded choices that are common within studies which often lead to conflicting conclusions depending on the choices made. This can often make comparisons between different LCAs problematic, especially as some LCAs are not fully transparent in the methodological choices which have been made. This comparison attempts to eliminate the disparities by having common bases for comparison, although this has not been possible in some cases.

In this report, the unit of comparison; the functional unit (FU) has been converted to kilogrammes of edible yield in the case of food and to mega joules of embodied energy content in the case of fuels to give a consistent basis for comparison. Although this is not ideal because the different edible fractions contain different nutrient profiles, such as omega-3 fatty acid contents in the case of marine products, and because the edible yield differs greatly depending on local attitudes to animal consumption, it offers a better unit for comparison than just the live weight at the farm gate, which many studies have presented. For example, the fillet yield of salmon is around 62% (Ramirez 2007) compared to 37% for tilapia (Pelletier and Tyedmers 2010). Edible yields have been used as presented in the specific paper where possible or have been taken from other articles used within the report and applied to all the reference studies consistently. Where these data have not been given within any of the LCA articles presented, other data sources have been used, such as trade association websites for feed conversions, FAO (1989) and Torrison *et al* 2011 for edible yields. Although there is a large number of publications on greenhouse gas (GHG) emission and LCAs for different livestock products and biofuels, the presentation of the results does not always make for easy comparison with many giving normalised results (e.g. % of national emissions) which cannot easily be converted. For aquaculture there are fewer studies available and some do not include all of the impact categories used here in some cases.

Figure 6.1 Sorting fish in a fish wholesale market in Bangkok, Thailand (Source © Richard Newton)

The LCA results of different species and commodities are presented as ranges which incorporate some of the different methodological decisions and also the wide range of production systems that can be found for some species. This uncertainty makes the comparison more robust than presenting single figures. It is also of note that very few LCA studies have presented any uncertainty within their results, despite the huge level of inherent uncertainty within much of the Life Cycle Inventory (LCI) data and the typical level of assumptions which are needed in order to construct the LCIs. Uncertainty methodology has recently been developed by Henriksson *et al* (2014a), which allows for inherent uncertainty, representativeness and horizontal spread of secondary literature data to be incorporated into individual LCA studies.

LCA is a fairly newly applied method to aquaculture and it has been dominated by species of most relevance to western consumers, in contrast to the major production centres in Asia. For major seaweed commodities produced for food, there is only one LCA study which is actually a biofuel study and for some other major species, such as Pacific oyster (*Crassostrea gigas*), there is only partial data available, sometimes outside of the major areas of cultivation. Therefore, it must be noted that the data is not fully representative of total global production for these species and provides a basic level of comparison. The purpose is also to direct where further research is required to increase understanding and improvement of the production systems.

All of the LCA studies used in this analysis are listed in Appendix A.

The comparison does not attempt to contextualise the results in the first instance because of the huge range of different systems, locations and production practices which are evident for the different species and commodities. Instead the comparison continues by breaking down the results into major contributing factors which may then be contextualised to the different species and systems which are presented. In the case of most mariculture food species, by far the largest contribution to most impact categories is from the production and manufacture of feed. In addition to the LCA results for different food and fuel commodities, the LCA results for key feed ingredients are presented together with the Feed Conversion Ratios (FCRs) for each species, in terms of feed in to edible yield out (from now on referred to as the yFCR).

6.2.1 Categories for Comparison

In LCA there are many different impact categories which have been used, largely dependent on the methodological approach. In most cases, these have been what are termed "mid-point" categories which look at the potential for harm from emissions, in contrast to end-point categories which may assess the final fate of an emission such as the level of sea level rise associated with global warming. Mid-point is regarded as a less subjective approach as many assumptions are needed to assess the final fate of emissions. Categories which are most often used are: Global Warming Potential (GWP, also known as Carbon Footprint), Acidification Potential (AP), Eutrophication Potential (EP), Cumulative Energy Use (CEU) and various toxicity potentials. In this study, toxicity potentials are not included because there is a lot of subjectivity around the characterisation of many emissions, and many of the chemicals commonly used in aquaculture for pesticides, antifoulants and disinfectants have yet to be characterised at all (Henriksson *et al*, 2015). Many of the studies included in this analysis do not have any data on toxic emissions. Toxic releases to the environment through feed provision may be considered to be a greater threat than the livestock production systems themselves through the use of pesticides used for crop protection such as cypermethrin (Dalgaard *et al* 2008).

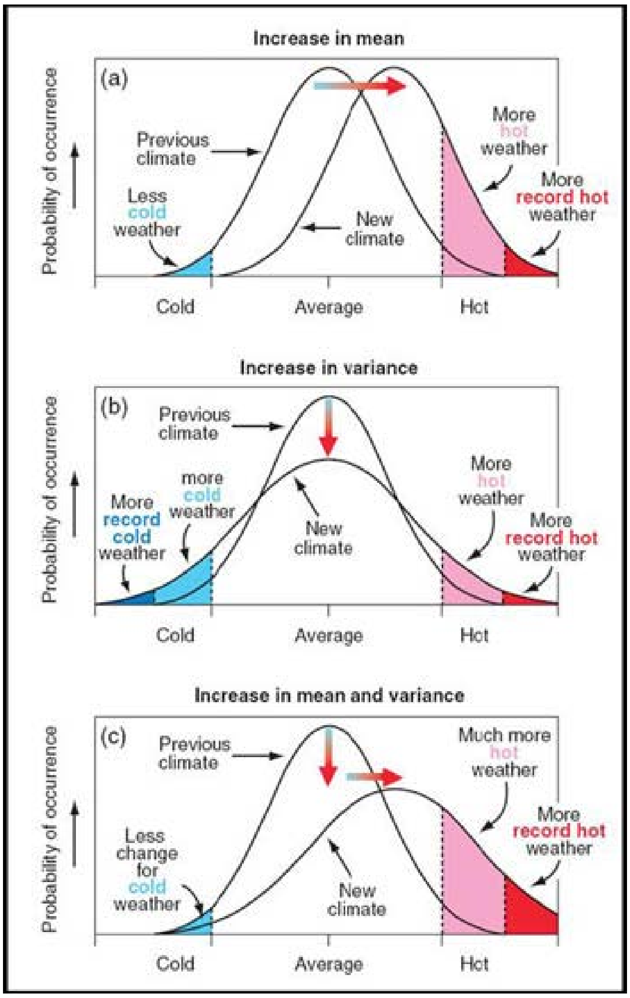
Impact categories which may be used in LCA are shown in Table 6.1. The impact categories which are used in the current assessment are described in further detail below.

Table 6.1 Impact categories used in LCA

LCA Impact Category	Used in Current Study
Global Warming Potential (GWP, also known as Carbon Footprint)*	Yes
Feed Conversion Ratio (FCR)	Yes, related to edible yield
Land Use (LU) / Land Use Change (LUC)	Yes
Freshwater Consumption and Dependency	Yes
Acidification Potential (AP)*	Yes
Eutrophication Potential (EP)*	Yes
Cumulative Energy Use (CEU)*	No, energy balance used for biofuels
Net Primary Production (NPP) or Biotic Resource Use (BRU)	No – Fish In/Fish Out (FIFO) ratio used instead – see Section 6.2.1.5
Various toxicity potentials*	No
* Categories which are most often used in LCA	

6.2.1.1 Global warming potential

Global Warming Potential (GWP) is the potential for gaseous emissions to warm the planet through radiative forcing i.e. affecting the energy balance of the Sun's radiation that enters the Earth's atmosphere versus that which is reflected back, known as the "Greenhouse Effect". The most common greenhouse gas (GHG) is carbon dioxide (CO_2), although not the most potent, therefore GWP is also commonly known as a carbon footprint. Gases such as methane, dinitrogen monoxide (N_2O) and other gases have a much larger GWP but are released in much lower concentrations globally. N_2O, for example is characterised as having a radioactive forcing potential of 298 times as much as CO_2 per kilogramme produced (CO_2 equivalent) and is commonly released from agricultural soil management. Methane has a CO_2eq of 25 and commonly comes from enteric emissions of livestock and anaerobic decomposition processes. GWP is now considered as one of the biggest threats to humanity, through sea level rise threatening coastal populations, increased water scarcity, increased disease vectors and not least because of the threat to food security. The 2100 target average global temperature rise of 2°C is predicted to cause more extreme conditions as shown in Figure 6.2 leading to periodic crop failure and reduced yields of major crop species of up to 30% overall.



(Source: Walsh 2010)

Figure 6.2 Shifts in the Distribution of Cold and Hot Weather

6.2.1.2 Feed conversion ratio (yFCR)

FCR is a common method for assessing the efficiency of feed utilisation by livestock. It is usually related to live weight of the animals and is calculated simply by dividing the weight gain over a certain period by the feed ingested during the same period. In the case of this report, all assessment categories are measured against the edible yield of the animal, including FCRs, for better comparison between different categories of livestock. FCR per edible yield (yFCR) might be considered as the most important category because many of the other impact categories are intrinsically linked to it.

6.2.1.3 Land use impact category

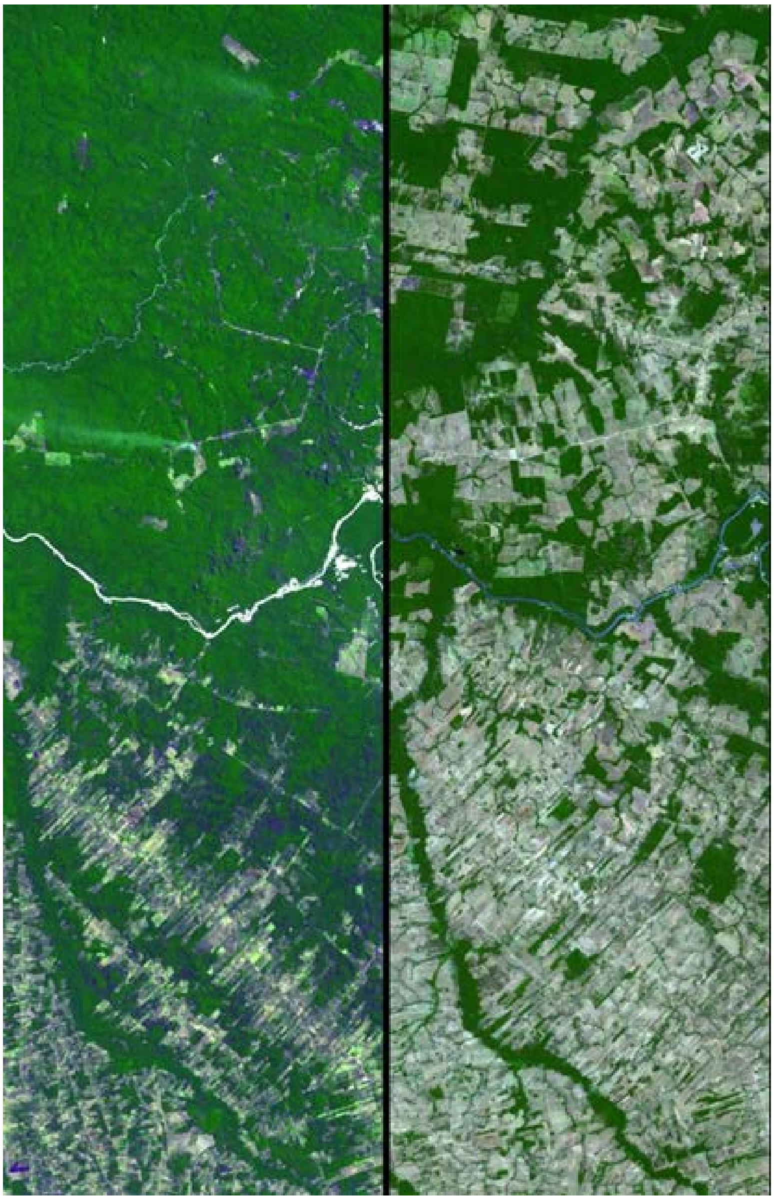
It has been estimated that approximately one third of agricultural crop land is devoted to the production of feed ingredients for various livestock (Robinson *et al* 2011). Although much of the increase in crop production in recent decades has come through improvements in yields rather than land expansion, land use change is a continual problem as land is degraded and ever more land is required to produce the crops needed for both direct human consumption and for livestock feeds (FAO 2006).

Land Use (LU) is becoming increasingly important within LCA studies, and land use change (LUC) is also of huge interest within the LCA community. In this study we have chosen only to include direct land use rather than Land Use/ Land Use Change (LULUC) because the methodology underpinning LULUC is still not fully developed and the subject of much controversy (Mila i Canals *et al* 2007). Much of the debate concerns the environmental services that land provides prior to and after transformation, such as carbon sequestration. Loss of biodiversity due to habitat loss and its impact is even more open to interpretation and difficult to quantify.

Many of the LCA studies used for this comparison do not include either LU or LULUC in the results. In the case of most mariculture, the vast majority of land required from a life cycle perspective relates to that which is used in the production of crops for feed and the processing activities associated with that feed provision, plus the land required to store equipment and service the production facilities.

Land transformation for the production of crops for feed production is of huge concern, especially in sensitive habitats found in South America (Figure 6.3) and Asia. Not only is LUC associated with widespread habitat loss of sensitive species and the disruption of the livelihoods of indigenous peoples, but may also lead to the release of GHG on several counts. Increases in GHG originate firstly through the release of carbon through loss of vegetative biomass; secondly, through the mineralisation and subsequent release of carbon and nitrogen compounds from the soil and thirdly, through the loss of sequestration potential. Current estimates for LUC from rainforest estimate that around 75 kg CO_2 sequestration is lost per m^2 over a thirty year period (i.e. about 2.5 kg per year) when converted to crop production (Nguyen *et al* 2010). Conversely, crop production on previously degraded land may improve carbon emissions and enhance biodiversity (Gnansounou *et al* 2009). Therefore, as land is transformed to crop production, livestock rearing or other uses, the various original uses of the land are not easy to determine, and the depreciation time of LUC is also debatable. Schmidt

(2010) argued that forest clearance in Brazil was three to four times greater than the level of agricultural land expansion and it was logging that was the major driver for forest loss. However, agricultural land use for major feed ingredients is expanding overall, and therefore the land required to grow crops for feed is presented in this section along with the major production areas but not any assumptions regarding carbon emissions associated with LUC. FAO data regarding the GHG emissions associated with land transformation for different regions have also been presented in Section 6.5.1.



(Source: NASA, 2015; accessed 2/5/2015)

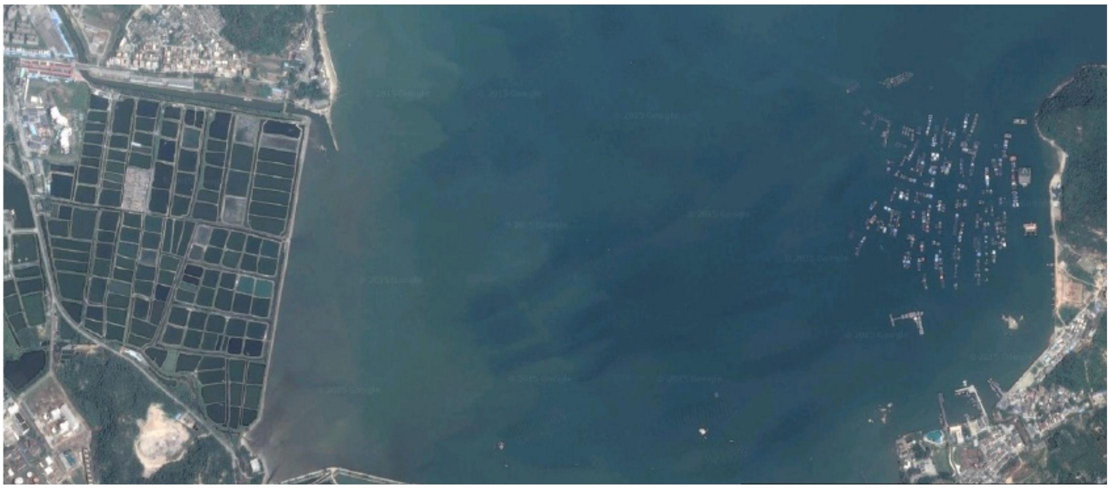
Figure 6.3 Forest clearance in Brazil between 1992 and 2006

6.2.1.4 Fresh water consumption and dependency

Freshwater use impact categories are also becoming increasingly used in LCAs, although they have not been widely used within aquaculture LCAs. A distinction must be made between that water which is used and immediately returned to the biosphere and that which is actually consumed by the system i.e. water dependence vs. consumptive use. Consumptive use refers to that which is consumed to the system and that which is lost through evapotranspiration.

In the case of many aquaculture systems, they are dependent on large volumes of water for the environmental services they supply for maintaining the health of the organism, e.g. oxygen supply and dilution of metabolites. However, the water is often returned to the environment with little consumption and differences in quality may be accounted for in other impact categories such as eutrophication potential. However, some impact categories regarding water quality are poorly characterised, in the case of toxicity potentials, or rarely included, in the case of Biological Oxygen Demand (BOD), for example. These categories not only affect the environment but may also have severe effects on human health. Although some regard the return of water to the biosphere as being consumed in many cases, because the quality has often been degraded (Pfister *et al* 2009), on a global scale the amount of dilution and treatment of emissions can vary. Consequently, the effect on the environment and human health is not only site specific according to physical properties of the region but will also depend on such factors as national development to provide sanitation and water purification technology. Added complications may arise when the degraded effluent from one industry is then utilised by another, which is the case for integrated agriculture/ aquaculture or livestock systems that are common in many parts of Asia. Therefore, it is highly complex to measure the level of degradation on a general basis for any particular species and only individual assessments can be made accurately.

Despite non-consumptive use, mariculture systems still require a certain volume of marine water and current speed to provide the ecological services to maintain a healthy stock. This is demonstrated by marine flow through systems that pump water ashore and coastal shrimp ponds that sometimes require tidal flushing to maintain water quality parameters. In some locations such as the Scottish coast, lack of appropriate sites is a considerable barrier to the continued expansion of the industry and in some areas of China, the large number of operational sites has led to serious water quality concerns (Figure 6.4).



(Source: Google Earth)

Figure 6.4 Chinese mariculture showing coastal shrimp and net pen systems (also present are seaweed long-lines)

Fed marine species, as well as other fed livestock, require feed in varying quantities, which in most cases requires large amounts of freshwater for crop production and for processing. In terms of freshwater use, it is common to split the water into different categories. Green water is considered that which is precipitated or present in the soil, blue water is that which must be extracted from surface or groundwater supplies and grey water is that which is required to dilute emissions and return degraded water from industry or agriculture to specific quality standards (Berger and Finkbeiner 2010). Whereas many studies focus on blue water consumption (i.e. irrigated water), this report has not attempted to distinguish between the different categories of consumption because it will vary hugely from location to location. Instead, the absolute blue and green water requirements of major feed ingredient crops are given based on rainfall requirements per hectare given by Brouwer and Heibloum (1986) which are adjusted to cubic metres of water per kilogramme of grain yield. Similarly, water availability both from precipitation and irrigation will vary from area to area and therefore suitability for crop production can be contextualised by presenting data on regional rainfall patterns and water stressed areas such as the water withdrawal to availability ratio (WTA) or Water Stress Index (WTA*) (Pfister *et al* 2009, Berger and Finkbeiner 2010).

In addition to water for feed production, aquaculture species are also dependent upon water to maintain minimum oxygen levels and to remove wastes in most cases. Despite water being returned to the channel from where it came, where the required flow of freshwater is high, this will preclude the culture of that species from the more highly water scarce regions unless Recirculating Aquaculture Systems are used.

6.2.1.5 Fishmeal and fish oil inclusions

A large number of criticisms particularly of marine carnivorous aquaculture have centred on the inclusion of marine ingredients within aqua-diets (e.g. Naylor *et a*l 2009, Alder *et al* 2008). The share of global fishmeal and fish oil production has been increasingly directed to aquaculture from other livestock and industrial sectors since the 1980s until over 70% was being directed to aquaculture in 2010, of which 75% was directed to salmonids, marine fish and crustaceans (Shepherd and Jackson 2013). This must also be taken in context of falling fishmeal supplies which peaked at 6.3 million tonnes in 2004 and dropped to a minimum of 4.3 million tonnes in 2010 but then rose to 5.2 million tonnes in 2012 (Shepherd and Jackson 2013). However, the volume share directed to aquaculture has remained fairly static at about 3 million tonnes for the last ten years leading to aquaculture utilising an increasing proportion of global supply (Newton *et al* 2014).

In many LCA studies, marine ingredient inclusion has been investigated using Net Primary Production appropriation (NPP), sometimes referred to as Biotic Resource Use (BRU). This is calculated from the cumulative consumption of carbon throughout the LCA adjusted to the trophic level of the species, where plants have a trophic level of 1 and each step up the food chain results in an order of magnitude increase in carbon content according to the methodology described by Pauly and Christenson (1995). However, this makes little allowance for the sensitivity of the biotic resource in most instances and is not used by any of the major certifiers in directing the best management practices for feed ingredient use (such as Aquaculture Stewardship Council (ASC), 2012; Global Aquaculture Alliance (GAA), 2011; GlobalGAP, 2012 and IFFO (The Marine Ingredients Organisation) RS, 2011). Instead, they tend to rely on "fish-in fish-out" (FIFO) ratios according to Jackson (2009) or similar methodology in the case of ASC for their fishmeal and fish oil dependency ratios. These are calculated according to the yields of fishmeal and oil obtained from the industrial fish resource, their inclusion within the aquaculture diet and the FCR (Jackson 2009). However, in the case of fishery by-products, these are assumed to be a waste resource and are discounted from the calculation, in contrast to some LCAs which attach heavy burdens to such resources (e.g. Pelletier and Tyedmers 2007). Where possible, in this report we have chosen to use FIFO as an indication of marine ingredient use according to Jackson 2009 because in many instances by-products from fisheries and aquaculture are still being wasted in large quantities and their use should be encouraged where they are from sustainable sources as highlighted by IFFO RS standard (2011), in order to ease the pressure on other marine protein ingredients and prevent waste. As the proportion of fishery by-product meal used in diets may vary from system to system, and species to species, in the case of Atlantic salmon, for example (Pelletier *et al* 2009), a global average for by-product use in fish meal manufacture may be appropriate for all species which would reduce the overall fish inclusion by up to 40%. However, in reality, the amount of by-product inclusion varies regionally as highlighted by Pelletier *et al* (2009) and for this report, the figures have been used as reported in the individual LCAs. Fishery and aquaculture by-product use in fishmeal has steadily been rising as stocks of wild fish used for reduction (to fishmeal and fish oil) have been fully exploited for at least ten years, (Newton *et al* 2014) and is now estimated to be in the region of 35% or more of global fishmeal production (IFFO unpublished data). All of our results are presented as inputs per edible yield, and therefore we do not present a traditional FIFO but a Fish In to Edible Yield Out Ratio (FIEYO).

Figure 6.5 Frozen trash fish (Source © Trevor Telfer)

6.2.1.6 Acidification potential

Acidifying emissions include sulphur dioxides (SO_2), nitric oxide and nitrogen dioxide (NO_x), and ammonium gases (NH_x), but not dinitrogen monoxide (N_2O). SO_2 and NO_x are primarily from the burning of coal and other fossil fuels in power station and engine emissions whereas NH_x commonly comes from volatisation of nitrogen from agriculture, especially related to managed soils (Guinee *et al* 2002, IPCC 2006). They are important pollutants for acid rain which can cause damage to vegetation, aquatic habitats and to building infrastructure (Guinee *et al* 2002).

6.2.1.7 Eutrophication potential

Eutrophication is the process by which water bodies become enriched with excessive macronutrients, particularly of nitrogen and phosphorous compounds leading to a shift in the species constituents and hence ecology of the aquatic ecosystem. This may render the water as unpotable or limit its uses for other industrial needs (Guinee *et al* 2002). Conversely, it can provide nutrients for downstream use such as fertilisation for agricultural activities or for biofuel production (see Section 5). Eutrophication is measured in phosphate equivalents, although phosphate is of more concern in freshwater ecosystems, nitrate is the limiting nutrient in marine systems.

6.2.1.8 Cumulative energy use

Cumulative Energy Use (CEU) is a common inclusion in LCA studies, however, it usually relates to the use of fossil fuels only and it does not include energy from renewable sources. Consequently, studies for the same species could have very different CEUs based on the energy that is available. Since the purpose of this report is to give a global overview of species production CEU has not been included. A measure of total energy use regardless of energy type would be more useful here for meaningful comparisons on a species level rather than a regional level.

6.3 Other Methodological Considerations

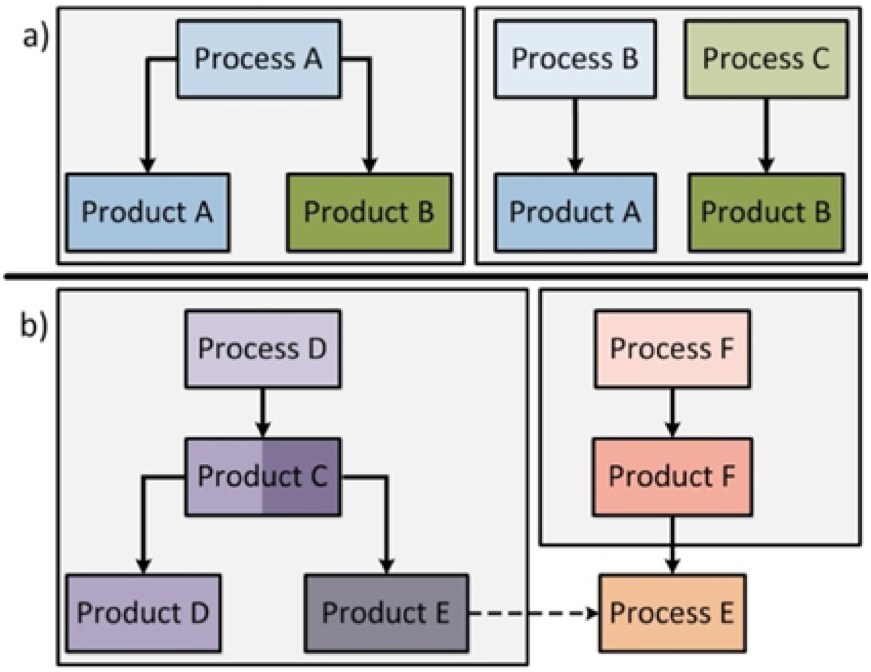
6.3.1 Carbon Sequestration

Carbon sequestration is not considered for crop production or for bivalve mollusc production. This is because in most circumstances, the entire product is consumed or disposed of with the carbon being returned to the biosphere in the short term. It is usual that when utilising a biogenic carbon source that carbon dioxide emissions are treated as neutral at the point of release. In the case of bivalve mollusc shells, it is uncertain what their fate is and they are regarded as a considerable waste problem in some areas as highlighted by Alvarenga *et al* (2012). In the case of biofuels, the carbon sequestered by algae or by crops is also not included and considered neutral at the point of release. The amount of energy and other emissions can be compared to the embodied energy that the biofuels contain, in this case per mega joule. With regards to aquatic systems, it is also debatable how much the removal of carbon sources from the sea contributes to reduction of global warming in long term carbon cycles as most marine carbon inputs are from dissolved minerals rather than CO_2 from the atmosphere.

6.3.2 Partitioning Procedures

The methodological choice that can have the most impact on the outcome of any LCA is that used for partitioning the impact between multiple products originating from a single process. A prime example in the case of mariculture is in feed provision where the by-products of agricultural, livestock and fishery industries are commonly incorporated into feed formulations. In the case of fishery by-product meal, a partitioning method must be applied to divide impacts between the edible portion of the fish and the by-product fraction that is directed to by-product meal at the processor stage.

ISO (2006b) provides a hierarchy for this decision. System expansion relies on replacing multifunctional processes with equivalent single function processes or expanding the study to incorporate the consequence of changes in the market. In the case of by-product use, it involves finding single function substitute products that are replaced by the by-product (Figure 6.6a) or for which the by-product can perform the same function (Figure 6.6b), in which case the impacts are subtracted as avoided burdens, e.g. in the case of fishery by-products, the avoided burden is from reduction fisheries (product F) which the by-product (Product E) replaces for use in fishmeal manufacture (Process E). This approach can lead to subjectivity, however, where the avoided product is not clear, and where the alternatives have very different impacts leading to a large range of possible outcomes. For example, Schmidt (2008) showed that different impacts were attributed to Danish wheat production depending on the consequences of different production and market scenarios. The choice of assumptions at various points in upstream processes, therefore have a large impact on the LCA output, adding more subjectivity and uncertainty to complex supply chains.



a) Two processes produce the same products as the multi-functional process; and
b) A single process produces a product that can perform the same function as that produced from a multi-functional process.

(Adapted from: ILCD General Guide for Life Cycle Assessment, EC 2010)

Figure 6.6 Simplified example of system expansion

Most practitioners use more simplistic approaches which can be consistently applied with relative ease. These have often relied on dividing impacts by the mass alone, the mass adjusted economic value or in some cases the embodied energy within the different co-products (Table 6.2). However, there is still a lot of debate as to which method is the most representative for the systems studied and they often lead to very contrasting conclusions. It is usual that by-products are lower in value than the target product and therefore carry a lower impact proportionally when compared to partitioning based on mass (or embodied energy). Despite this, not all of the studies presented here mention the methodology they use to separate impacts between co-products. This report does not critique the method of partitioning and has presented all of the results from the various studies in their published state. However, all figures are presented as the edible yield (or energy content in the case of biofuels) which in some cases needed to be adjusted from live weight or other FUs, assuming that no impact is attached to the non-edible yield which is essentially a waste product. In reality, this is not the case in most instances, as will be discussed later.

Table 6.2 Methodology and assumptions of the included aquaculture and livestock LCA studies

Species	Number of Studies (Systems)	Systems Included	Methodology / FU/ Allocation
Atlantic salmon** *Salmo salar*	4 (10)	Net pen in Canada, Chile, Norway and UK	FU Live weight. Allocation mostly by gross energy
Sea bass** *Dicentrarchus labrax*	3 (4)	Net pen, France, Turkey. Pumped flow through, Tunisia	FU Live weight. Allocation not mentioned
Trout*** *Onchoynchus mykiss*	5 (9)	Ponds, France, Germany Finland. RAS* France	FU Live weight Allocation economic, system expansion, none.
Milkfish** *Chanos chanos*	2 (2)	Pond polyculture, net pen monoculture, Philippines, national average.	FU Live weight Allocation economic, not mentioned
Tilapia*** *Oreochromis niloticus*	2 (4)	Pond and net pen* polyculture and monoculture	FU Live weight Allocation economic, gross energy
Carp*** *Cyprinus carpio*	1 (2)	Large and small scale net pen* polyculture system with tilapia	FU Live weight Allocation economic
Penaeid shrimp** Mainly *Litopenaeus vannamei*, some *Penaeus monodon*	3 (14)	Extensive to intensive polyculture and monoculture, Bangladesh, China, Thailand and Vietnam	FU Live weight, processed edible yield Allocation economic
Oyster** *Crassostrea gigas*	2 (2)	Brazil and UK Trestle (UK)	FU live weight Allocation none
Mussel** *Mytilus edulis and M. galloprovincialis*	4(4)	Long line raft Spain, Sweden, UK	FU live weight / canned meat Allocation, system expansion, none
Beef Various breeds	9 (19)	Various, pasture and feed lot plus national averages. Ireland, Sweden, EU, Australia, US	FU mainly live weight or carcass weight Allocation mass, gross energy, system expansion

Species	Number of Studies (Systems)	Systems Included	Methodology / FU/ Allocation
Chicken Various breeds	9 (17)	Conventional, free range, premium. Brazil, France, Portugal, UK, Australia, Sweden, Reunion.	FU mainly live weight Allocation economic or system expansion
Pork Various breeds	6 (14)	Conventional, traditional, organic, certification scheme. Denmark, Germany, France Spain Netherlands, US.	FU mainly live weight Allocation economic, system expansion, gross energy

* RAS = Recirculating Aquaculture System. Indonesian carp and tilapia net pen systems were a 2 cage polyculture system in one article.
** Species considered to represent 'mariculture' species in the current study (i.e. cultured in marine or brackish water)
*** Species cultured in freshwater

6.4 LCA of Mariculture Production With Selected Terrestrial and Freshwater Aquaculture Species

The results below show the comparisons between key mariculture finfish, bivalves and shrimp, key freshwater aquaculture and terrestrial livestock species. All results are displayed per kg of edible yield. Beef had the highest impact in most categories, with other species performing variably across the different impact categories. Shrimp include some of the most diverse range of systems, from intensive monoculture which dominates Thai production, to large extensive systems that dominate Bangladeshi systems and are also present in Vietnam. There are also a large range of polyculture systems in the more brackish to freshwater areas in which shrimp are grown. This large variation in system type leads to the high range of values that appear in Figure 6.7 for shrimp. This is also the case for sea bass production which includes a Tunisian flow through system that relied on pumped seawater.

6.4.1 Feed Conversion Ratio per Edible Yield

Comparisons of the ranges of FCRs encountered per edible yield (yFCR) are shown in Figure 6.7. Despite significant improvements in efficiency within the beef and dairy sectors (Capper 2011), beef still has the worst yFCR by far out of the studied species. However, it is important to remember that the edible portions of different animals vary greatly according to local preference. This report only shows the deboned meat from each species, whereas in reality, in many cases, far more of the animal is consumed. In the case of most terrestrial animals, the liver and kidneys may be consumed directly, whereas other parts may be directed to pet foods, with skins being used for leather, in some cases. For many aquatic species the utilisation strategies for the by-products are less developed and may contribute to waste problems. However, in Asian and African cultures, often most of the animal is consumed with little wastage. Much of the cattle feed in this study was hay and silage that was produced on-farm in many cases, which contributes to the larger variation seen for beef than for the other food products. So the range of efficiencies in feed conversion is related to the quality of feed as well as the biology of the species (Capper 2011). This includes beef feed-lot systems that do not rely solely on formulated diets. Table 6.3 gives typical feed ingredients for formulated diets for major aquaculture and livestock species included in this report.

Table 6.3 Examples of formulated diets of selected aquaculture and livestock species

Ingredient	Beef[1]	Pork[2]	Chicken[3]	Salmon[4]	Seabass[5]	Shrimp[6]	Tilapia[7]
Fishmeal				37.8	42	46.2	3.0
Fish oil				25.2	8.0	2.8	2.0
Soybean meal	8.5	24.4	19.3	13.2	15.5	11.0	50.0
Wheat	1.9				22.0	24.0	32.0
Gluten				5.1	8.0		3.0
Maize	17.9	70.0	65.1			8.5	
Whey	71.7	2.0					
Pea protein concentrate				7.4			
Rapeseed				4.1			
Distillers dried grains with solubles (DDGS)			10.0				4.0
Meat and bonemeal (MBM)			2.9				
Sunflower†				7.8			
Minerals		3.6	5.6		8.0	7.5	4.0
Others							2.0

(Source: [1]. Pelletier *et al* 2010a; [2]. Pelletier *et al* 2010b (supporting info); [3]. Bundgaard *et al* 2014; [4]. Pelletier *et al* 2009 (supporting info); [5]. Aubin *et al* 2009; [6]. Cao *et al* 2011 (supporting info); [7]. Pelletier and Tyedmers 2010)

Oysters and mussels are not fed species and therefore have an FCR of zero. For carp, the only studies included were part of polyculture systems including tilapia and other fed species. The feed attributed to each could not be subdivided between the species and was therefore allocated based on economic value. In many extensive systems, carp are not fed at all, but rely on the primary productivity of the pond, which may be encouraged by fertilisation with organic or inorganic fertilisers. In the case of grass carp, globally the most cultured fin-fish species, in the past up to 50% of their feed came from grass from pasture land, which may or may not have been fertilised. Farmers now use more formulated feeds, possibly because of the price of labour to cut enough grass to meet requirements (Edwards 2013). This is something of a knowledge gap as the industry is dynamic and systems are highly diverse, therefore figures on different feed usage could not be found. Farmers often use polycultures of fed species e.g. grass carp with filter feeders such as silver carp in ratios of around 80:20 (Edwards 2012). Non-fed systems are also evident in some of the extensive shrimp studies included, although now there is a move towards what is termed “improved extensive” in Bangladesh and especially Vietnam, which still use comparatively low stocking densities of up 10 post larvae per m^2, but do include some limited supplementary feeding and fertilisation. These systems are also extremely diverse and are typically polycultures. All the marine and freshwater aquaculture species score better than the terrestrial food products except chicken.

Notable for the mariculture species, is that they use considerably more marine ingredients than the freshwater aquaculture and the terrestrial livestock species, which use more vegetable proteins and carbohydrates. The aquaculture industry is actively reducing its reliance on fishmeal and fish oil in the face of stiff competition for the resource as will be discussed further in Section 6.4.7.

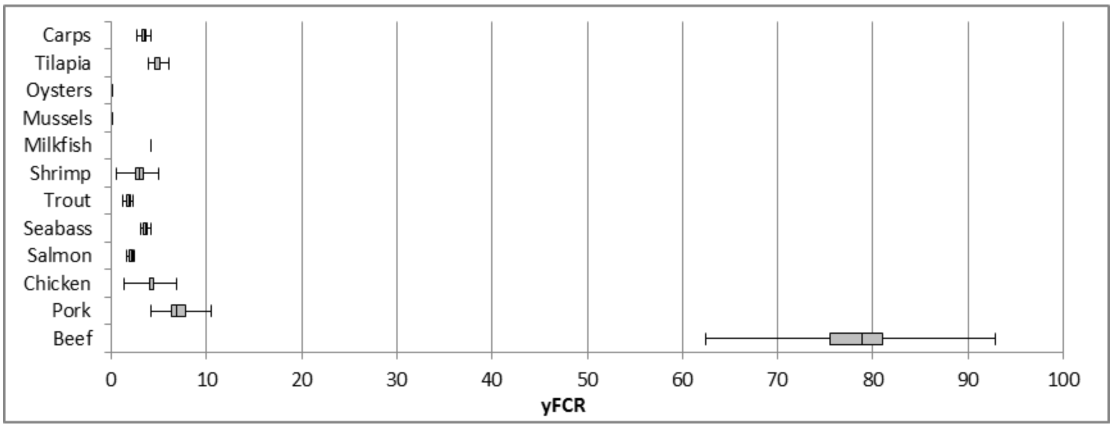


Figure 6.7 FCR to edible yield of major mariculture species compared to fresh water aquaculture and terrestrial livestock species. Medians, 25% and 75% quartiles and 95% confidence limits

It must also be considered that the LCA studies often concentrate on intensive systems which are not fully representative of global production averages. There are many extensive systems for shrimp that use very little feed inputs, some of which have been included in our analysis (Henriksson *et al* in press), and there are also many polyculture systems where it is problematic to subdivide how the feed input is utilised between the various species.

For beef production, feed-lot systems that use the feed ingredients above are representative of only a small amount of global production. It would not be representative of global production to extrapolate the yFCR and global production quantities to the feed inclusions given above because a large proportion of beef production relies on natural grazing of grass lands for all or part of the production period in most systems.

6.4.2 Land Use

Land use has been included in relatively few aquaculture LCAs compared to the terrestrial livestock species, despite the evidence that feed provision is the largest contributor to impacts overall. As mentioned in Section 6.2.1.3, land use is a controversial impact category for several reasons. This is mainly concerned with LUC but also there is contention regarding the suitability of land for different purposes. It is simplistic to suggest that land used for beef production could be converted to arable land for crop production. In many cases the open grass lands of the USA and parts of South America are of poor soil quality and totally unsuitable for crop production according to Capper (2011) who stated that only 8% of pastureland was suitable for crop production in the US. However, most beef is not produced solely on extensive grasslands, but relies on large quantities of feed inputs during a fattening stage. It was claimed by Dudley *et al* (2014) that US beef feed was not sourced from areas sensitive to LUC such as Brazil and consequently, emissions were lower. However, those same feed resources could be redirected to more efficient species elsewhere from a global view point and, despite increases in efficiency of overall land use by as much as 33% in 40 years (Capper 2011), beef still requires up to ten times the quantity of land that most aquaculture species do (Figure 6.8). Reduction of beef production could therefore lead to some feed ingredients being directed to direct human consumption or species with superior yFCRs and reduce the pressures on land utilisation in those areas that are more sensitive to LUC.

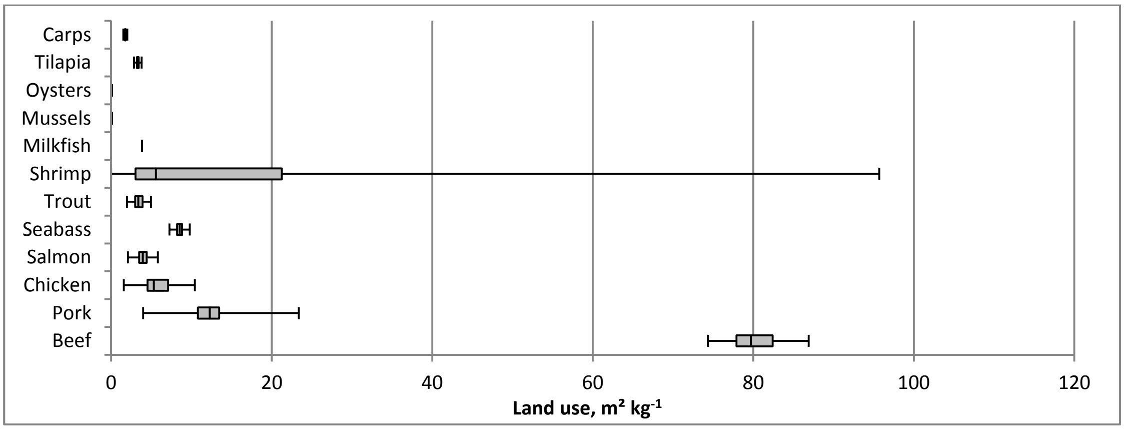


Figure 6.8 Land use for major mariculture, FW aquaculture and terrestrial livestock species. Medians, 25% and 75% quartiles and 95% confidence limits

Land use related to crop production is discussed in Section 6.5.1, however, the land use for mariculture species is intrinsically linked to the feed and its efficient utilisation as the quantity of land directly taken up by culture and processing is minimal in comparison in most cases. The range of land used is proportional to the ranges in yFCRs and the land required for the production of the various feed ingredients. However, this is not necessarily the case for shrimp systems which are grown in coastal ponds and other large polyculture systems common to Asia. The huge range of systems require varying amounts of land, from small intensive ponds that are common mostly in Thailand and China, to much more extensive systems which dominate Bangladesh production (Figure 6.9) and can also be seen widely in Vietnam. These systems often extend over several hectares and have sometimes been continually expanded in efforts to overcome degradation and disease issues from poor water and sediment quality (Bush *et al* 2010).

(Source: © David Little)

Figure 6.9 Harvesting shrimp in Bangladesh

Land use change (LUC) and the emissions associated with it have not been included in this comparison because of the uncertainty described in Section 6.2.1.3. However, carbon emissions related to the production of major feed ingredients are described in Section 6.5.

6.4.3 Freshwater Use

According to FAO (2006), agriculture accounts for at least 70% of global freshwater use. Despite the seemingly inexhaustible supply of water on the planet, there is only a small percentage of fresh water and of the estimated 110,000km^3 of annual global precipitation, only around 12,500km^3 are usable by human populations (Postel 1996) and according to Turner *et al* (2004), around 3,000 litres of water are required for food provision per person per day.

Water Use is a relatively new category in LCA and the majority of the studies used for this report did not include any reference to it at all. Of course most of the marine species included here do not require any freshwater inputs at the culture stage, the exception being Atlantic salmon which requires good quality, well oxygenated water for juvenile production. However, all fed species require water to produce the crops and often to process the ingredients into formulated feeds. Therefore, like land use, for marine species, the amount of water is directly related to the efficiency of feed use.

Unlike marine species, freshwater species require the environmental services of freshwater to keep their environment clean and to provide them with oxygen, although this can also be supplied through aeration or oxygen injection. The flow rate to supply the necessary oxygen is dependent on the species and also other factors such as temperature, especially, can influence solubility of oxygen, and therefore the required flow to deliver sufficient quantities to the cultured animals. Similarly, different species can tolerate different water quality parameters such as ammonia concentration. Build-up of ammonia and other metabolites exert Chemical Oxygen Demand (COD) on the system and therefore they become a double edged sword and must be diluted to maintain the water quality conditions that the more sensitive species require, such as salmonids. Freshwater requirements for major feed ingredients are included in Section 6.5.

Terrestrial livestock species obviously differ in that they must be supplied with water for drinking to survive and maintain general performance, although this varies considerably according to the region and hence environmental conditions that they are kept because of increased metabolic rates and water lost through sweat (FAO, 2006). Cattle and other grazing animals may obtain considerable moisture from their food in wet climates, whereas those fed on formulated diets may require more to be supplied separately. All animals can obtain some water through condensation reactions in anabolic processes. In addition animals also require water for cleaning their living areas and for other service requirements. However, according to the figures from FAO (2006), the quantity of water consumed by terrestrial livestock at the grow-out farm is negligible compared to those estimated for the provision of feed, and is shown in Table 6.4.

Table 6.4 Water dependency of selected freshwater fish species and terrestrial livestock on farm

Species	Water Requirement per kg, m^3	Estimated Total Water Use 2012, km^3
Beef[1]	0.25	15.3
Pig[1]	0.061	6.6
Chicken[1]	0.017	1.5
Trout[2]	252	215.7
Tilapia[3]	9-21	67.4
Carp[3]	5-12	179.5
Note: That in the case of freshwater aquaculture species, the table shows the water used but the vast majority is then returned to the water-course and may often be reused for different purposes such as agriculture. The water used by terrestrial livestock is drunk and apart from that excreted, cannot be reused for any purpose.		

(Sources: [1]. FAO, 2006; [2] Muir and Beveridge, 1987; [3] Phillips *et al*, 1991)

6.4.4 GWP

Beef is also the poorest performer in terms of GHG emissions. Although large proportions of the diet are from low input farm sources, cattle also produce large quantities of enteric methane which has a carbon equivalent twenty five times higher than CO_2. The assumption that for animal production most of the GWP impacts are from the provision of feed is not necessarily the case as shown in Figures 6.8 and 6.9 (the latter of which shows the contribution analysis to GWP of selected species in the assessment). This is because of the wide range of systems which are employed that use variable amounts of energy in their operation. A prime example is sea bass which included only 3 studies, one of which used large amounts of energy to pump seawater ashore in a flow through system, in contrast to a net pen system that used very little energy on farm. Atlantic salmon, in contrast to sea bass has been well studied but the systems are universally net pen culture. The variability within the results for salmon originates from the feed ingredients used, the allocation methodology to partition impacts to by-products and from variation in the FCR (Figure 6.10). Mussels and oysters have surprisingly high GWP considering there is no feed input (Figure 6.11). Most of the energy used is during the depuration stage which often uses UV light to sterilise the water used for depuration (Fry 2012). The amount of depuration that bivalves require depends upon the water quality in which they are grown. For oysters, the underlying data also included energy for 'on farm' operations (see Figure 6.9), relating to the husbandry undertaken during the time taken to reach marketable size (3.5 years + in the 3 farms included in the data used; see Auchterlonie *et al*, 2014). Such operations included grading and re-bagging, using specialist equipment requiring diesel and electricity, although it should be noted that the electricity used per tonne of harvested oysters varied by a factor of 17 between the farms.

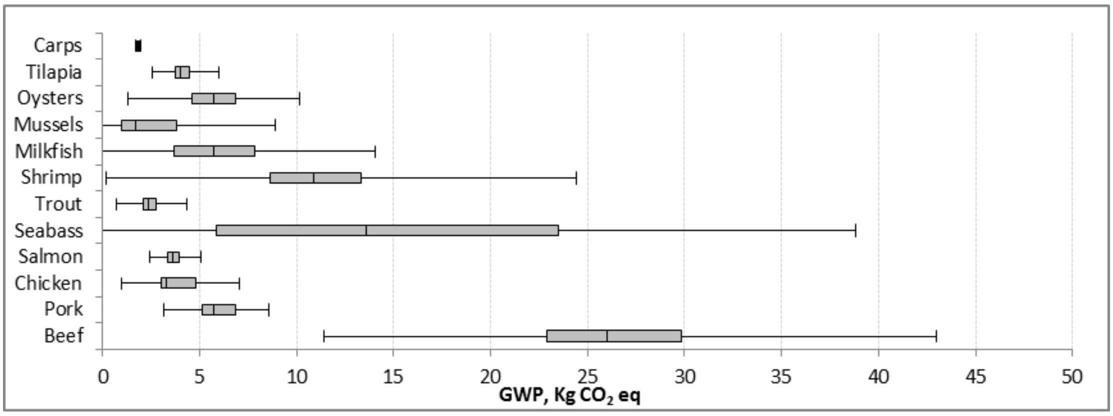


Figure 6.10 Global Warming Potential for major mariculture, FW aquaculture species and terrestrial livestock. Medians 25% and 75% quartiles, 95% confidence limits

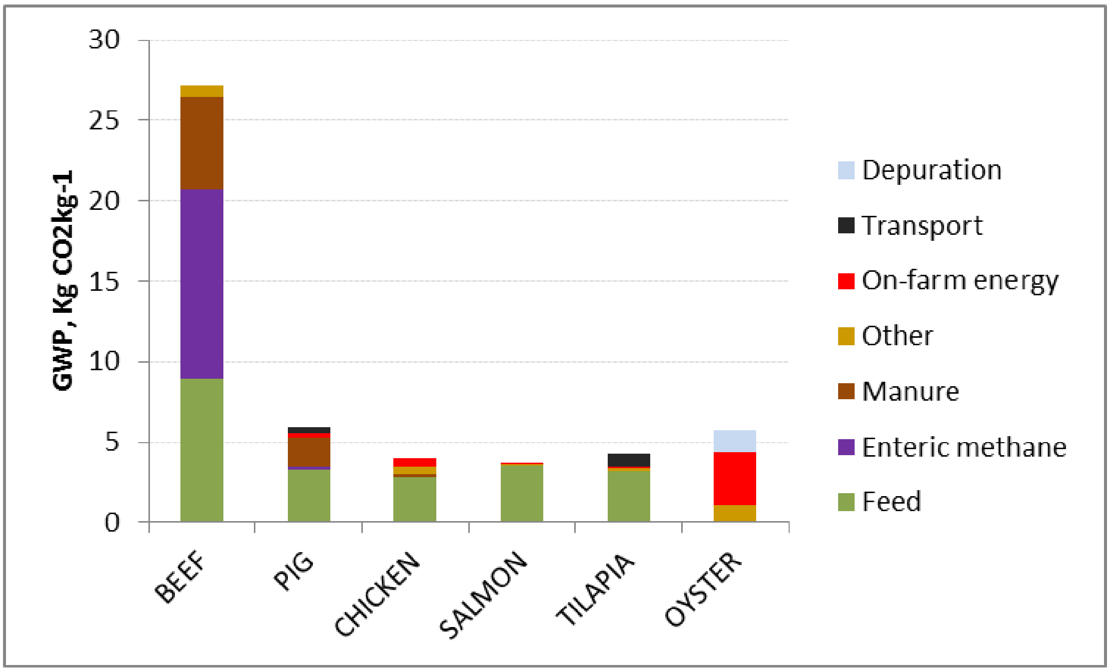


Figure 6.11 Contribution analysis to GWP of selected aquaculture and terrestrial livestock species (Sources: totals are from this study, contributions extrapolated from: Pelletier *et al* 2010a, 2010b, 2009, Mungkung *et al* 2013, Leinonen *et al* 2013, Fry, 2012[24], Nguyen *et al,* 2010)

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24 The 'on farm energy' shown for oysters relates to farm operations during the cultivation and harvesting of the oysters, which included bagging, grading and washing (but not depuration which is shown separately). Hence this energy represents the electricity and fuel used to power and fuel the specialist equipment required for those operations such as seawater pumps, conveyors and grading machines. The outputs are based on data from three oyster farms (Fry, 2012).

6.4.5 Acidification

Acidification is linked to sulphur dioxide emissions from energy provision through fuel combustion, nitrogenous emissions from fuel combustion and agricultural processes from field management, which lead to the high variability seen in Figure 6.12.

In the case of shrimp which has a huge amount of variation, a high energy demand can arise from the use of on-farm aeration powered either by diesel motors or by electricity depending on the location and the infrastructure of the farm.

The range of production intensity also leads to various levels of aeration, other infrastructure and feed inputs. High feed conversion ratios, using energy intensive feeds also can lead to high acidification. The variation also arises from the feeding processes that use large amounts of unprocessed feed stuffs such as rice and wheat brans associated with nitrogenous releases from the soil and fertilisers.

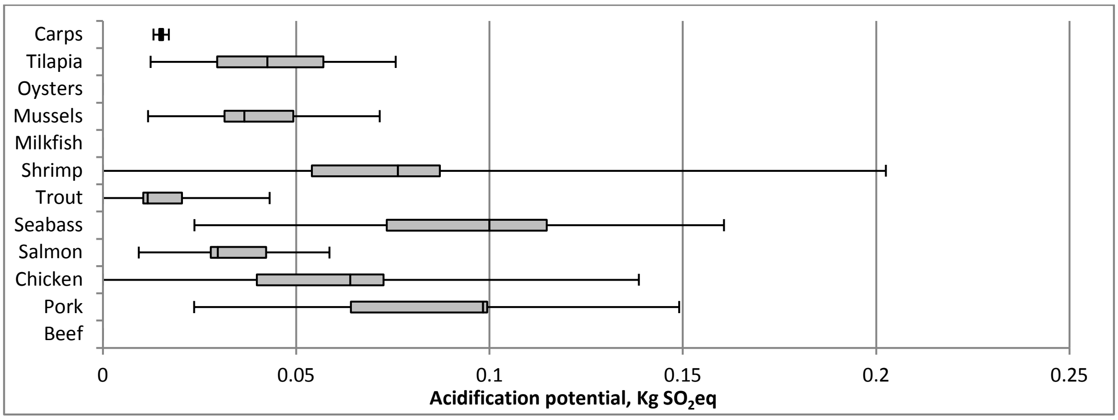


Figure 6.12 Acidification potential for major mariculture, FW aquaculture species and terrestrial livestock. Medians 25% and 75% quartiles, 95% confidence limits. No figures could be obtained for beef or milkfish

6.4.6 Eutrophication

The results for eutrophication were highly varied as can be seen in Figure 6.13. This is especially so for shrimp and for sea bass which both had very high ranges. For shrimp extensive systems such as those in Bangladesh and Vietnam can sometimes act as a sink for nutrients, in which case negative eutrophication can occur (Henriksson *et al* 2014b), in contrast to much more intensive systems with low water exchange where the build up of sediment can cause water quality problems. For sea bass excessively high eutrophication potentials were related to pumped on-shore raceway systems in Tunisia (Jerbi *et al* 2012) which had high rates of uneaten feed. The eutrophication was also relatively high for tilapia and carp which may be related to poorer feed conversion performances on small scale farms in Indonesia (Mungkung *et a*l 2013). The best performers were chicken, mussels and milkfish. Mussels, as non-fed species, had the lowest eutrophying emissions and may be considered as net removers of nutrients overall as they remove large quantities of phytoplankton. However, in certain circumstances, they can add to localised impact because they deposit pseudofaeces, when in normal circumstances the suspended nutrients may be dispersed by prevailing sea currents. No data was available for oyster production.

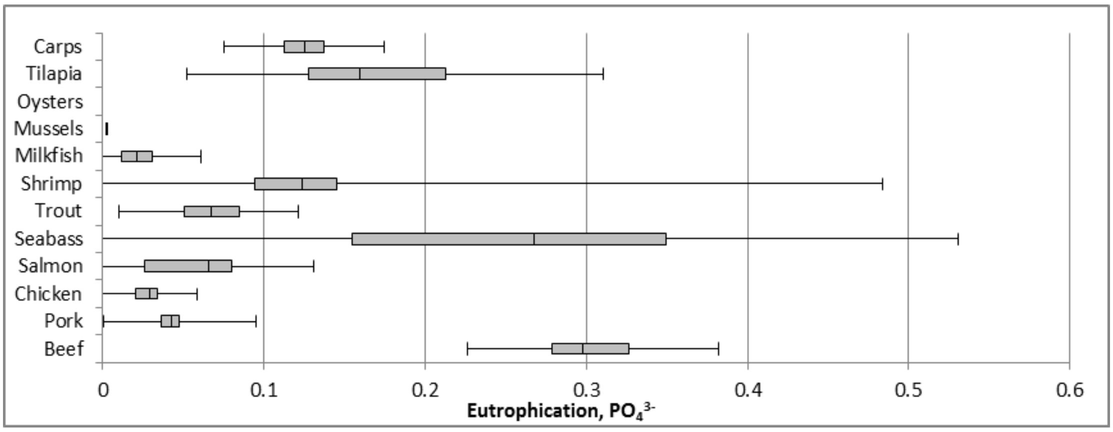


Figure 6.13 Eutrophication potential for major mariculture, FW aquaculture species and terrestrial livestock. Medians 25% and 75% quartiles, 95% confidence limits

6.4.7 Fish In Edible Yield Out

The Fish In Edible Yield Out (FIEYO) ratio for major fed species can be seen in Figure 6.14. Although fishmeal and fish oil is commonly used in terrestrial livestock feed, only one chicken study could be found that included fishmeal in the diet (at less than 1%). No pig study could be found that included fishmeal although it is still used extensively, especially in weaner[25] diets to increase survival. It is likely that fishmeal will continue to be used in livestock diets for other species apart from aquaculture because of high digestibility and lower mortality. In Vietnam it is common to use the by-products from pangasius catfish (*Pangasiadon hypophthalmus*) in pig and other livestock diets (Newton *et al* 2014) although according to major certification and IFFO RS methodology, this would be discounted from the FIFO calculation. In contrast, Pelletier and Tyedmers (2007) and Pelletier *et al*, (2009) discourage the use of fishery by-products because of the high embodied energy within them.

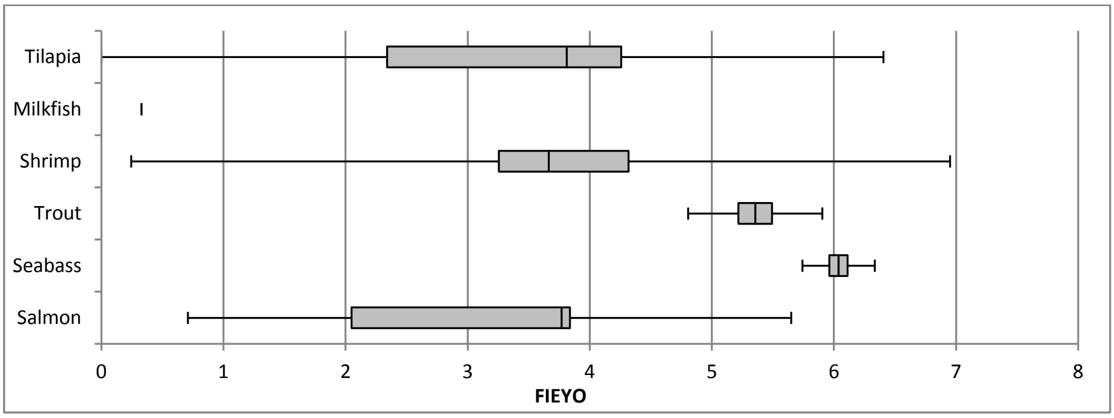


Figure 6.14 Fish In Edible Yield Out ratio for major mariculture and FW aquaculture species. Medians 25% and 75% quartiles, 95% confidence limits. The FIEYO is related to edible yield out according to FAO 1989 and not total live weight FIFO which is most common

25 A animal weaned in the current year

LCA generally handles the use of biological resources quite poorly as it is difficult to relate the particular sensitivity of a resource, as it only reports in general terms at a global level. Fishmeal from reduction fisheries is at its sustainable limit and over-exploited in some cases. There still remains some room for expansion from fishery and aquaculture by-products although economic and logistical issues also need to be considered. For example, many fishing boats dispose of viscera and other by-products at sea because they are of low value and highly perishable. In order to utilise them, storage that could be used for saleable catch would need to be used or hazardous solutions such as ensiling may need to be employed. In any case, if all of the approximately 90 million tonnes of global fisheries and aquaculture production was fully processed and all of the by-products directed to fishmeal, this would only amount to around 10 million tonnes of fishmeal yield.

Figure 6.15 Sorting Pangasius by-products before reduction to fishmeal (Source © Richard Newton)

An estimated 33% of the 5.5 million tonnes of fishmeal produced already comes from by-products and therefore only an extra 8 million tonnes could be obtained. Clearly this is not adequate to sustain the levels of fishmeal in aquaculture and livestock diets at their current levels in the long term. It is also unrealistic for many cultures which have different and perhaps more efficient fish consumption patterns such as China and parts of south east Asia which tend to buy fish whole and often live, and consume much more of the animal than in Western countries. However, the extra inputs from live transport associated with the water and oxygen required may well negate any benefits. Little work has been done on these aspects and there is also little information on the levels of “plate waste” from fish consumption in any society. Attitudes to fish consumption may change as convenience and price become more important issues, but in the short term it should be a priority to fully utilise the by-products from processing that is already in operation. The strong consumer preference for whole fish in some areas results in far less by-product made available for value addition and therefore only an estimated 2.5 million tonnes of fishmeal may be obtained if the infrastructure investment could be made to utilise the resource. Although a considerable amount, it still falls short of that which would be required for various aquaculture and livestock projections at the current rate of growth (see Section 7). However, China is most in demand for extra fishmeal and it also has the greatest opportunity for directing more seafood product to processing and creating by-product opportunities. As more producers become more vertically integrated, this may provide the driver for this change along with well-targeted and marketed seafood products for domestic and export markets.

Figure 6.16 Fish market, Korea (Source © John Bostock)

No attempt was made to distinguish between fish input sources because only some papers supplied this information. The high variation in salmon FIEYOs, despite a consistent FCR, are reflective of a high range of fish inclusions, whereas variation in shrimp diets are more concerned with the variable FCR.

In global terms, salmonids, marine fish and shrimp consume the larger share of fishmeal although freshwater fish do account for a large proportion of the total supply. For example, carp diets generally do not include large quantities of fishmeal, although the small inclusions in carp diets do account for a large proportion of global supply because of the greater production volumes of carp. The inclusion of fishmeal in tilapia diets is very varied depending on location, with as much as 15% inclusion in China in some feeds. The best performer was milkfish, for which only one data point was obtained, but had a fish inclusion of less than 1% of diet.

For Atlantic salmon the figures in Table 6.3 are largely out-dated with fishmeal and fish oil inclusions each in the region of 20% to 25% and vegetable proteins making up to 30%. Updated values are hard to obtain due to commercial sensitivities around fish feed production. Issues surrounding fishmeal use are well documented (E.g. Naylor *et al* 2009. Alder *et al* 2008) and it has been the trend to replace fishmeal with vegetable based alternatives such as soymeal and fava beans. However, the majority of the supply of soybean to the EU is from South American production. Therefore, there is a trade-off between impacts in sensitive habitats either in the marine or terrestrial ecosystems with regard to food webs and land use that can affect a broad range of biodiversity issues, which is discussed further in Section 7.

Discouraging the waste of valuable by-products from agriculture and animal processing could help to alleviate some of the burdens experienced in these ecosystems. The EU recently allowed the use of monogastric animal by-products in fish feeds (EC 2013) after a ban of more than a decade in response to the BSE crisis of the 1990s and early 2000s and there is now extensive research into the transformation of wastes to valuable feed resources through insect larvae (Barroso *et al* 2014). How widely these ingredients will be accepted by different sectors of the industry is not known. Currently there is significant resistance to the use of terrestrial livestock by-products in European production from retailers, although the producers themselves may push for a relaxation in the face of competition from outside the EU by producers who do use them and export their products to the EU. Insect products may be widely accepted by the retailers, however, difficulties in producing insect protein of consistent quality and quantities may still remain a challenge in the short to medium terms at least. Lack of consistency is likely to result in lack of uptake by major feed manufacturers, although it remains an option for small scale producers seeking to provide supplementary feeds in locations where waste stream management can be optimised and smallholder farms dominate such as Bangladesh.

Figure 6.17 Black soldier fly larvae produced for tilapia feeds, Ghana (Source © Richard Newton)

Lower omega-3 fatty acid levels within the final product have resulted from decreased dietary fishmeal and fish oil inclusion and it is now recognised that with current technology, the limit to which fishmeal and oil can be replaced in the diets of particularly early stages of marine fish without affecting the performance has been reached (Shepherd and Jackson 2013). Therefore there are other issues at stake, including the human health benefits of the final product, its economic value and not least the welfare of the carnivorous animals being cultured on "unnatural" vegetarian diets. Recent work on GM production of false flax (*Camelina spp*.) containing omega-3 fatty acids may help to address the increasing fish oil shortage (Betancor *et al* 2015), of which over 80% is directed to aquaculture, and improve the final product. However, the performance of carnivorous fish fed on increasingly vegetarian diets may be more complex. Fish breeding programs have often been concerned with growth performance as well as disease issues and flesh quality, but matching the nutrition research objectives alongside breeding programmes that improving fish responses to changing diet formulation has not been a high priority.

6.4.8 Summary of LCA of Mariculture and Livestock Production

- It is clear from the results presented here that the worst performer for GWP, land and water use is beef, although the results must be tempered by the caveat that a full weighted study combining LCAs of global systems was not possible because of lack of data and incompatibility of data in some cases. Having said that, this report is in broad agreement with other similar studies such as by Nijdam *et al* (2012). The analysis does not go into details regarding all of the co-products from the various species and systems. For example, the supply of leather, gelatin and other by-products of cattle production are not included which are well established markets and add to the efficiency of beef production;
- Aquaculture production systems are extremely diverse compared to terrestrial livestock production. Much of the world's aquaculture is produced in polyculture where different species perform different functions in balanced systems. In these systems it is difficult to assess which species is contributing to what proportion of impact and the system should be regarded as a whole;
- The situations regarding land and water use are also very complex. With regards to land, its suitability for different production systems is not certain and cannot easily be converted to uses which are perceived to be more productive, e.g. converting pasture to crop production. In the case of water, aquaculture species in freshwater systems may be dependent on water for environmental services, but the water may not be consumed. Despite being grown in marine water, mariculture species still have a heavy dependence on freshwater for the provision of feed which is made from crop ingredients that have required extensive irrigation in some circumstances. Hence marine species may consume more freshwater than freshwater species because of this dependence on feed. As many other LCAs have stated, it is the efficient use of feed which directly determines the overall efficiency of fed species and this should be the focus of improving the environmental performance of all such species;
- With regards to shellfish, the situation is more complicated. Although they are not fed species, they often require a lot of energy for their servicing, including harvesting, processing and depuration, particularly in areas of poor water quality where more depuration is required. Unfortunately, these areas are the ones where growth has been largest and where demand is likely to increase further such as in East Asia. More research into better depuration efficiency could significantly improve the performance of these species, alternatively only using pristine sites would also improve their performance, but might incur greater impacts on biodiversity and through transportation. Apart from the impacts from shellfish processing, which this report has not included, the requirement for freshwater and terrestrial land space for shellfish species is minimal; and
- Although fishmeal from forage fish is at its limit, the quantity used overall by aquaculture is not increasing despite the growth in aquaculture production. Increasing amounts of fishmeal are coming from by-products and there is significant opportunity to continue to increase this supply from both capture fisheries and aquaculture processing. Careful direction of these resources to where they are most nutritionally

efficient, in terms of both the cultured aquatic and terrestrial animals and for the humans who ultimately consume them should be a priority. Despite obvious concerns over the effect of overfishing for fishmeal, in other environmental impact categories, it is comparable or better than other feed ingredients, including vegetable sources.

6.5 LCA of Major Feed Ingredient Inclusions

As described in Section 6.4, the majority of LCA impacts arising from the production of species assessed relate to the production of their feed. As such, this section undertakes an LCA comparison of the major feed ingredients (sunflower, rapeseed, maize, wheat, soybean meal and fishmeal) included in the diets of the species assessed.

6.5.1 Land Use

Land use for crops is intrinsic to that of fed aquaculture as described above. Despite ecological considerations raised in several high profile publications, fishmeal from marine sources has a clear advantage in this respect, from a life cycle perspective, as the only land which is required is that needed to service the fishing boats and to process the fish into fishmeal and fish oil. These are negligible compared to the land required to grow vegetable proteins and oils which are commonly regarded as substitutes for fishmeal inclusion. Figure 6.18 shows that maize is clearly the best performer with regards to land use with sunflower as the worst performer.

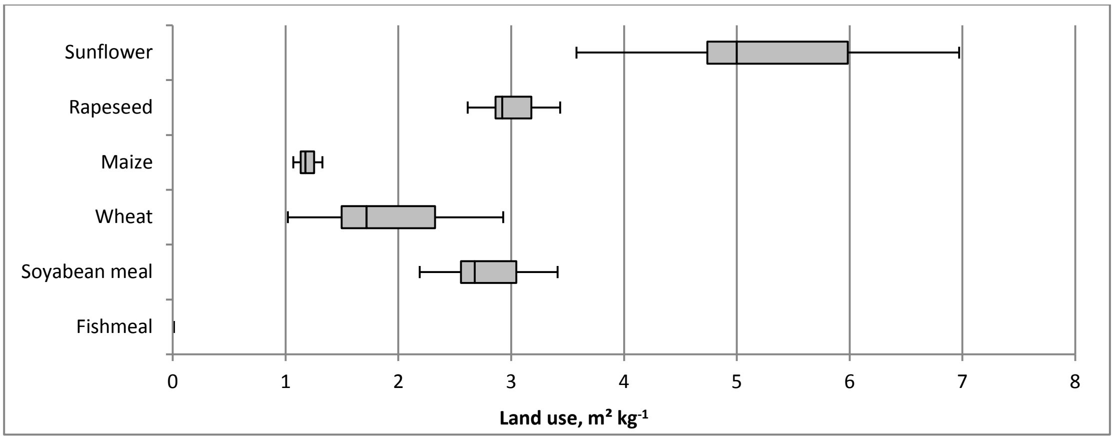


Figure 6.18 Land use per kg of grain or fishmeal produced. Medians 25% and 75% quartiles, 95% confidence limits

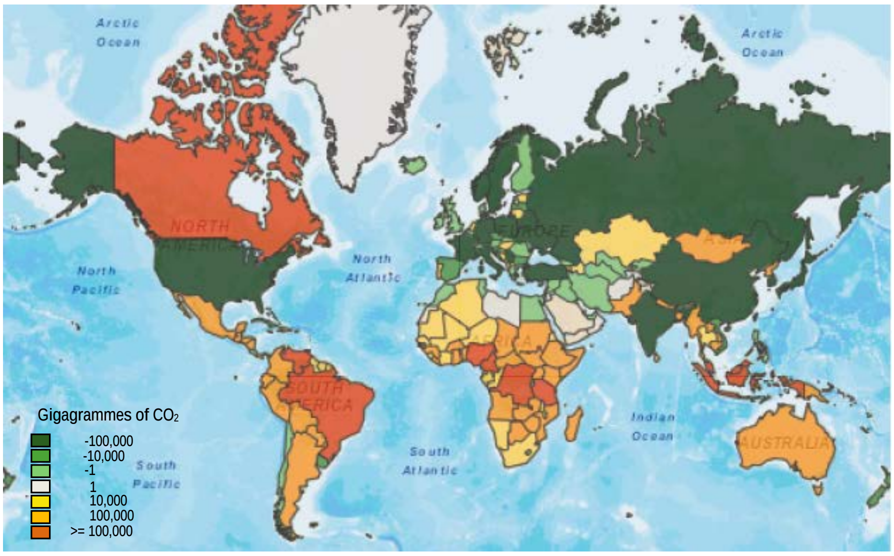
No LUC category has been included in this report because of the issues raised concerning generalizability and subjectivity (see Section 6.2.1.3). However Table 6.5 shows the major crop producing countries ranked by land used for production of the six major feed ingredients shown in Table 6.3, the five year change in land allocated to those crops and the percentage of each countries land mass devoted to their production. The quantity of land devoted to crop production has actually shrunk in the USA which still has the largest area of crop production overall. This is due to a reduction in wheat and especially sunflower production, but may also be because of continuing improvements in yields. The Ukraine has seen the largest increase in the percentage of its land which is devoted to crop production but in absolute land area, Brazil followed by India has had the biggest increase. This is particularly worrying for LUC in terms of habitat loss and CO_2 sequestration services that may be offered by Amazonian rainforest for example.

Figure 6.19 shows the GHG emissions which have been associated with land use change over ten years from 2002 to 2012 according to FAOSTAT[26]. It can be seen that much of the CO_2 emissions are associated with LUC in highly forested equatorial regions of South America, Africa and SE Asia where concerns over habitat loss are of particular concern. By contrast some more developed nations have well managed forestry and have embarked on replanting schemes to replace that lost previously.

Table 6.5 Ranked top 10 producers by land occupation for six key feed ingredient crops (maize, wheat, soya bean, rapeseed, sunflower seed and dry pea), showing land use in 2013 and the change from 2008

Country	Land Used for Crop Production, 1000s km²	5 yr Change in Land Used, 1000s km²	% of Country Land Mass Used, 2013	Largest Product by Volume
USA	861	-2.14	9.4	Maize
China	753	42.0	8.1	Maize
India	591	50.5	20.6	Wheat
Brazil	455	73.0	5.4	Soy
Russia	358	0.23	2.2	Wheat
Argentina	292	24.4	10.7	Soy
Canada	231	25.5	2.5	Wheat
Ukraine	191	31.8	34.5	Wheat
Australia	161	4.42	2.1	Wheat
Kazakhstan	143	6.03	5.3	Wheat

(Source: FAOStat - accessed 10/3/2015; Land areas from Wikipedia.com - accessed 10/3/15)



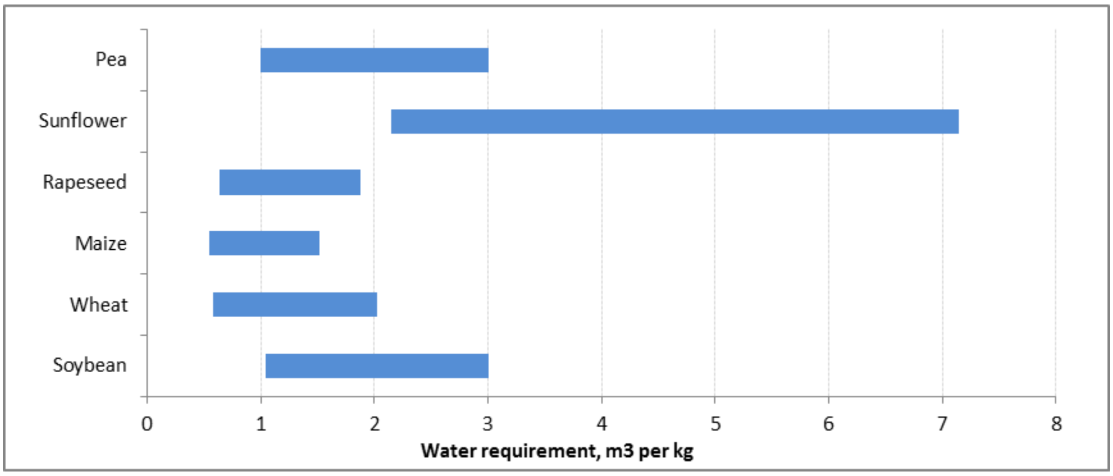
(Source: FAOSTAT 2015)

Figure 6.19 GHG emissions associated with LUC, average per annum 2002 to 2012.

26 Accessed 6/3/15.

6.5.2 Water Use

The water consumption from individual LCA studies has generally not been reported well and in many cases it has been difficult to distinguish the source of the water provision. In most cases the water consumption is reported as only that provided by irrigation which offers little insight as water availability is extremely varied from country to country and catchment to catchment. Generally the requirements of a particular crop will vary according to the soil type and the evapo-transpiration rate. The FAO supplies data on upper and lower limits of water requirements based on these factors in terms of mm of rainfall required. This has been extrapolated to give cubic metres of water requirement per kg of grain produced based on upper and lower limits of yield per hectare production (Figure 6.20). These figures are broadly in agreement with Mekonnen and Hoekstra (2011 and 2014), who published global values for blue, green and grey water footprints for some major crop commodities in different regions.

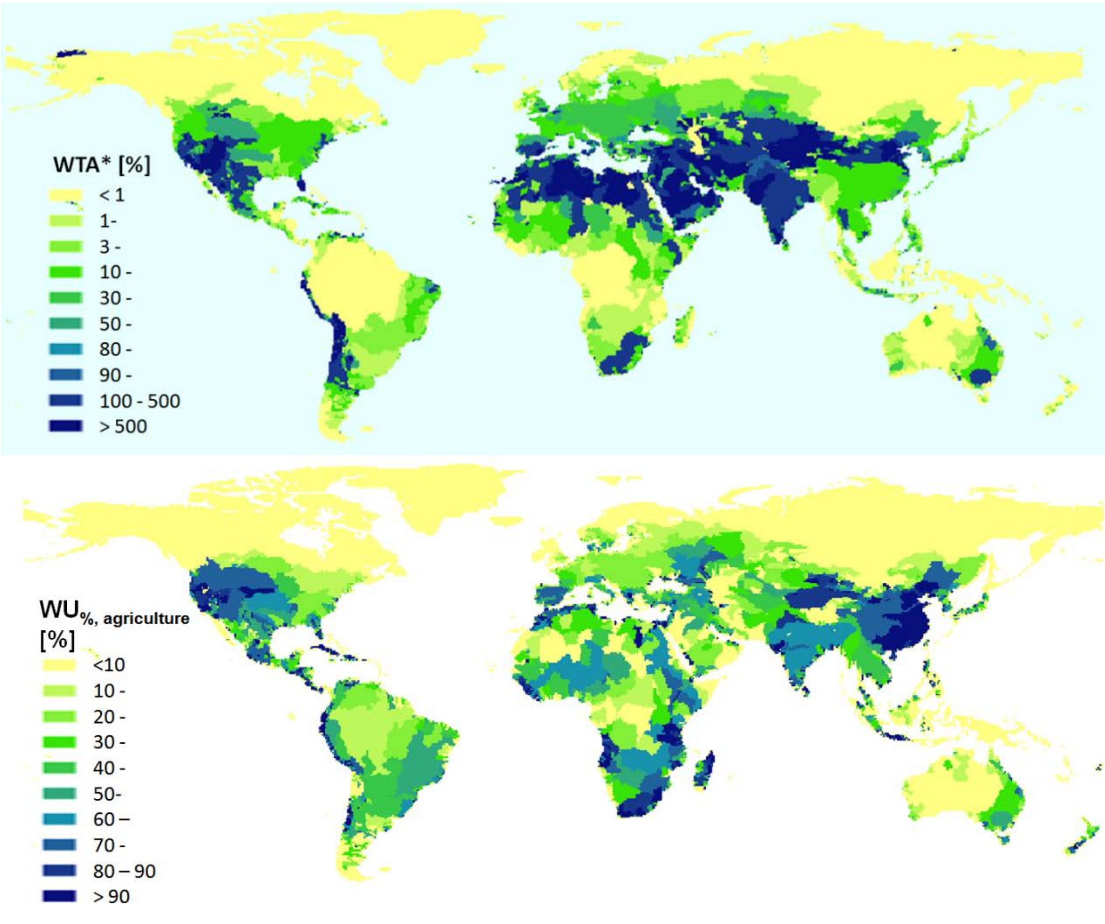


(Extrapolated from Brouwer and Heibloum. 1986, Dalgaard *et al* 2008, Hererra Huerta *et al* 2012, Wang *et al* 2014, Williams *et* a 2010l, Murphy and Kendall, 2013 Goglio *et al* 2012, Irriarte *et al* 2010, Spugnoli *et* a 2012 , Spinelli *et al* 2013, Schmidt, 2010 , Felten *et al*, 2013)

Figure 6.20 Water requirements (all sources) per kg of crop grain yield

It can be seen that all crops are in a similar range except for sunflower which requires substantially more water per kg production. This may partly explain the decline in production in the USA, especially when viewed in regards to Figure 6.21. Figure 6.21a shows the global water scarcity factor, WTA* (given by Pfister *et al*, 2009) as the water availability to withdrawal ratio multiplied by a variation factor based on variations in global precipitation patterns) and 6.15b shows the percentage of water use that is devoted to agriculture. According to Pfister *et al* (2009), severe water stress starts to occur at WTA* of above 40%, which can be seen in large agriculture producing areas of the USA, central and southern Europe and Asia, northern and southern Africa. Water stress in India is of particular concern with its high population and rapidly increasing agricultural output. Some areas are withdrawing well in excess of the annual recharge rate which could lead to saline intrusion. Salinization has been linked with declines in crop production yields as well as degradation of pasturelands according to FAO (2006). However, there is still room for huge savings in water efficiency through better irrigation and wastage in many locations. According to FAO (2006), irrigation efficiency remained at below 50% in many water scarce, population dense, high crop production areas such as South Asia.

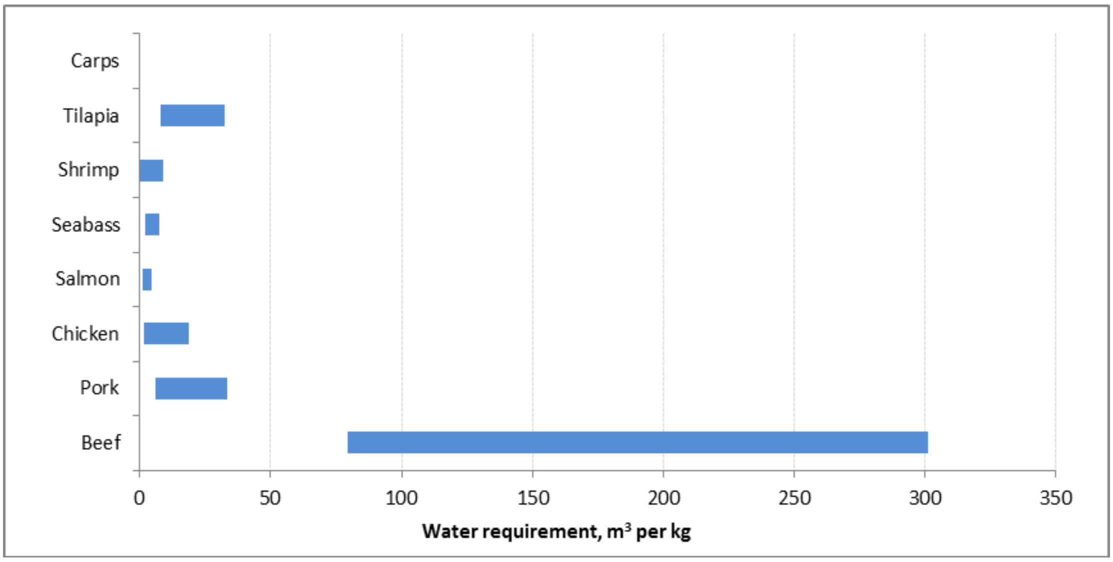
The water requirement figures for crops have been extrapolated to give a total water requirement for fed livestock and aquaculture species (per kg edible yield) as shown in Figure 6.22. However, it is important to note that the requirement is based purely on the provision of crop grain and does not include any water required in the processing of the crop or that required in feed formulation which can be substantial in some circumstances. Therefore the figure relates particularly to the feed conversion ratio and the composition of feed. As such, species with high fishmeal inclusions perform better compared to species which rely solely on water intensive crops. This can be seen when comparing salmon to tilapia, where salmon has relatively low FCR and lower inclusion of vegetable ingredients in its diet (see Figure 6.22).



a) Global water scarcity factor (WTA*) showing areas of high water extraction compared to availability; and
b) % Water used for agriculture. Both figures are based on catchment at 10km resolution.

(Source: Pfister *et al* (2009) supporting info)

Figure 6.21 Total water requirement for fed livestock and aquaculture species (per kg edible yield)



(Extrapolated from: feed compositions given in Table 6.3; yFCRs in Figure 6.5; and crop water requirements in Figure 6.14)

Figure 6.22 Water requirements per kg edible yield of major fed mariculture, FW aquaculture and terrestrial livestock species

The total estimates of water requirements presented in Figure 6.22 are somewhat higher than the global weighted averages from Mekonnen and Hoekstra (2012) although most of their figures fall within the lower range of our projections. The figures for beef in Figure 6.22 are much higher and this may be because of different assumptions used in the extrapolation from crops used in feed-lot systems as opposed to pasture-raised beef. The figures used in the current analysis were taken from an FAO report from 1986, and it is possible that efficiencies have improved, but similarly, feed conversion efficiencies for animal products and some other assumptions used by Mekonnen and Hoekstra (2012) were taken from Hendy *et al* (1995) who based some of their conversions on "guestimates", which have also been improved upon. However, whereas our calculations are based purely on feed-lot systems, Mekonnen and Hoeksta's (2012) show a higher water footprint for grazed animals than industrially produced, in which case their total water footprint should be higher than ours. Figures given for pork and chicken by Mekonnen and Hoekstra (2012) are within the ranges shown in Figure 6.22 but towards the lower end at 5.99 m^3 and 4.33m^3 per kg of meat respectively. Despite this, it can be seen that comparatively, beef is still the worst performer by several fold, which is in agreement with Mekonnen and Hoekstra (2012).

The water footprint for salmon is higher than that given by Auchterlonie *et al* (2014) at 2.36m^3 in the current analysis compared to 2.05 m^3 per kg of fillet, however Auchterlonie *et al* (2014) used a slightly different diet composition with more fishmeal but a lower fillet yield than this study.

6.5.3 Global Warming Potential

The GWP for fishmeal and major crop species used for feed ingredients is shown in Figure 6.23. There are wide ranges reported and this may be due to location as well as methodological choice. Large amounts of GHG may be emitted by soils depending on how they are managed and the types of fertilisers used. Variation in the GWP in fishmeal production is due to by-products coming from various different species in different locations and how the upstream impacts are attributed. Almost all of the data for fishmeal came from supporting information from Pelletier *et a*l (2009).

It can be seen that in terms of GWP, most ingredients are within the same range except for maize and to some extent rapeseed which are have lower GWPs than the other ingredients. However, it should be noted that ingredients such as gluten from maize and wheat are especially energy intensive with impacts higher than that of fishmeal (Pelletier *et al* 2009). No specific publications could be found for the production of maize or wheat glutens although US maize gluten has a GWP of over ten times that of Peruvian fishmeal per kg using economic allocation from the Ecoinvent 2.2, database.

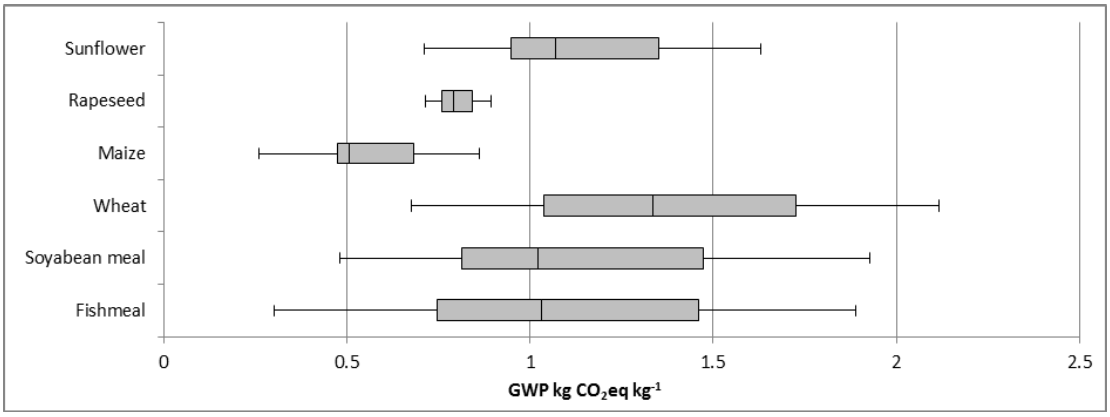


Figure 6.23 GWP per kg of fishmeal and grain for major crop species contributing to livestock feeds. Medians 25% and 75% quartiles, 95% confidence limits

6.5.4 Acidification and Eutrophication

These impact categories for feed ingredients are more variable than the previous impact categories with wheat having high acidification impacts but low eutrophication impacts and soyabean meal the inverse of this, compared to the other terrestrial crop ingredients (Figures 6.24 and 6.25). The production of maize is extremely varied in its eutrophication impacts especially, which is mainly due to contrasting results from China and the USA, due to excessive fertiliser use in some Chinese systems (Wang *et al* 2014). This could be for many reasons, including different types of fuel use, different agricultural practices, such as fertiliser application and tilling, or soil types that release various nitrogenous gases during their management. The global variations in production and many factors involved make it very difficult to determine what is representative of global crop production and then to extrapolate those to a representative overview of aquaculture and livestock production. This can be seen for acidification especially in Figure 6.24 where there is a huge range of values within different species.

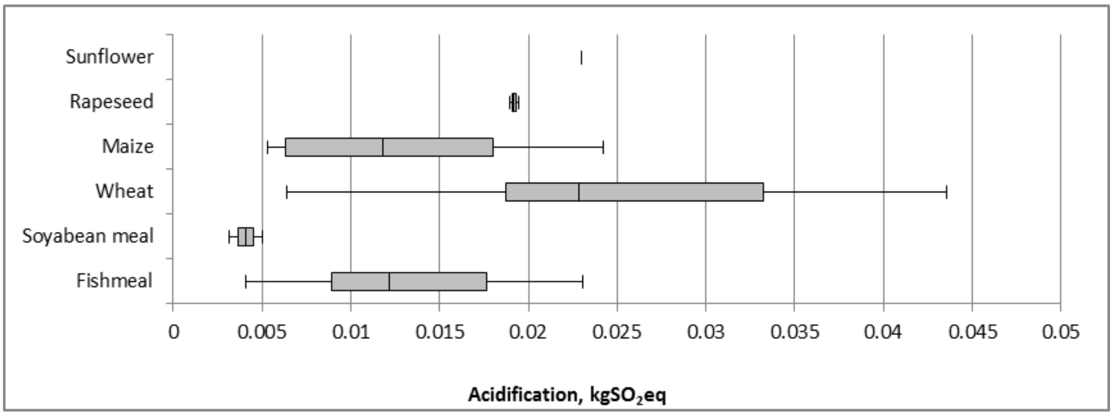


Figure 6.24 Acidification potential per kg of fishmeal and grain for major crop species contributing to livestock feeds. Medians 25% and 75% quartiles, 95% confidence limits

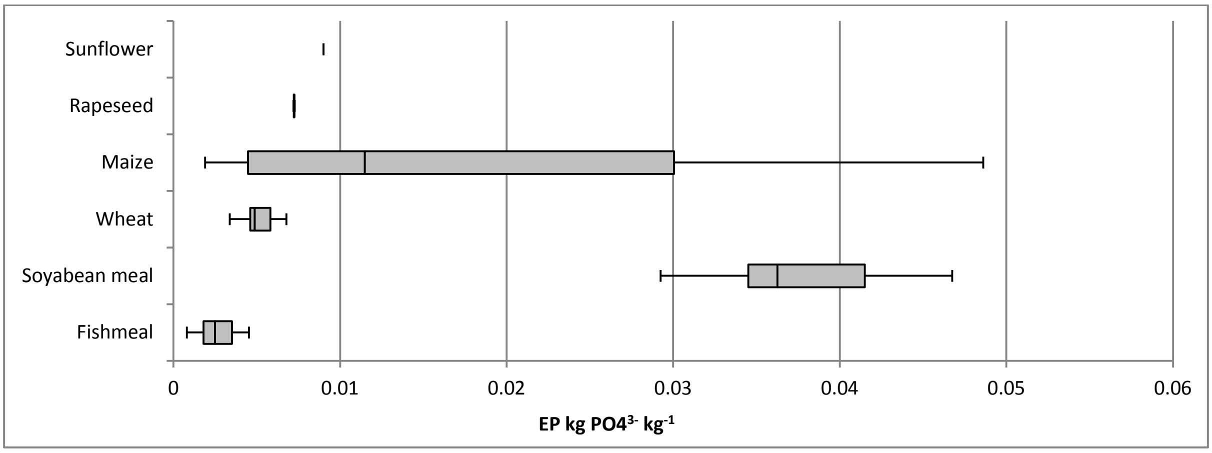


Figure 6.25 Eutrophication potential per kg of fishmeal and grain for major crop species contributing to livestock feeds. Medians 25% and 75% quartiles, 95% confidence limits

6.5.5 Summary of LCA of Major Feed Ingredient Inclusions

- Although mariculture has been proposed as a potential solution to limited available land resources for further expansion of terrestrial livestock production, due to the inclusion of land-based crops within feed for mariculture and freshwater aquaculture species, mariculture production is still intrinsically linked to land-use.
- For this reason, with regard to land use impacts, the use of fishmeal in mariculture feed is advantageous, although it is associated with other ecological impacts and considerations as described in Sections 3 and 7;
- The largest absolute area of land used for crop production (including those used in livestock and aquaculture feed) is in the USA, China, Brazil and India and the highest

levels of GHG emissions related to land use change (although not necessarily related to crop production) occur in highly forested equatorial regions of South America, Africa and SE Asia.

- Based on the water requirement for the production of the crops used in livestock and aquaculture feed, the general composition of feed for each species produced and the species FCR, the results indicate that species with high FCRs and diets with higher fishmeal to vegetable ingredients necessarily have less impact on water use;
- GHG emissions for all feed ingredients were similar, although the results suggested that emissions related to maize and rapeseed production may be lower than the other products compared. Wheat, and the further processing of maize to produce gluten had a higher GWP compared to that of fishmeal;
- Acidification and eutrophication impacts were extremely variable for all feed ingredients, although the results suggested that the eutrophication impact of fishmeal production was clearly lower compared to that of most other terrestrial crops
- Overall, this analysis shows that efficient use of feed is the key to reducing environmental impacts of most aquatic and terrestrial species.

6.6 LCA of Mariculture for Energy

According to the EIA (2013) the petroleum industry is responsible for the largest proportion in growth of liquid transportation fuels, which grows on average at about 1.1% per annum and the largest proportion of this growth is occurring in developing nations with immature transport sectors. Although, the number of vehicles globally is likely to continue to increase with emerging middle classes in developing nations, the quantity of fuel required will not rise in parallel as engines become more efficient and vehicles become lighter with improved designs and technology (Sachs, 2007). Consequently, fuel consumption for transport in OECD countries is projected to decline but could double in non-OECD countries by 2040 (EIA, 2013). China continues to urbanise and improve its transport network with the number of cars quadrupling in the first decade of the millennium. However, it too has invested significantly in new energy vehicles, offering large subsidies on them and imposing limits on vehicle numbers in major cities in an effort to reduce overall emissions (EIA, 2013). Growth has been slower in other non-OECD countries but this may change as emerging economies such as India improve their transport networks (EIA, 2013). Overall, the EIA (2013) has projected that demand for liquid fuels may increase by nearly 40% by 2040 from 2010 levels. The USA continues to be the largest producer of biofuels and has seen the largest growth in volume over the last five years (Table 6.6). Brazil is the second largest producer but growth has stagnated. Together the USA and Brazil represent almost 75% of the world's biofuel production in 2012 (EIA, 2015).

A review of energy production from mariculture was given in Section 5 for microalgae and macro-algae production systems. It is clear that not only are there many different species of micro-algae being cultured for energy production but that the systems are also extremely diverse. The vast majority of studies are of laboratory or pilot-scale operations with little commercialisation, mainly because of the high investment required but also because the pilots suggest efficiencies are erratic. Whilst marine biofuels vastly reduce the freshwater consumption of terrestrial biofuels, they may require more specialist equipment to cope with the corrosive nature of sea water, especially with regards to micro-algae (Razon and Tan, 2011).

However, in many respects, the processes and challenges regarding marine and freshwater micro-algae diesel production are the same.

Table 6.6 Top ten producers of biofuel (all feedstocks) by volume and percentage growth between 2008 and 2012. Thousands of barrels per day

Country	2008	2012	% of World Production 2012	5 Year % Increase
USA	649.68	939.56	49.42	44.62
Brazil	486.35	449.20	23.63	-7.64
Germany	65.00	68.07	3.58	4.72
China	39.40	58.90	3.10	49.49
Argentina	14.10	52.20	2.75	270.21
France	50.40	49.70	2.61	-1.39
Indonesia	2.20	37.91	1.99	1623.24
Canada	16.70	36.30	1.91	117.37
Thailand	13.40	23.63	1.24	76.31
Columbia	5.80	17.00	0.89	193.10

The main differences in production relate to the use of pond systems, photo-bioreactor systems or combinations of the two for micro-algae compared to raft systems for macro-algae. Also, micro-algae is mostly concerned with the extraction of lipid content for biodiesel sometimes in conjunction with anaerobic digestion for biogas, whereas macro algae is more concerned with ethanol production from fermentation of polysaccharides, also in conjunction with anaerobic digestion. The number of species multiplied by the different technologies reveal a vast number of options and there are also trade-offs between, for example, yields of lipid vs. biogas and other co-products which can be achieved (e.g. Taelman *et al* 2014). On that basis, the distinction between the production of energy from micro and macroalgae are too complex to report them all individually, based on the variations of species and systems used (especially for micro-algae).

This section aims to highlight the various efficiencies of production as well as other resource use such as land and water utilisation compared to terrestrial biofuel production. However, the results reported are highly varied. This may relate to the differences in production but also the system boundaries and assumptions made by LCA practitioners who may not be familiar with technology innovations in an emerging industry (Slade and Bauen 2013). Many of the studies have been conducted on laboratory or pilot-scale production and some based purely on theoretical computer based modelling. Moreover yields and return on investment claims made by the industry have also been optimistic. As micro-algae can produce multiple outputs, how the impacts are partitioned between them is also of considerable influence when presenting the results. Most micro-algae studies have only presented results for biodiesel with little mention of how the co-products such as biogas or livestock feeds are treated and the allocation of impacts to them, which could greatly affect the overall efficiency of the production system. Many of the results have also been presented as "well to wheel" that is they assess the performance of the fuel in vehicles rather than demonstrating the energy content of the fuel and associated efficiencies. In this report, where, possible, the results have been presented as impacts associated with 1MJ of total fuel output, biodiesel or ethanol for micro-algae or macro-algae respectively, together with methane from anaerobic digestion in both cases. This is the most consistent approach to dealing with multiple fuel outputs from the system where methane is rarely used as a transport fuel. However, the lack of clarity and consistency within the LCA reporting has severely limited the number of usable studies for this report.

The results from LCA studies are highly focussed on energy efficiency and GHG emissions and as such, very few of them report other considerations such as acidification or eutrophication, despite the possibility of reducing overall eutrophication by absorption of nutrients. Data for energy production from algae is not often presented in the same format as for food or other products. As the focus is generally on energy efficiency, results often focus around the energy balance i.e. energy content of the fuel minus or divided by the energy inputs of production.

However, in many locations macro-algae has a long tradition of being used for fertilisers, fodders, direct human food and fuel. According to Fei *et al* (1999), the technology regarding seaweed cultivation improved considerably during the latter part of the last century enabling huge growth in production. According to Mazarassa *et al* (2014) over 99% of seaweed cultivation occurs in Asia with most grown for traditional food, although a large number of the recent patents for seaweed products have concerned their use in cosmetics and chemical extracts. This is in contrast to the LCA focus which is more concerned with energy provision and bioremediation. A lack of LCA studies which take all of these factors into account has not enabled assessment of the environmental impact of the combined options that are representative of global seaweed cultivation. The number of LCA studies and systems which have been included in this report can be seen in Table 6.7. Whilst it is acknowledged that sugar cane is one of the most commonly used first generation biofuel feedstocks, it has not been included in this LCA analysis as the study has focussed on terrestrially derived crops used as both feed inclusions and feedstock for biofuel production.

Table 6.7 Number of LCA studies (systems in brackets) and methodological choices for biofuel production from mariculture and selected terrestrial crops

Industry	Number of Studies (Systems)	Systems Included	Methodology / FU /Allocation
Micro algae	9(17)	Ponds, race ways and bioreactors.	FU MJ energy, dry weight of algal biomass. Allocation, system expansion and substitution. Economic, mass.
Macro algae	2 (6)	Long-line and bottom planting	FU MJ energy, dry weight of algal biomass. Allocation, system expansion
Maize	3 (10)	Ethanol from fermentation	FU MJ of fuel
Wheat	1 (1)	Ethanol from fermentation	FU Ha production converted to MJ
Oilseed rape	1 (1)	Biodiesel	FU MJ of fuel
Soybean	2 (2)	Biodiesel	FU MJ of fuel and kg biomass converted to fuel. Allocation, economic.

6.6.1 Energy Balance

One of the biggest energy costs to producing biofuel from micro-algae has been highlighted as that of drying algae from the wet slurry prior to lipid extraction (a prerequisite for lipid extraction is that the biomass be dried to 90% of its wet weight (w/w) (Zaimes and Khanna 2013)). Sills *et al* (2012) reported energy inputs for drying at 1.8MJ and Yanfen *et al* (2012) reported it as

59.3% of the energy inputs to the production process, prior to fuel extraction, per MJ of fuel energy content output. The extraction can also be energy intensive according to Sills *et al* (2012) who reported energy inputs for extraction and processing (including hydrothermal liquefaction and transesterification) of biodiesel from wet algae at 1.6MJ per MJ of fuel output. The cultivation process itself can also exert high energy demands for mixing and separation. With the use of cheap, clean, renewable electricity in more efficient extraction processes from wet algae, efficient use of residual algal biomass to produce methane and other valuable co-products, biofuel from microalgae could become more feasible. However, currently in most cases, the high energy demand makes biofuel from micro-algae extremely inefficient economically and energetically (see also Section 5).

In contrast to micro-algae, the major energy inputs in macro-algae biofuel production are at the algae production stage, arising from petrol and diesel fuel use to service the production (Alvarado-Morales *et al,* 2013). The process of fermentation is generally not energy intensive, however, work is still required to make it more economically feasible (see Section 5).

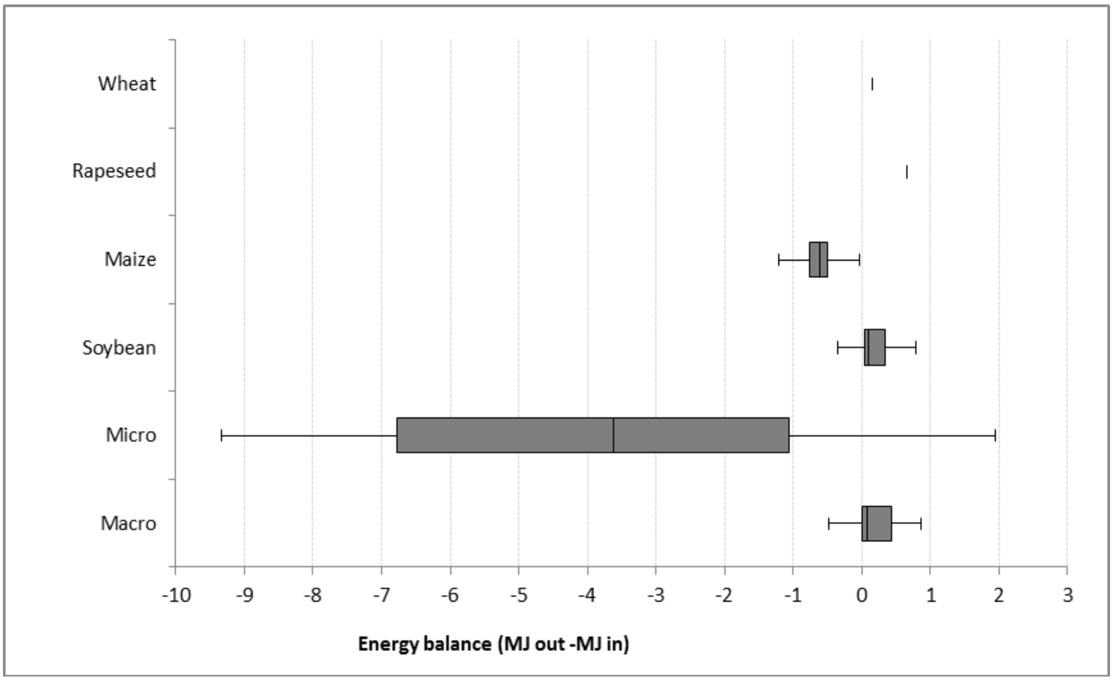


Figure 6.26 Energy balance for marine and selected terrestrial crop biofuel production. Medians, 25% and 75% quartiles and 95% confidence limits where available

Terrestrial crops for biofuels perform much better environmentally and economically and they are well established as alternative fuels in many regions. Many are based on the by-products or the whole of established agricultural crops and therefore there is less innovation required to utilise them and the production of the feedstock for the energy production process is cheap in comparison to micro-algae especially. In addition, the by-products from terrestrial biofuel production such as dry distillers grains with solubles (DDGS) have well established markets, in contrast to the current situation with regards to algal mariculture where yields for biofuels can be low and markets for the other products are not well established, thus limiting the economic feasibility of the whole venture. However, with regard to Asian macro-algae production, there is a very large established industry where there has been substantial growth within the last decade (see Section 4). How the various products from the industry may fit into global food security and whether any of the by-products can contribute to fuel production as part of an integrated industry has generated little attention in the West.

6.6.2 Land Use

Generally land use for micro-algae is low compared to agricultural crop production with perhaps 20 tonnes of oil per hectare per year possible in pond systems (Jorquera *et al* 2010). The use of photobioreactors can reduce this land use even further; however, this is dependent on the system and location. Where these systems are placed outside and rely on ambient light and temperature, they are highly dependent on the region of production. Land use for macro-algae is generally even lower as the majority of systems are long-line systems suspended from rafts and the only land requirement is for the processing of the biomass once it is brought ashore. However, competition for coastal area also faces stiff competition as highlighted in Section 3 and discussed further in Section 7.

In contrast, the land required for terrestrial biofuel production can be extremely large as can be shown in Section 6.5.1. The redirection of food crops to biofuels has raised serious concern, particularly where this has been occurring in food deficit countries. However, Sachs (2007) noted that food scarcity is not necessarily the problem, but purchasing power to buy food amongst the world's poorest and biofuels may also be obtained from the inedible by-products of terrestrial food crops such as maize (stover), leaving huge scope for the integration of the biofuels industry with the food industry rather than competition between the two.

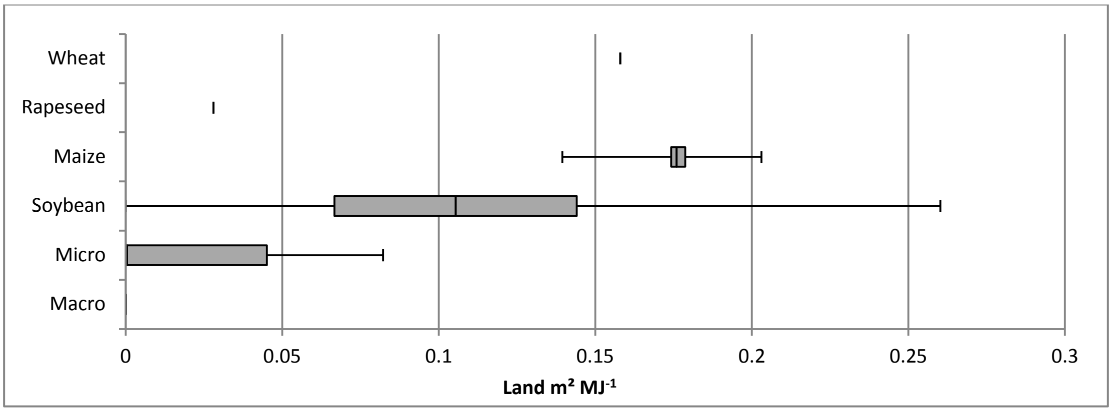


Figure 6.27 Land use required for marine and selected terrestrial crop biofuel production. Medians, 25% and 75% quartiles and 95% confidence limits

6.6.3 Water Use

Water use has not been considered for marine biofuels systems as minimal quantities are used and the main issue is extraction of sea water from the biomass. For terrestrial biofuels, the water consumption is highest for the production of crops as shown in Figure 6.20.

6.6.4 GWP

As can be seen from Figure 6.28, microalgae biofuels perform much worse than macroalgae or any of the terrestrial crops. The huge range of results not only reflects the massive range of systems and species as noted above, but also the differences in methodological approaches and assumptions within the various assessments that have been published. Macroalgae in contrast performs within the same range as the terrestrial fuels, from the one study that provided data on this (Alvarado-Morales *et al* 2013). The other major study by Aitken *et al* (2014) showed some similar results, but CO_2 uptake due to sequestration was included in their overall figures and could not be separated from the CO_2 emissions for use in this analysis. However, early indications show that further investigation of culturing macroalgae for fuels could be warranted if it could be shown to be economically attractive (see Section 5).

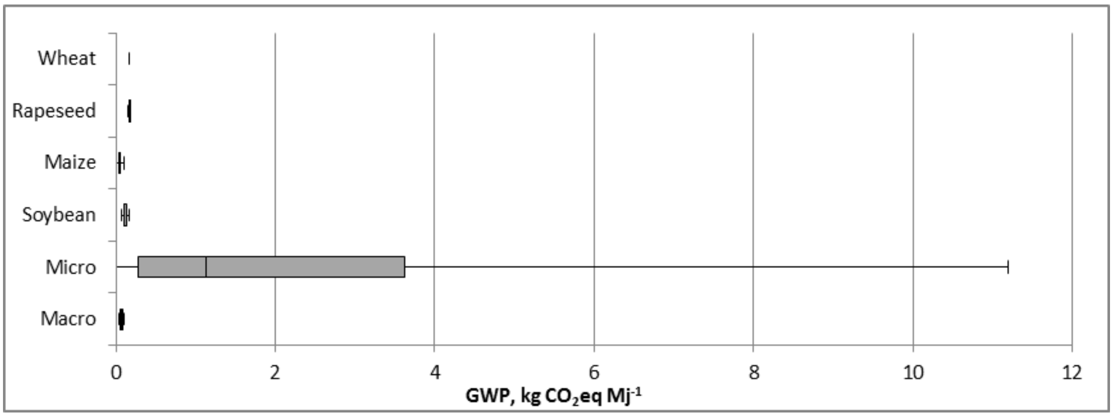


Figure 6.28 GWP for marine and selected terrestrial crop biofuel production. Medians, 25% and 75% quartiles and 95% confidence limits

6.6.5 Acid and Eutrophication

Acidification and eutrophication were not included in the analysis of biofuels due to lack of data, especially with regards to the terrestrial crop production. This could be extrapolated from the crop assessments given in Section 6.5 and combined with various yields of biofuels from other studies but this would depend greatly on the different methodologies between them, leading to huge uncertainty and is beyond the scope of this report. Lack of inclusion of these key categories is of surprise given the emissions associated with fertiliser application and management of soils discussed in Section 6.4.

6.6.6 Summary of LCA of Algal Mariculture for Energy Production

- From the literature available, it seems clear that at present, the production of biofuel from microalgae is inefficient at best. The energy inputs vastly outweigh what can be achieved with current technology. There may be some niche role for the biofuel if cheap clean electricity is used to produce it but it is unlikely to compete with terrestrial biofuels or indeed fossil fuels in the short to medium terms; and

- Possibilities for producing fuel from macroalgae seems more promising. However, it is most likely that the by-product from producing seaweeds for other uses in areas of rapid expansion such as Indonesia would be the most likely and globally beneficial resource rather than producing seaweed for a dedicated fuel industry. As such, the by-product would probably be one component of a mixed feedstock for anaerobic digestion. The possibilities of producing such a fuel in an integrated waste management system is deserving of some more research in areas of well established and fast developing seaweed production.

7. Assessment of the Potential for Mariculture to Contribute to Future Food Production and the Associated Risks and Benefits

This section presents the results of a risk benefit analysis of expanding future mariculture production to help meet projected global demands for food in 2050. The approach and limitations of the analysis are presented in Section 7.1 and the quantitative results are presented in Section 7.2. Considerations of the wider environmental and socio-economic risks and benefits of expanding mariculture are discussed in Section 7.3 and a summary of the risks and benefits of expanding global mariculture is presented in Section 7.4.

7.1 Approach to the Risk Benefit Analysis

As described in Section 1, there are limited resources for continued increases in agricultural livestock and crop production to meet potential future demand. The purpose of this section is to investigate whether the pressure on these resources can be reduced by transferring protein production from land (in the form of livestock) to sea (in the form of finfish and shellfish, collectively referred to as fish). The specific question addressed is whether the footprint of future food production (particularly with respect to land and water use and GHG emissions) can be reduced through increasing the supply of protein from seafood products cultured within the marine environment.

Due to the uncertainty regarding the technical and economic feasibility of commercial scale biofuel production from algal biomass (see Section 5) and the energy efficiency of doing so (see Section 6), the risks and benefits of expanding global algal mariculture to contribute to future energy demands have not been assessed in this section.

The analysis used the quantitative outputs of the LCA analysis presented in Section 6 within theoretical scenarios where the proportion of agricultural meat products and mariculture products were varied. The indicative quantitative environmental impacts from these scenarios are discussed in the context of the wider environmental and socio-economic impacts which are likely to arise from the scenarios and which are known not to be accounted for in LCAs. The discussion also addresses the potential to achieve such expansion, for example in relation to available coastal and marine areas for such expansion and whether future technology may help mitigate against any identified risks.

The study has sought to assess the impact of the following simple theoretical future scenarios on GWP, land and freshwater use:

- Scenario 1: BAU scenario, in which the future projected production and edible yield volumes of the livestock and fish species/groups assessed in Section 6 were based on the linear growth rates of these products between 2003-2012;
- Scenario 2: Production of the three lowest impact mariculture species (oyster, mussel and salmon) are substantially increased above the BAU projections by a defined amount; and

- Scenario 3: Production of all marine (including brackish) and freshwater aquaculture species are doubled compared to the BAU scenario to assess whether greater reductions in impacts can be obtained through increasing both mariculture and freshwater production in tandem.

Two further 'visionary' scenarios were then also assessed, in which mariculture production and seafood consumption were increased to relatively extreme levels, to determine the potential effect on the global footprint of food production of achieving such visionary scenarios:

- Scenario 4: A scenario in which 50% of projected protein (meat and fish) demand in 2050 is provided by shellfish (oysters and mussels); and
- Scenario 5: A scenario in which the global per capita fish supply is 70 kg/person live weight equivalent (i.e. the same level of per capita fish supply as Hong Kong in 2012) for a population of 9 billion people.

The development of the above theoretical scenarios is described in more detail in Section 7.1.2 below. It is important to note that the changes in production levels tested within the scenarios are indicative only and have been designed to represent situations in which either current production trends continue (Business as Usual (BAU)) or in which certain types of culture (e.g. shellfish, marine and/or freshwater) are deliberately increased substantially above the projected BAU scenario to assess the risks and benefits of doing so.

The feasibility and relative risks and benefits of increasing global mariculture were then assessed further utilising the following:

- A high level assessment of the challenges to increasing global mariculture, including a high level quantitative exploration of the potential space required and a qualitative assessment of technological requirements;
- A high level qualitative assessments of the wider socio-economic and environmental impacts of increasing global mariculture;
- Key opportunities, including technological advancements, to minimise the risks and maximise the benefits of expanding global mariculture.

7.1.1 Methodological Limitations

The limitations of the LCA analysis are discussed in detail in Section 6 and the outputs of this analysis must be interpreted in the light of these limitations (i.e. the quantitative outputs of the scenarios must be considered to be indicative only). Furthermore, due to the qualitative nature of the majority of information underlying the assessment (particularly with regard to wider environmental and socio-economic impacts), the outputs of the risk/benefit analysis only enable comparison of the relative risks and benefits between the scenarios.

The project specification was to assess the risks and benefits of expanding mariculture, particularly on GHG emissions and land and water use at a global level and, for this reason, the quantitative assessment of the impacts of future projected food production scenarios considered the GWP, land and freshwater use as the most important impact categories to assess. The eutrophication impact assessed in Section 6 is more relevant at a local level and must be contextualised in those terms (see Section 6) and hence is not considered further within this section. It would be possible to take the eutrophication results and other water quality parameters and apply them to the assimilative capacity of a local water body to assess the maximum production capacity for any species using those results. Although acidification is of global relevance, it was generally poorly reported within LCA studies and therefore was omitted from these projections.

Furthermore, as described in previous sections, mariculture species, production systems and impacts vary greatly by region (i.e. Americas, Asia, Africa, Europe and Oceania) and between sites within regions. As such the outputs of the risk benefit analysis is necessarily high level, however the discussion of the wider environmental and socio-economic risks and benefits of expanding mariculture to the levels described in the scenarios is contextualised as far as possible in Section 7.3.

To develop the scenarios for the risk/benefit analysis it was necessary to make a number of general assumptions and acknowledge specific limitations which are listed below:

- Nutritional quality of animal protein – it was outwith the scope of the current study to address the difference in nutritional quality or calorific value of the animal protein being assessed. As such, for the purpose of this study it has necessarily been assumed in the scenarios that 1kg of edible meat is equivalent with respect to food provision to 1kg edible yield of fish (finfish, shellfish or crustacean), although it is acknowledged that this is not likely to be the case. Comparison of nutritional quality between fish and meat products is complex, relating not only to calorific value and protein content but also to the quality of lipid, vitamin and mineral content. Although an adequate animal protein supply can be obtained from other sources (e.g. meat, cereals), fish are an important source of both macronutrients (which provide energy and protein) and micronutrients (vitamins and minerals) with well documented health benefits (e.g. see Haraksingh Thilsted *et al*, undated).
- A major limitation in this analysis is the relative lack of LCA data for the production of cultured aquatic species (marine or freshwater). For example, with respect to livestock, data were available for beef, pork and chicken which together in 2012 comprised 88% of meat production. In contrast, the farmed aquatic species for which adequate LCA data were available (salmon, tilapia, shrimp, oyster, mussel, trout, seabass and milkfish) only comprised about 26% of total global farmed production, with carp and other fish collectively comprising the other 74% of production. The lack of LCA data specifically for the monoculture production of freshwater species of carp (most data related to polycultures which included carp) is a major limitation in the current study given its dominance in global production. The implications of this limitation is that assessment of the impact of varying the proportion of farmed aquatic species is being based on a subset of species which collectively only comprise about 25% of total global aquaculture production. Further improvements in LCA data availability for other cultivated aquatic species, and general improvements in LCA methodology (see recommendations in Section 8) will help to enable a more accurate assessment of global impacts of marine and freshwater aquaculture in the future;

- As a result of the above limitation, it has only been possible in this analysis to compare the relative impacts on GHG emissions, land and water use from varying a sub-set of livestock meat products and fish products whilst the overall production of edible protein yield has been held constant. The outputs therefore represent indicative impact levels of the species assessed in relation to these specific factors;
- It is also important to note that the absolute production and edible yields of meat and fish are only indicative and have been produced to enable comparison of the relative impacts of shifting the focus of animal protein (meat) production from the land to the sea (in the form of fish and shellfish) in theoretical future scenarios. The potential for increasing production levels of mariculture and the potential sea space required to do so are discussed further in Section 7.2.1.

7.1.2 Development of the Theoretical Scenarios and Future Food Production

7.1.2.1 Scenario parameters

The following parameters were considered within the quantitative risk/benefit analysis to assess the impacts on GHG emissions, water and land use.

- Meat - Quantitative data from the LCA analysis were included for beef, pork and chicken which comprised 88% of meat production in 2012. Due to insufficient data, ‘other meat’, for example mutton and goat, were not included in the LCA analysis in Section 6 and hence no quantitative information for these other meat products could be included in the risk/benefit analysis. As such, within the scenarios, the production volumes of ‘other meat’ is either held constant at 2012 production levels or reduced at the same proportion as the beef, pork and chicken meat within the scenarios;
- Fish (finfish, shellfish and crustaceans) produced via mariculture – Quantitative data for the mariculture species assessed in Section 6 were included in the analysis. These species were Atlantic salmon, European seabass, milkfish, Penaeid shrimp, Pacific oyster and mussel. Due to insufficient data, ‘other’ mariculture and freshwater species which contribute to global production statistics were not included in the LCA and hence no quantitative information for these species could be included in the risk/benefit analysis. As such, within the scenarios the production volumes of ‘other fish’ was held constant at 2012 production levels or increased at the same proportion as the other assessed marine species within the scenarios.
- Fish (finfish) produced via freshwater aquaculture - Quantitative data for the freshwater aquaculture species assessed in Section 6 were included in the analysis. These species were tilapia and rainbow trout. Due to the lack of LCA data relating to the production of carp in monocultures (see above and Section 6), the LCA data relating to the impact of carp production were not included in the quantitative analysis presented in this section. However, given the importance of carp in global aquaculture production, the projected volumes in each of the scenarios are presented for context. Note as above, the production volume of ‘other’ cultured marine and freshwater aquaculture species was held constant at 2012 production levels or increased at the same proportion as the other fish species/groups within the scenarios.

- Cereal – The environmental impact of crop production has been assessed in Section 6. Within this section, likely future developments in feed technology for higher trophic level aquaculture species are briefly reviewed and the implications for the risk benefit analysis are discussed in Section 7.3.

The following parameters were not considered within the risk/benefit analysis to assess the impacts on GHG emissions, water and land use:

- Milk and eggs – the dietary importance of these animal protein sources for a large proportion of the global population (e.g. South and Southeast Asia) is recognised. However these were not considered substitutes in the current analysis for meat and fish products;
- Wild capture fisheries – For the purpose of the risk benefit analysis, total landings from wild capture fisheries has been assumed to remain constant between scenarios, which is in line with the general view that wild capture fisheries have plateaued and that in the future increasing demand for seafood will be met through increased aquaculture production; and
- Neither aquatic plants produced by freshwater aquaculture or macroalgae produced by mariculture were included in the quantitative analysis. However although macroalgae cannot be considered as an alternative to meat production to address meeting future food demand, there may be potential for cultivated algae to substitute some irrigated vegetable production and crops in formulated aquaculture and animal feeds (see Section 4.5).

7.1.2.2 Production statistics

Production statistics for beef, pork and chicken were obtained from the FAOSTAT database. The data sourced related to meat in tonnes (cattle, pig and chicken meat from the FAOSTAT production category 'livestock primary'), defined by the FAO as:

> *"the flesh of animals used for food. In the statistical language, meat is intended to be with bone-in, unless otherwise stated, and to exclude meat unfit for human consumption. From the term "meat" are to be excluded edible offals and slaughtered fats."*

The yields in Table 7.1 were used to convert the tonnage of meat (which FAO stated contained bone) to tonnes of edible yield. The volume of 'other' meat produced (e.g. including mutton) was calculated by subtracting the total volume of beef, pig and chicken meat from the 'total meat' tonnage sourced from FAOSTAT (see Table 7.2).

Production statistics for fish were obtained from the FAO Fishstat database and the production tonnages represent the live weight equivalent (i.e. whole fish and shellfish). The yields in Table 7.1 were used to convert tonnage of fish to tonnes of edible yield.

Table 7.1 Yields of edible product from finfish and shellfish species

Product	Edible Yield
Beef meat	0.84
Pork meat	0.82
Chicken	0.46
Other meat	0.83
Atlantic Salmon	0.62
Rainbow Trout	0.62
European sea bass	0.54
Penaeid shrimp	0.49
Mussel *M. edulis* and *M. galloprovincialis*	0.18
Milkfish	0.61
Pacific oyster (*Crassostrea gigas*)	0.16
Tilapia	0.37
Carps	0.55
Sources: Beef and pork meat yields – FAO (1991); chicken and fish yields - see Section 6. Note – the yields for 'other meat' was calculated as the average yield of beef and pork. The yield for 'other fish' was calculated as the average of all the aquatic species listed above, as other fish may comprise finfish, shellfish or other invertebrates and hence and only an indicative value could be used.	

7.1.2.3 Projected scenarios

Scenario 1 (Business as Usual)

As noted in Section 1, the world's population has been predicted to increase from seven billion in 2012 to over nine billion by 2050 with associated increased demands for food, which in turn will require more land, water and energy resources. Numerous reviews and articles have estimated global food and energy requirements in 2050 (for examples see Section 1). In the current study, projected tonnages of meat and fish in 2050 were made from a baseline year of 2012, using linear growth rates calculated for the time period 2003 to 2012 (see Figure 7.1).

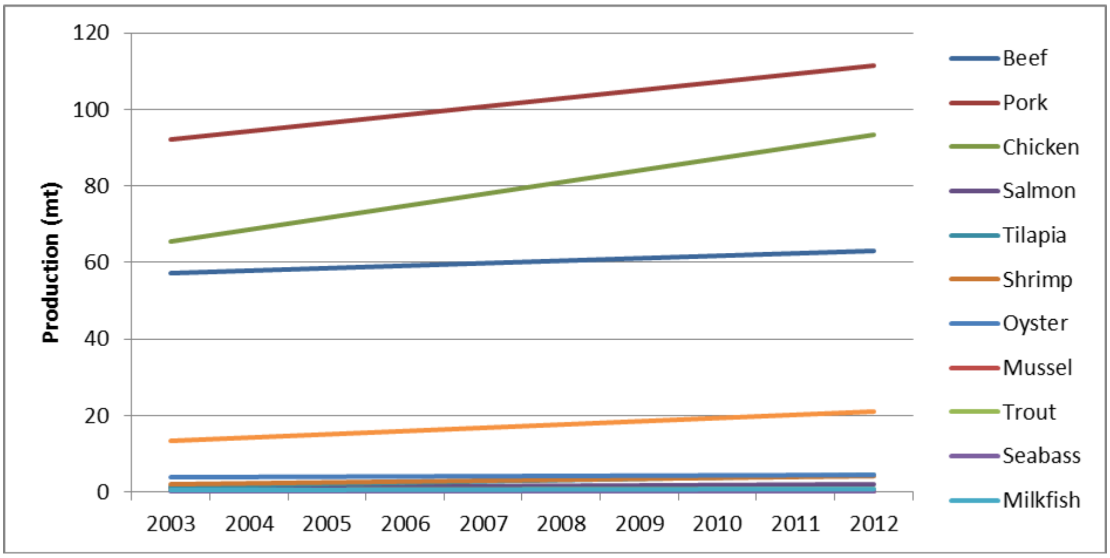


Figure 7.1 Linear growth rates of meat and fish products between 2003 and 2012.

The baseline production levels in 2012, calculated growth rates and projected production tonnages are shown in Table 7.2. The percentage that each product type contributes to total global meat and fish production, and edible yield, in 2012 and in 2050 in the Business as Usual (BAU) Scenario 1 are shown in Figures 7.2 to 7.5.

Table 7.2 Projected agricultural meat and mariculture/freshwater fish production in 2050 (million tonnes per annum)

Product Type	Baseline Production 2012 (mt)	Baseline Edible Yield 2012 (mt)	Growth in Production (2003-2012) (mt/pa)	Projected Production 2050 (BAU; Scenario 1) (mt)	Change in Production in 2050 (BAU) (%)	Projected Edible Yield in 2050 (BAU) (mt)
Beef	63.18	53.07	0.61	86.29	+37%	72.48
Pork	111.40	91.35	1.91	184.08	+65%	150.95
Chicken	93.43	43.07	2.81	200.11	+114%	92.25
Other meat	36.84	30.58	0.00*	36.84	No change	30.58
Total meat	304.85	218.07	-	507.33	+66%	346.26
Salmon	2.05	1.27	0.09	5.50	+168%	3.41
Tilapia	4.49	1.66	0.29	15.57	+246%	5.76
Shrimp	4.21	2.06	0.23	12.88	+206%	6.31
Oyster	4.59	0.73	0.07	7.15	+56%	1.14
Mussel	0.30	0.05	0.00**	0.30	No change	0.05
Rainbow Trout	0.86	0.53	0.03	2.02	+136%	1.25
Seabass	0.15	0.08	0.01	0.46	+198%	0.25
Milkfish	0.94	0.58	0.04	2.43	+158%	1.48
Carp	21.12	11.62	0.77	50.37	+138%	27.71
Other fish	28.28	13.00	0.00*	28.30	No change	13.01
Total fish	67.00	31.59	-	124.97	+87%	60.37
Total meat and fish	371.85	249.66		632.30	170%	406.62

* For the purposes of this analysis, any product type that was not included in the LCA analysis in Section 6 was classed as 'other' types of meat or fish and the growth rate was assumed to be zero.
** The growth rate of mussels over last 10 years was slightly negative, but not expected to persist over next 40 years, so assumed mussel production would be static
mt Million tonnes
pa per annum

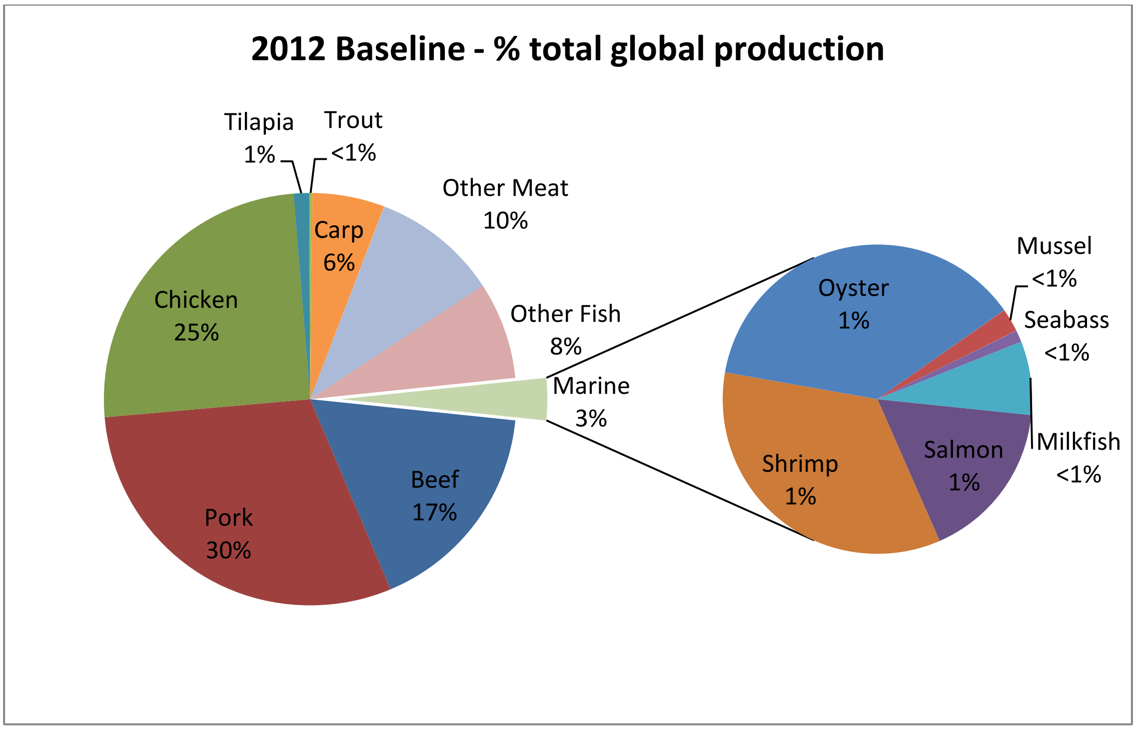


Figure 7.2 Percentage of the total global production of each meat and fish product in 2012

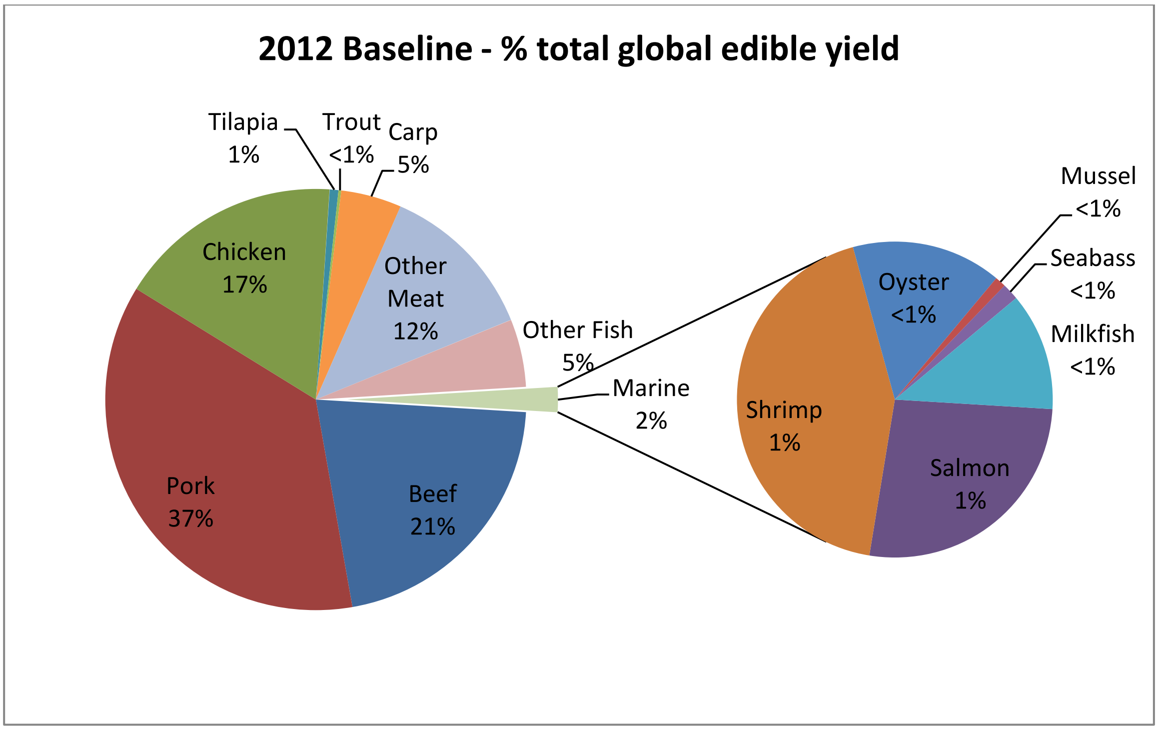


Figure 7.3 Percentage of the total global edible yield of each meat and fish product in 2012

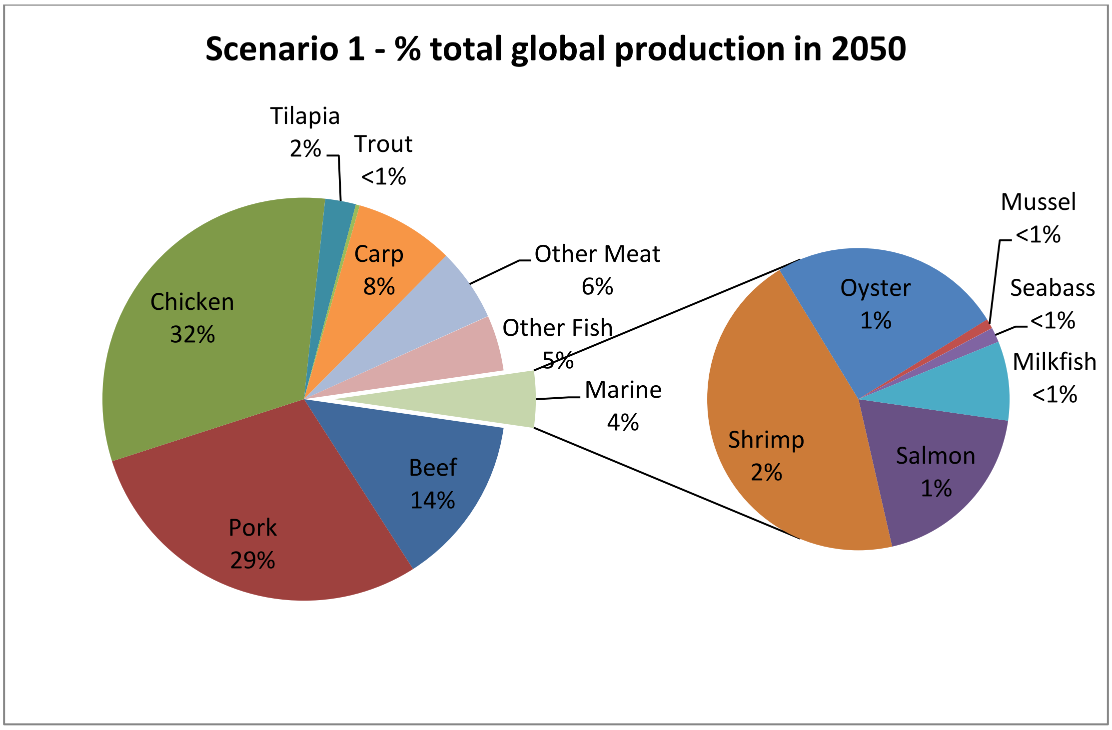


Figure 7.4 Percentage of the total global production of each meat and fish product in 2050 in the BAU Scenario 1

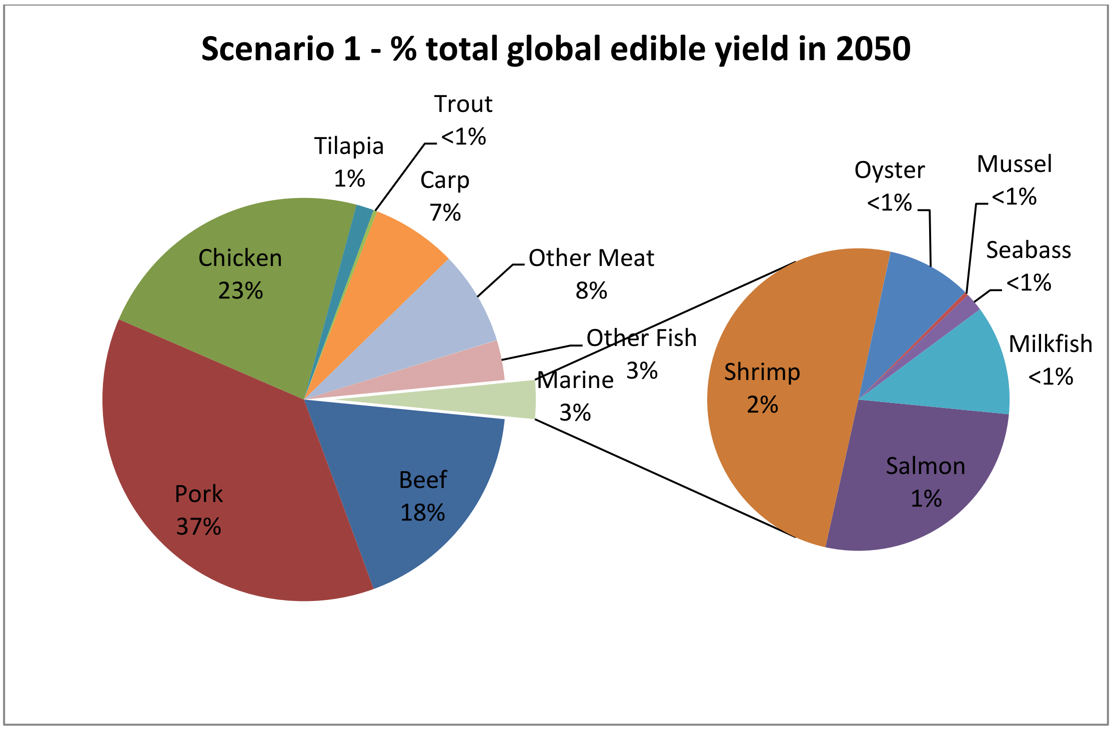


Figure 7.5 Percentage of the total global edible yield of each meat and fish product in 2050 in the BAU Scenario 1

The BAU scenario resulted in a total of 507mt of agricultural meat and 125mt of fish production in 2050 (an increase of 66% and 87% in meat and fish production respectively compared to baseline, based on their growth rates from 2003-2012), from which a total edible yield of about 407mt was projected. Beef, pork and chicken meat production were projected to increase by 37%, 65% and 114% in 2050 compared to 2012 levels respectively, with the result that the projected production of chicken was greater than that of pork in 2050. Salmon, shrimp, Pacific oyster, seabass and milkfish ('mariculture' species) were projected to increase 168%, 206%, 56%, 198% and 158% respectively. The linear growth rate calculated for mussel (the fifth mariculture species in the analysis) from FAO statistics between 2003 and 2012 was negative and hence if this value had been used, the production of mussel would have decreased in 2050 compared to 2012. For the purposes of this study this was considered unlikely and the growth rate was adjusted to be 0% (based on FAO statistics which have shown mussel production values to fluctuate over the last 30 years but not substantially grow), such that mussel production would remain static between 2012 and 2050 in this scenario.

Scenario 2

In Scenario 2, the aim was to assess the effect of increasing production levels of 'low impact' mariculture species (determined by the LCA analysis in Section 6), with a particular focus on increasing the production of bivalve molluscs, whilst agricultural meat production was reduced and freshwater aquaculture was held constant. The scenario involved the following:

- Increasing salmon production by 100% and increasing the production of oyster and mussel (which had the smallest impact in the LCA assessment due to not requiring feed or water input) by 300%. Production levels of shrimp (which scored highest in all of the LCA impact categories i.e. was the worst performing mariculture species) and of all freshwater aquaculture species were kept equal to that produced in Scenario 1;
- This scenario resulted in the total production of fish increasing to 153mt (see Table 7.3) with an edible yield of 67mt (an increase in edible yiels of fish of 12% and 113% compared to Scenario 1 and the 2012 baseline respectively) created through increased production of salmon, oyster and mussel; and
- The total edible yield of beef, pork, chicken and other meat combined was reduced by 7mt compared to the BAU Scenario 1 (the absolute amount of additional edible yield produced by the increased production of salmon, oyster and mussel) with the relative proportion of each meat product remaining constant, to keep the overall edible yield of meat and fish produced constant at 407 mt. The small reduction in meat production reflected the fact that although shellfish production had been increased by 300%, due to the small yields obtained from shellfish such as mussel and oyster, this only resulted in a relatively small increase in total edible fish yield compared to the BAU Scenario 1 (67mt compared to 60mt; an increase of 12% edible yield).

The projected production tonnages and edible yields in Scenario 2 are shown in Table 7.3 and the proportion that each product type contributes to total global meat and fish production/edible yield is shown in Figures 7.6 and 7.7.

Table 7.3 Calculated projected production levels for Scenario 2

Product Type	Change in Production Scenario 2*	Projected Production 2050	Projected Edible Yield 2050
	(%)	(mt)	(mt)
Beef	-2%	84.54	71.01
Pork	-2%	180.36	147.89
Chicken	-2%	196.07	90.39
Other meat	-2%	36.10	29.96
Total meat	-2%	497.07	339.26
Salmon	+100%	10.99	6.82
Tilapia	No change	15.57	5.76
Shrimp	No change	12.88	6.31
Oyster	+300%	28.62	4.58
Mussel	+300%	1.19	0.21
Rainbow Trout	No change	2.02	1.25
European seabass	No change	0.46	0.25
Milkfish	No change	2.43	1.48
Carp	No change	50.37	27.71
Other' fish	No change	28.30	13.01
Total fish	+22%	152.83	67.38
Total meat and fish		649.90	406.62

* Relative to Scenario 1 (BAU)
mt Million tonnes

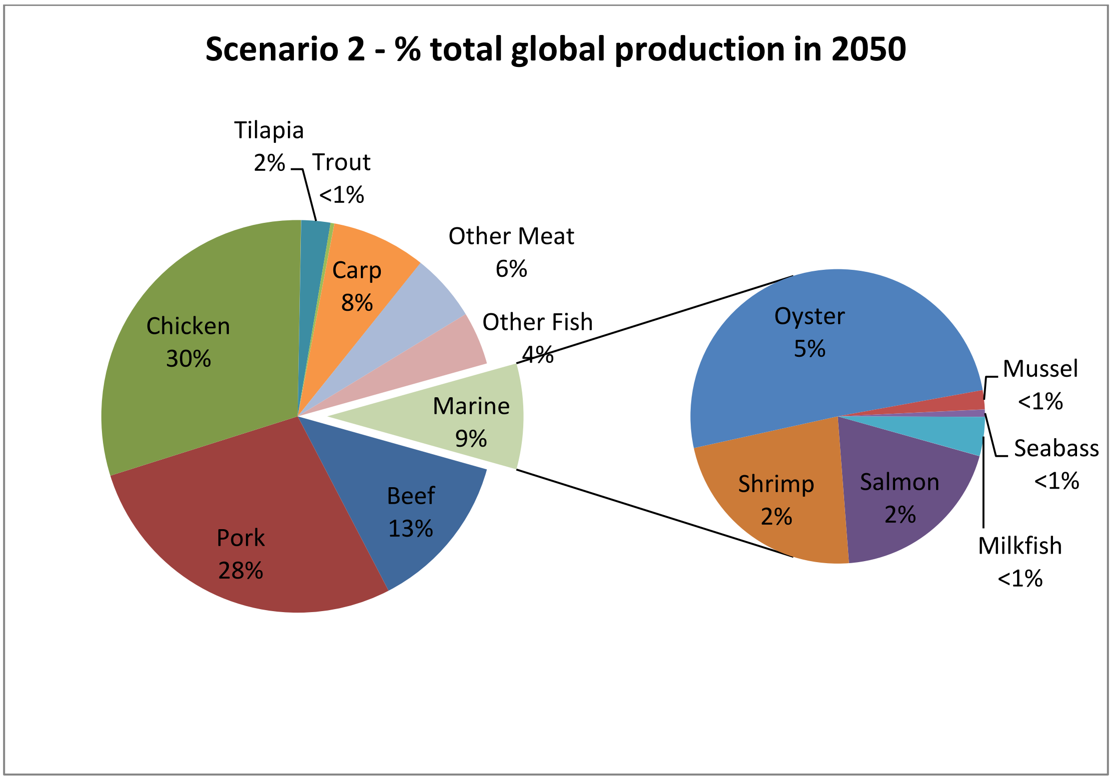


Figure 7.6 Percentage of the total global production of each meat and fish product in 2050 in Scenario 2

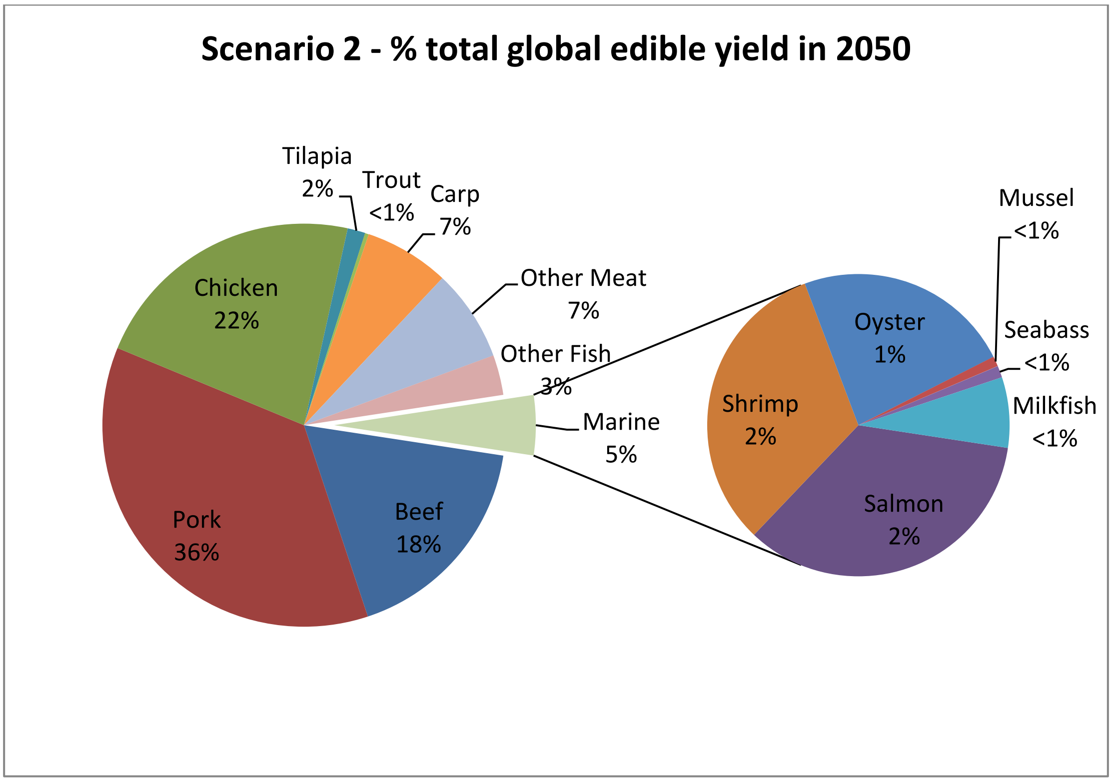


Figure 7.7 Percentage of the total global edible yield of each meat and fish product in 2050 in Scenario 2

Scenario 3

In Scenario 3, the aim was to assess the effect of increasing production levels of all aquaculture products (both mariculture and freshwater) in order to enable comparison of the impacts with Scenario 2 in which just the 'best performing' mariculture species had been increased. As such:

- The production of all freshwater aquaculture and mariculture species were increased by 100% compared to the BAU Scenario 1;
- This scenario resulted in the total production of fish increasing to 250mt (see Table 7.4) with an edible yield of 121mt (an increase in edible yield of 79%, 100% and 282% compared to Scenario 2, Scenario 1 and the 2012 baseline respectively).
- The total edible yield of beef, pork, chicken and other meat combined was reduced by 60mt compared to the BAU Scenario 1 (the absolute amount of additional edible yield produced by the increased production of all cultured fish and shellfish species), with the proportion of edible yield of each meat product staying the same as in the BAU Scenario 1 (21%, 44%, 27% and 9% for beef, pork, chicken and other meat respectively);
- The overall edible yield of meat and fish produced was kept constant at 407mt as per Scenarios 1 and 2.

The projected production tonnages and edible yields in Scenario 3 are shown in Table 7.4 and the proportion that each product type contributes to total global meat and fish production/edible yield is shown in Figures 7.8 and 7.9.

Table 7.4 Calculated projected production levels for Scenario 3

Product Type	Change in Production Scenario 3*	Projected Production 2050	Projected Edible Yield
	(%)	(mt)	(mt)
Beef	-17%	71.24	59.84
Pork	-17%	151.99	124.63
Chicken	-17%	165.23	76.17
Other meat	-17%	30.42	25.25
Total meat	-17%	418.88	285.90
Salmon	+100%	10.99	6.82
Tilapia	+100%	31.13	11.52
Shrimp	+100%	25.76	12.62
Oyster	+100%	14.31	2.29
Mussel	+100%	0.60	0.11
Rainbow Trout	+100%	4.03	2.50
European seabass	+100%	0.91	0.49
Milkfish	+100%	4.86	2.96
Carp	+100%	100.75	55.41
Other fish	+100%	56.56	26.01
Total Fish	+100%	249.91	120.73
Total meat and fish		668.79	406.62

* Relative to Scenario 1 (BAU)
mt Million tonnes

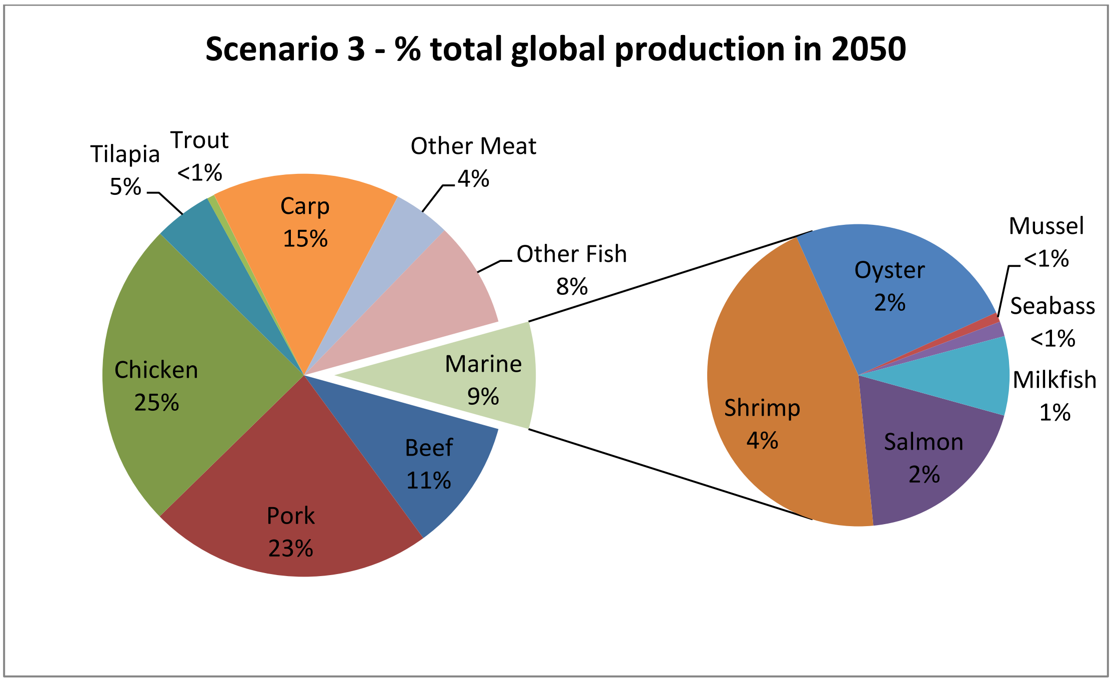


Figure 7.8 Percentage of the total global production of each meat and fish product in 2050 in Scenario 3

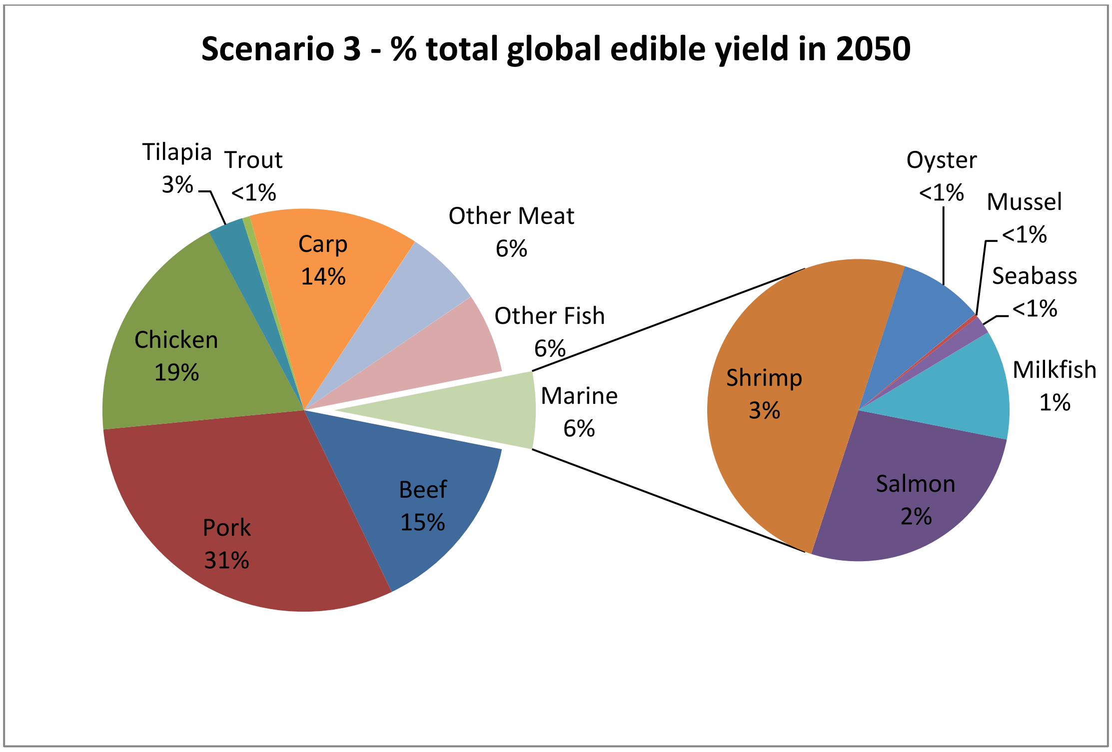


Figure 7.9 Percentage of the total global edible yield of each meat and fish product in 2050 in Scenario 3

Scenario 4

In Scenario 4, the aim was to assess the effect of visionary changes in global food production, in which 50% of the projected future food demand (edible yield) in 2050 is provided by shellfish (50% oyster and 50% mussels), for which land and water use impacts were negligible in this study. As such:

- The production of oysters and mussels were increased to provide a combined edible yield of 203mt (see Table 7.5);
- The production volume of the other mariculture and freshwater aquaculture species was maintained at the projected BAU level;
- The total edible yield of beef, pork, chicken and other meat was reduced by 203mt compared to the BAU Scenario 1 (the absolute amount of additional edible yield produced by the increased production of shellfish), with the proportion of each meat product staying the same as in the BAU Scenario 1 (21%, 44%, 27% and 9% for beef, pork, chicken and other meat respectively);
- The overall edible yield of meat and fish produced was kept constant at 407mt as per Scenarios 1, 2 and 3.

The projected production tonnages and edible yields in Scenario 4 are shown in Table 7.5 and the proportion that each product type contributes to total global meat and fish production/edible yield is shown in Figures 7.10 and 7.11.

Table 7.5 Calculated projected production levels for Scenario 4

Product Type	Change in Production Scenario 4*	Projected Production 2050	Projected Edible Yield
	(%)	(mt)	(mt)
Beef	-58%	35.92	30.17
Pork	-58%	76.63	62.84
Chicken	-58%	83.31	38.40
Other meat	-58%	15.34	12.73
Total meat	-58%	211.20	144.15
Salmon	0%	5.50	3.41
Tilapia	0%	15.57	5.76
Shrimp	0%	12.88	6.31
Oyster	+8,781%	635.35	101.66
Mussel	+19,1195%	571.10	101.66
Rainbow Trout	0%	2.02	1.25
European seabass	0%	0.46	0.25
Milkfish	0%	2.43	1.48
Carp	0%	50.37	27.71
Other fish	0%	28.28	13.00
Total Fish	+960%	1323.95	262.48
Total meat and fish		1535.15	406.62

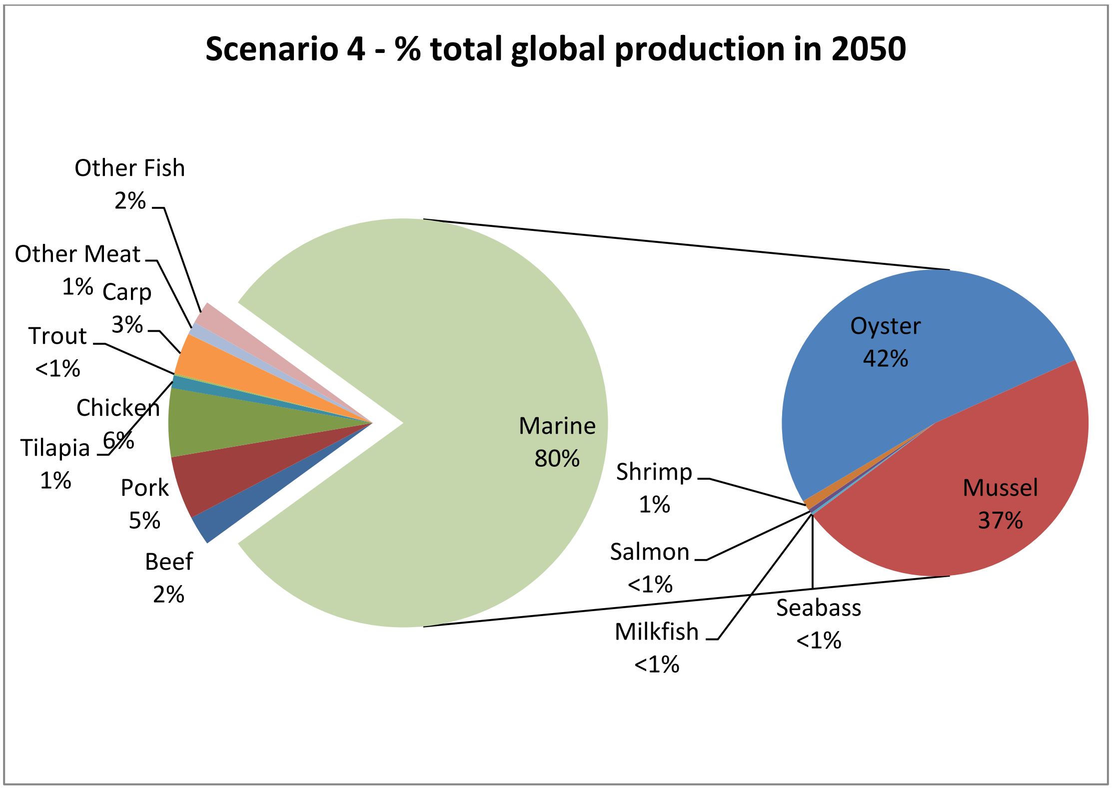


Figure 7.10 Percentage of the total global production of each meat and fish product in 2050 in Scenario 4

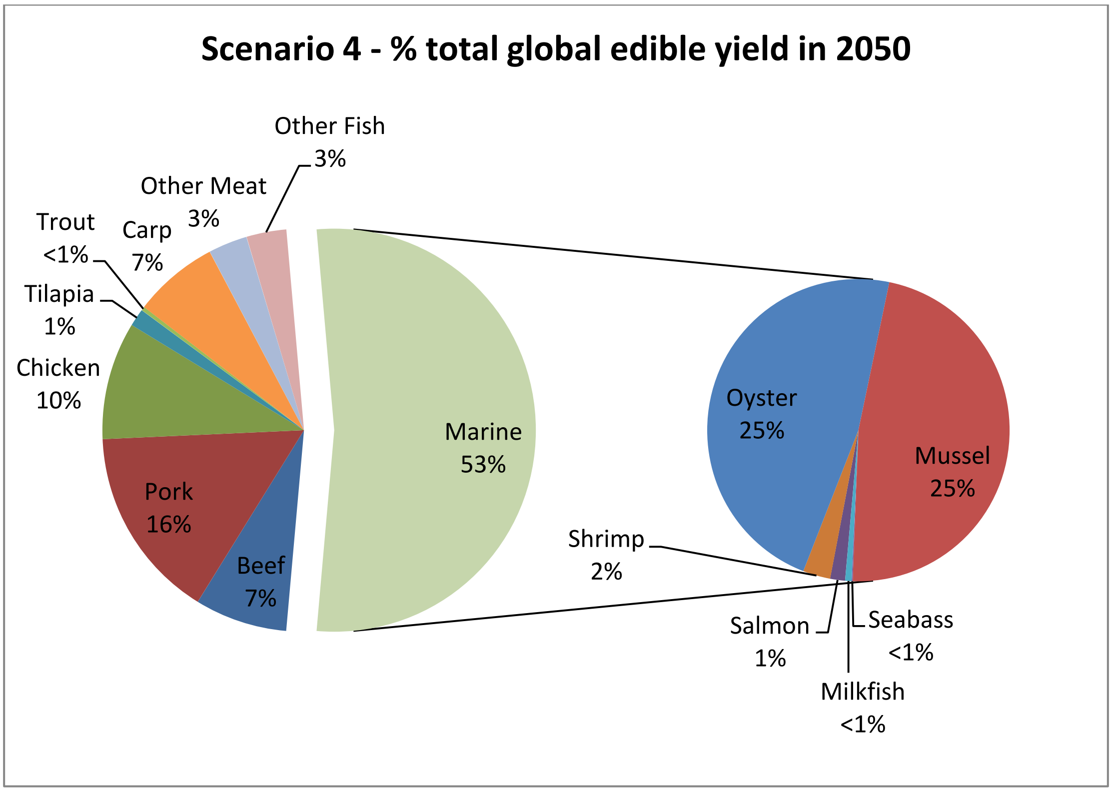


Figure 7.11 Percentage of the total global edible yield of each meat and fish product in 2050 in Scenario 4

Scenario 5

In Scenario 5, the aim was to assess the effect of another visionary scenario in which the global per capita fish supply in 2050 was 70kg/person (the same as in Hong Kong in 2012) for a global population of 9 billion people. It was calculated that this would require the production of 630mt of mariculture products[27]. As such:

- The production of all mariculture species was increased, in the same proportions projected in the BAU Scenario 1, to produce a combined total of 630mt (see Table 7.6);
- The production volume of freshwater aquaculture species was maintained at the projected BAU level;
- The total edible yield of beef, pork, chicken and other meat combined was reduced by 265mt compared to the BAU Scenario 1 (the absolute amount of additional edible yield produced by the increased production of mariculture species), with the proportion of each meat product staying the same as in the BAU Scenario 1 (21%, 44%, 27% and 9% for beef, pork, chicken and other meat respectively);
- The overall edible yield of meat and fish produced was kept constant at 407mt as per Scenarios 1, 2, 3 and 4.

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27 70kg fish /person for 9 billion people = 630,000,000,000kg fish (630 million tonnes)

The projected production tonnages and edible yields in Scenario 5 are shown in Table 7.6 and the proportion that each product type contributes to total global meat and fish production/edible yield is shown in Figure 7.12 and 7.13.

Table 7.6 Calculated projected production levels for Scenario 5

Product Type	Change in Production Scenario 5* (%)	Projected Production 2050 (mt)	Projected Edible Yield (mt)
Beef	-76%	20.30	17.05
Pork	-76%	43.31	35.51
Chicken	-76%	47.08	21.70
Other meat	-76%	8.67	7.19
Total meat		119.36	81.47
Salmon	+2,094%	120.60	74.77
Tilapia	0%	15.57	5.76
Shrimp	+2,094%	282.59	138.47
Oyster	+2,094%	156.94	25.11
Mussel	+2,094%	6.55	1.17
Rainbow Trout	0%	2.02	1.25
European seabass	+2,094%	10.02	5.41
Milkfish	+2,094%	53.30	32.52
Carp	0%	50.37	27.71
Other fish	0%	28.28	13.00
Total Fish	+439	726.24	325.16
Total meat and fish		845.60	406.62

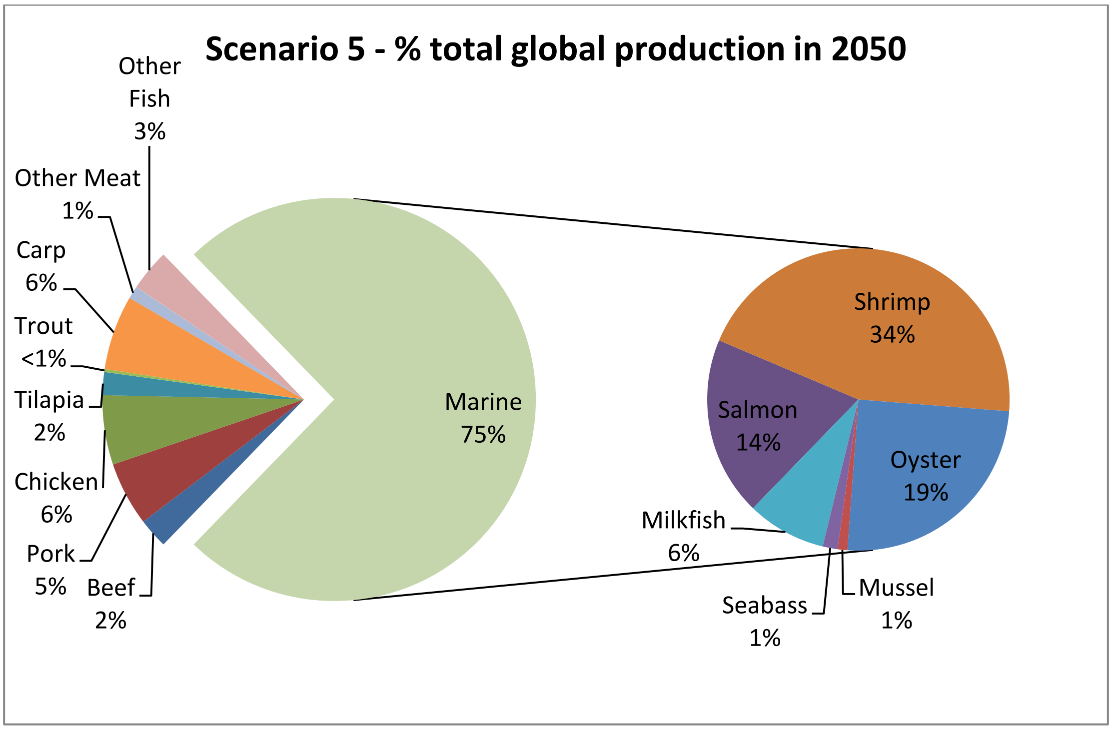

Figure 7.12 Percentage of the total global production of each meat and fish product in 2050 in Scenario 5

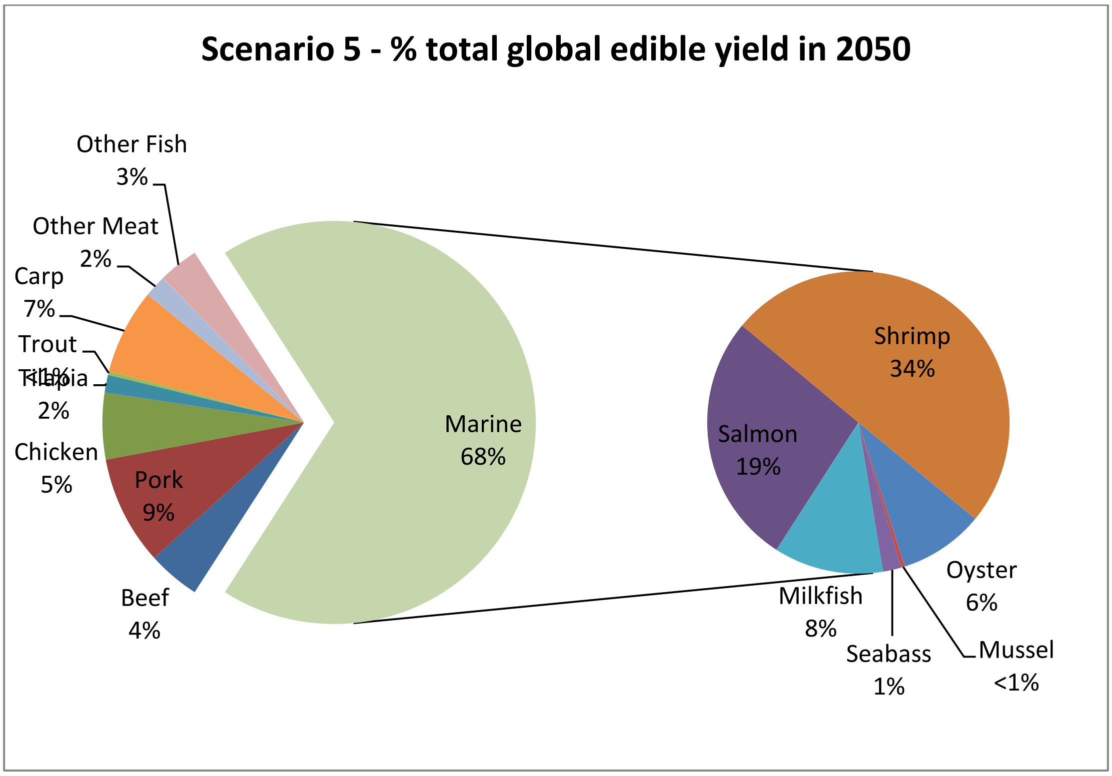

Figure 7.13 Percentage of the total global edible yield of each meat and fish product in 2050 in Scenario 5

7.1.2.4 Calculation of indicative sea space requirements for the future scenarios

The study has sought to estimate the potential sea space requirements for future production. The marine area required for mariculture production will depend on the species being produced, the production method and the intensity of production (e.g. extensive, semi-intensive or intensive) (see Sections 3 and 4). In order to provide an example of the sea area requirement for each scenario the following data were utilised to calculate an indicative sea area required for the production of mariculture products within each scenario (Table 7.7). It is important to note that these numbers should only be used for relative comparison of sea area between scenarios and do not represent the absolute sea area which would be required for the reasons stated above. It should also be noted that these generic sea areas are only considered indicative of the area in which production occurs and do not represent the area occupied by the farm infrastructure (e.g. moorings etc) and/or any spacing requirements to minimise any environmental and cumulative impacts which will be required in some regions. The indicative sea areas calculated using these numbers are presented for marine and brackish culture species in Table 7.8, using the indicative live weight production volumes for Scenarios 1, 2, 3, 4 and 5 from Tables 7.2, 7.3, 7.4, 7.5 and 7.6 respectively.

Table 7.7 Mariculture species yields (t/ha) used to calculate indicative sea area required for production tonnages in projected scenarios

Product Type	Cultivation Method	Yield (t/ha)			
		Min	Max	Mean	Source
Salmon	Sea cages / pens			2,000	Section 3
Shrimp	Pond (extensive)	0.1	2.5	6.7	Section 3
	Pond (semi-intensive)	1.5	8		Section 3
	Pond (intensive)	8	20		Section 3
Oyster	Not specified (methods include on-bottom, trestle, suspended)	25	70	48	FAO, 2015
Mussel	On-bottom	50	70	40	FAO, 2015
	Rope (suspended)	18	20		FAO, 2015
Seabass	Extensive lagoon	50	150	350	FAO, 2015
	Semi-intensive lagoon	500	700		FAO, 2015
Milkfish	Pond culture	0.8	2	1	FAO, 2015

Table 7.8 Increases in sea area required for production tonnages in projected scenarios

Product Type	Indicative Sea Area required per Scenario (ha) and % Change from 2012 Baseline (in brackets)					
	2012 Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Salmon	1,027	2,749 (168%)	5,497 (435%)	5,497 (435%)	2,749 (168%)	60,300 (5,773%)
Shrimp	629,782	1,927,308 (206%)	1,927,308 (206%)	3,854,616 (512%)	1,927,308 (206%)	42,282,207 (6,614%)
Oyster	96,654	150,607 (56%)	602,429 (523%)	301,215 (212%)	13,375,810 (13739%)	3,304,097 (3,318%)
Mussel	7,558	7,558 (0%)	30,232 (300%)	15,116 (100%)	14,458,279 (1991195%)	165,814 (2,094%)
Seabass	438	1,304 (198%)	1,304 (198%)	2,609 (496%)	1,304 (198%)	28,615 (6,438%)
Milkfish	673,756	1,735,520 (158%)	1,735,520 (415%)	3,471,040 (2,322%)	1,735,520 (158%)	38,074,670 (5,551%)
Total	1,409,215	3,825,046 (+171%)	4,302,291 (+205%)	7,650,092 (+443%)	31,500,970 (2,135%)	83,915,703 (5,855%)

7.1.2.5 Calculation of GWP, land and water use impacts

To compare relative impacts between the above scenarios, the mean GHG emission, land and water use impacts for each product type calculated in Section 6 were used (Table 7.9). It is important to note that these values are indicative only due to the data limitations described in Sections 6 and 7.1.1.

Table 7.9 Mean GWP, land and freshwater impacts for each product type used in the projected scenarios

Product	Mean GWP ($kg\ CO_2$/kg Edible Yield)	Mean Land Use (m^2/kg Edible Yield)	Mean Freshwater Water Use (m^3/kg Edible Yield)
Beef	27	81	150
Pork	6	14	17
Chicken	4	6	9
Salmon	4	4	2
Tilapia	4	3	16
Shrimp	11	22	3
Oyster	6	0	0
Mussel	3	0	0
Rainbow Trout	3	3	0
European seabass	5	9	4
Milkfish	6	4	0

7.2 Outputs of the Quantitative Risk/Benefit Analysis of Future Mariculture Scenarios

Table 7.10 shows the outputs of the impact assessment for Scenarios 1 to 5. It is important to note that the production and edible yield volumes shown in Section 7.1 are only indicative numbers (based on the LCA analysis in Section 6) to enable quantitative comparison of impacts between the scenarios. As such, the table below presents the % changes in edible yield between the scenarios, the % changes in indicative sea space required and the associated GWP, land and freshwater use.

Table 7.10 Comparison of GWP, land and water use impacts between theoretical future scenarios

Product Type	Baseline Edible Yield (2012) (mt)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Changes in edible yields of meat and fish products (% change from baseline)						
Beef*	53.07	+37%	+34%	+13%	-43%	-68%
Pork*	91.35	+65%	+62%	+36%	-31%	-61%
Chicken*	43.07	+114%	+110%	+77%	-11%	-50%
Other meat	30.58	no change	-2%	-17%	-58%	-76%
Total meat	218.07	+59%	+56%	+31%	-34%	-63%
Salmon*	1.27	+168%	+435%	+435%	+168%	+5,773%
Tilapia*	1.66	+246%	+246%	+593%	+246%	+246%
Shrimp*	2.06	+206%	+206%	+512%	+206%	+6,614%
Oyster*	0.73	+56%	+523%	+212%	+13,739%	+3,318%
Mussel*	0.05	no change	+300%	+100%	+191,195%	+2,094%
Rainbow Trout*	0.53	+136%	+136%	+371%	+136%	+136%
European seabass*	0.08	+198%	+198%	+496%	+198%	+6,438%
Milkfish*	0.58	+158%	+158%	+415%	+158%	+5,551%
Carp	11.62	+138%	+138%	+377%	+138%	+138%
Other fish	13.00	no change	no change	+100%	no change	no change
Total fish	31.59	+91%	+113%	+282%	+731%	+929%
Total edible yield (mt)	249.66	406.62	406.62	406.62	406.62	406.62
% Change in total edible yield from baseline		+163%	+163%	+163%	+163%	+163%
Change in area required for increases in marine and brackish species production (note excludes changes in area that would be required for the increases in freshwater aquaculture)						
Area (ha)	1,409,215	3,825,046 (+171%)	4,302,291 (+205%)	7,650,092 (+443%)	31,500,970 (+2135%)	83,915,703 (+5855%)
Environmental impacts of scenarios						
GWP (million tonnes CO_2 eq.)	2,198	3,357	3,325	2,923	2,358	3,000
Land use (km^2/yr ('000s)	5,847	8,645	8,488	7,354	3,706	5,538
Freshwater use (m^3 billions)	9,948	14,405	14,124	12,036	6,067	4,053

* Denote species which contributed to the GWP, land and freshwater use. The yields of the species and groups that are greyed out have not contributed to the GWP, land and water impacts quantified due to lack of available LCA data. Hence it is important to note that changes in impacts relate to changes in the production tonnages of a sub-set of meat and fish products (shown in Table 7.9) and not to the impact produced by all products listed above (including greyed out ones).

The total GWP, land and water use impact per scenario are shown graphically in Figures 7.14, 7.15 and 7.16 respectively. Within each of these figures, the relative contribution of each of the meat and fish products (for which an LCA was undertaken in Section 6) to the total impact is shown.

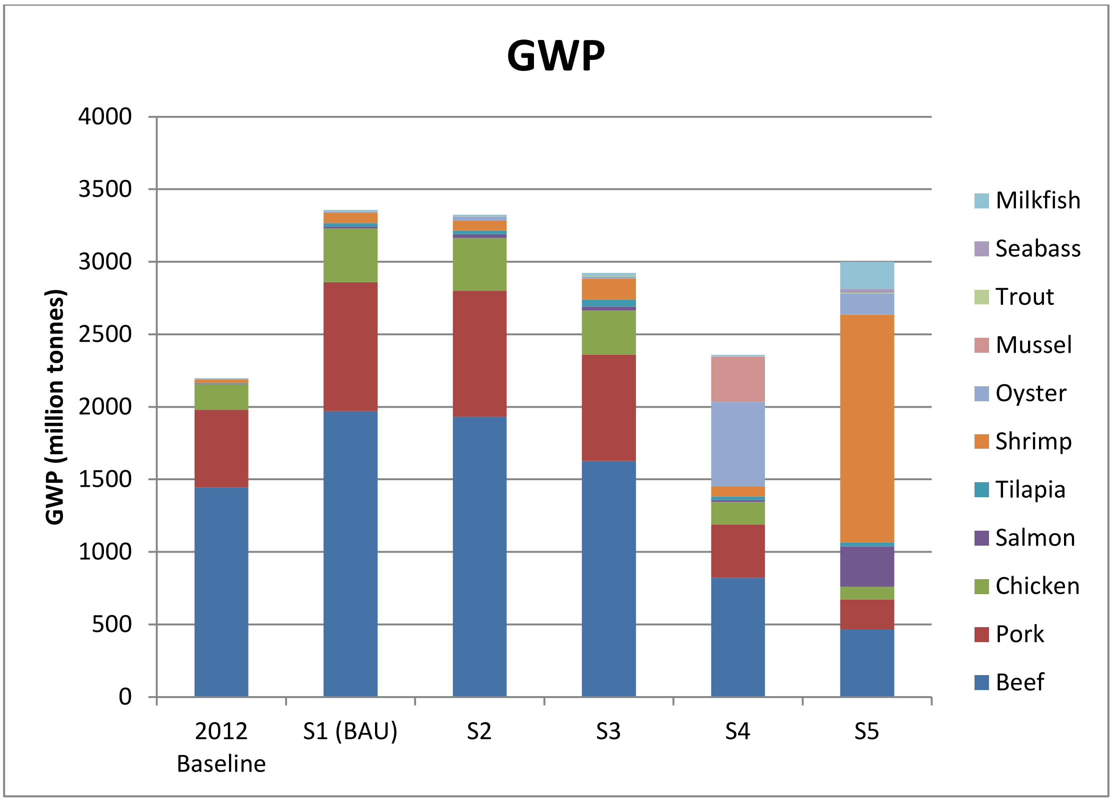

Figure 7.14 Global Warming Potential for the 2012 baseline and Scenarios 1 to 5

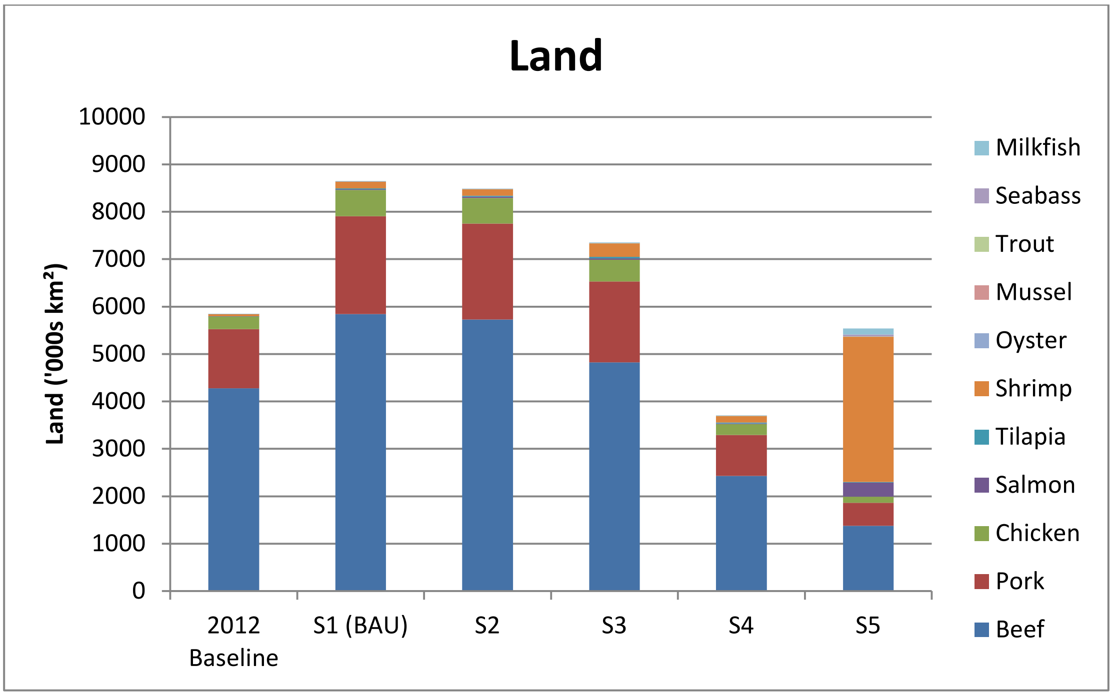

Figure 7.15 Land use for the 2012 baseline and Scenarios 1 to 5

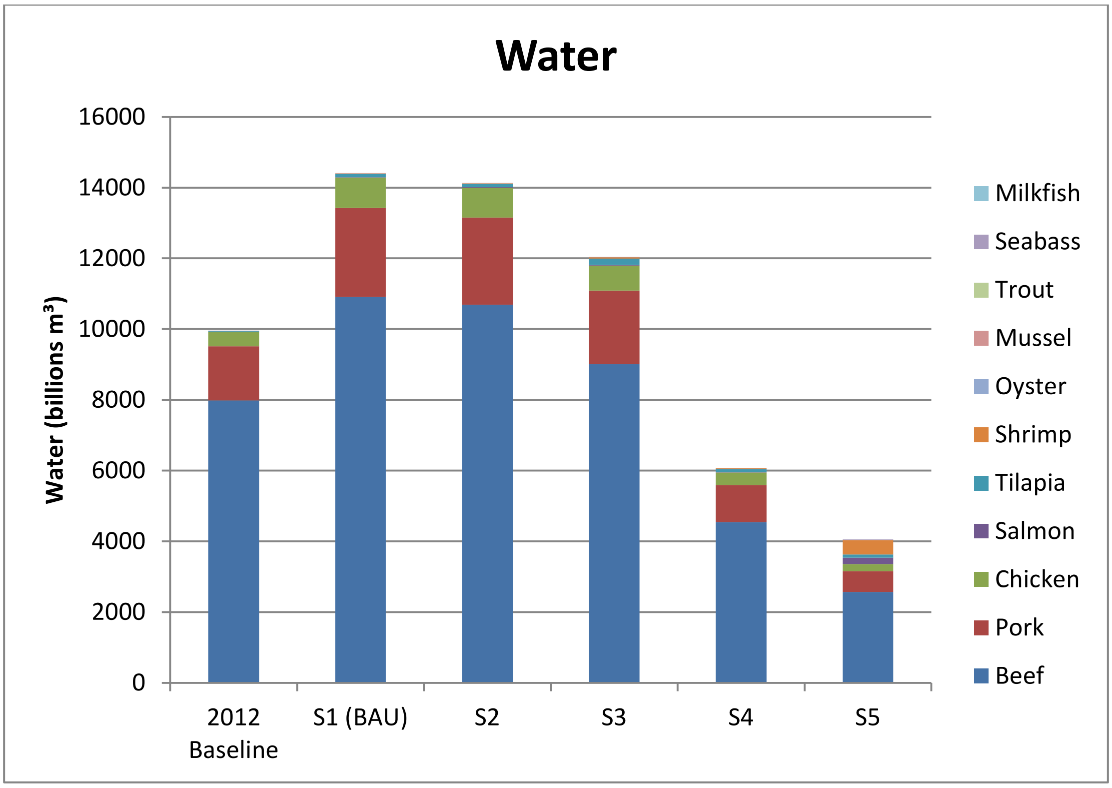

Figure 7.16 Freshwater use for the 2012 baseline and Scenarios 1 to 5

It is important to note that the total GWP, land and water use impacts shown in Table 7.10 and Figures 7.14 to 7.16 only relate to the impacts arising from the species for which there was robust enough LCA data (indicated with '*' in Table 7.10 above) and the overall edible yield produced from this subset of products differed between the scenarios. As such in Table 7.11 and Figure 7.17, the GWP, land and water impacts have been standardised per million tonne of edible yield of the LCA species. The implications of the scenario outputs are discussed below in the context of these standardised results. The benefit of showing the role of non-LCA species in Table 7.10 was to indicate the significant limitation of assessing the global footprint of future scenarios in the light of the large proportion of fish production that will comprise carp and other species for which there is currently insufficiently robust data to incorporate them into the risk/benefit analysis.

Table 7.11 Standardised impact per mt edible yield of LCA species

	Baseline (2012)	Scenario 1 (BAU)	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total edible yields of LCA species (mt)*	194.46	335.34	335.95	299.96	353.19	358.72
GWP (million tonnes CO_2/mt edible yield)	11.30	10.01	9.90	9.75	6.68	8.36
Land ('000 km²/mt edible yield)	30.07	25.78	25.26	24.52	10.49	15.44
Freshwater use (m³ billions/mt edible yield)	51.15	42.96	42.04	40.13	17.18	11.30
* Edible yield (mt) represents the total edible yield of the following species in each Scenario: beef, pork, chicken, salmon, tilapia, shrimp, oyster, mussel, rainbow trout, seabass and milkfish.						

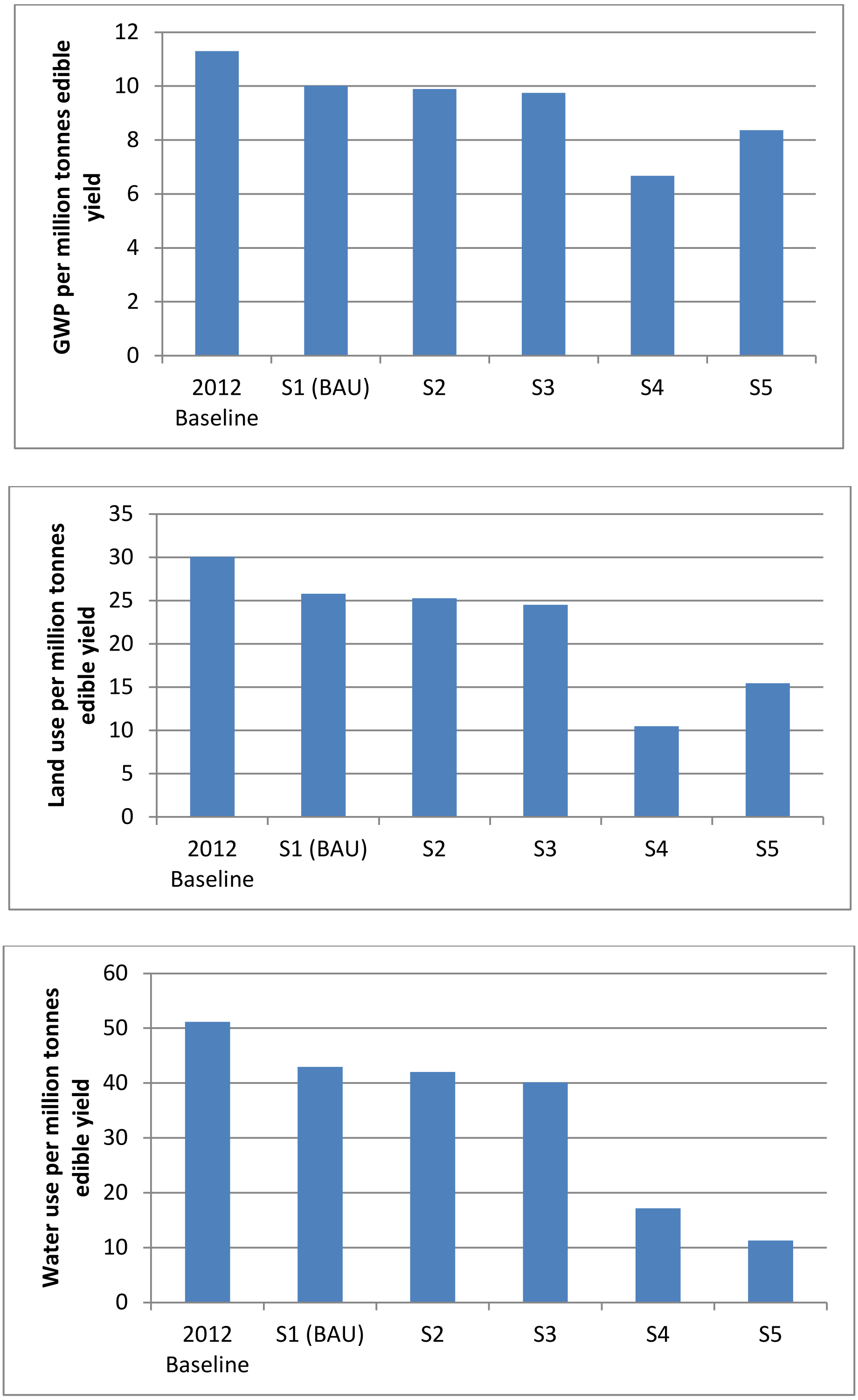

Figure 7.17 Standardised GWP (top), land use (middle) and water use (bottom graph) per million tonnes total edible yield of beef, pork, chicken, salmon, tilapia, shrimp, oyster, mussel, rainbow, trout, seabass and milk fish in 2012 and each future scenario.

Scenario 1 projected the GWP, land and water use in 2050, based on recent historical production trends of the species assessed in the LCA analysis in Section 6. Although the absolute production volumes (and hence edible yields) of all meat and fish products will increase substantially in 2050 compared to the 2012 baseline (see Table 7.10), the standardised results in Table 7.11 show that there is a small reduction in all impact categories in 2050. This is due to the greater increase in pork and chicken production in the BAU Scenario (65% and 114% respectively), which have a lower impact in all categories, compared to the projected increase in beef production (37%).

The aim of Scenarios 2 and 3 were to assess the effects of increasing some or all mariculture/freshwater aquaculture production and reducing meat production.

In Scenario 2, substantial increases in the production of low impact mariculture species (oyster, mussel and salmon) resulted in a further small reduction of impacts across all categories. The reduction in impacts was marginal despite shellfish production being increased by 300%, because the edible yield from shellfish is relatively very low and hence terrestrial meat production was only reduced overall by 1% to keep edible yield constant (note, the benefits of further increases in shellfish production vs. reductions in meat production were explored in Scenario 4).

In Scenario 3, doubling the production of all mariculture and freshwater aquaculture species produced a further relatively small reduction in the magnitude of GWP, land and water use, with the largest benefit observed in the water use impact category. The latter benefit was due almost entirely to the reduction in meat production as fish production was increased. Hence, this scenario suggests that the global footprint of food production can be reduced by substituting fish production for terrestrial meat production (albeit by a relatively small amount in this instance) and that this can be achieved through increasing both marine and freshwater aquaculture species in tandem, a scenario which is more realistic in the light of the dominance of global freshwater production (see Section 3).

The aim of Scenarios 4 and 5 were to assess the potential benefits which may be associated with visionary (very large) changes in global mariculture production and seafood consumption.

Scenario 4, in which 50% of the projected demand for animal protein from meat and fish in 2050 was supplied through oysters and mussels, resulted in the lowest GWP and land use impacts of all of the scenarios. This was despite Scenario 4 producing almost double the amount of terrestrial meat compared to Scenario 5 and having a substantially higher GWP relating to on-farm operations for oyster production and depuration requirements for mussel and oyster production, compared to the other scenarios[28]. It can be assumed that future improvements in the energy efficiency of operational processes involved in bivalve shellfish production, advances in energy production (e.g. renewables) and, where possible, shellfish production in waters not requiring depuration, would further reduce the GWP in this scenario.

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28 It should be noted that the on-farm operation energy requirements for oysters in the LCA analysis (see Figure 6.9) was based on data from three oyster farms in Scotland (Auchterlonie *et al*, 2014) and hence is unlikely to be representative of GWP relating to global oyster production.

Further inspection of the data revealed that the lower GWP and land use in Scenario 4 was predominately influenced by the lower level of shrimp production, which resulted in substantially lower GWP and land use compared to Scenario 5 (the large standard deviation in the underlying shrimp LCA data must be noted).

Water use in Scenario 4 was substantially reduced, compared to the BAU Scenario 1 (60% reduction in Scenario 4) whilst the greatest relative reduction in water use was achieved in Scenario 5 (74% reduction compared to BAU Scenario 1) due predominately to this scenario having the lowest level of meat production and the highest level of fish production of all of the scenarios.

Overall, the results suggest that increasing global mariculture production has the potential to reduce impacts on land and water resources and GHG emissions, although only relatively small changes to the projected impacts were achieved in Scenarios 2 and 3 despite substantial increases in marine and/or freshwater aquaculture production. More substantial reductions in the global footprint of food production were only indicated to occur through the visionary changes in global mariculture production and seafood consumption presented in Scenarios 4 and 5. It is important to note that the results do not account for any differences in the nutritional value of edible yield produced in any of the scenarios or take account of potential constraints to the expansion of mariculture (e.g. available marine space, technology, feed availability etc. which are discussed further in Sections 7.2.1 and 7.3). As such, it may be that significant reductions in impacts will need to be sought through concurrent substantial changes in other sectors, for example, through improvements in feed technology (see below) and increases in energy production from renewable sources.

The results indicate there are some areas where the impacts of mariculture could be further reduced in terms of reducing GHG emissions, land and water use which should be investigated further. For example:

- The relatively small reduction in footprint associated with increasing mariculture production in this study (i.e. in Scenarios 2 and 3) relates primarily to the link between the use of land and water resources for formulated aquaculture feed. Improvements in feed technology (see Section 7.2.1 below) could further reduce the pressure on these resources and hence reduce the footprint of mariculture production;
- Scenario 3 suggested that the greatest reduction in footprint could be obtained via a strategy to expand both marine and freshwater production, a scenario which is more likely based on the fact that freshwater culture currently dominates production and is the area of largest growth. Future improvements in feed technology which reduce the reliance of formulated feed on land based crops, such as improving FCRs, will help to further reduce the footprint of freshwater aquaculture as well as mariculture. There may be potential to reduce the pressure of freshwater aquaculture on land use through the transfer of saline tolerant species such as tilapia to marine based systems at an appropriate stage in their life cycle and this is an area that should be further investigated;
- The current study has conservatively kept meat proportions constant throughout the scenarios. However, as beef production clearly has the highest impact across all categories (see Section 6), an obvious strategy for gaining maximum reductions in

GHG emissions, water and land use is likely to involve substantial reductions in beef production. The impacts associated with pork and chicken production were relatively similar to the impacts of fish production in the current study, and hence further investigation of the optimal ratios of these products is required;

- In terms of space requirements, the current study used crude calculations to estimate the increase in marine space that would be required for each scenario. The indicative results suggest a potential increase in sea area of about 171%, 205%, 443%, 2,135% and 5,855% in Scenarios 1, 2, 3, 4 and 5 respectively, although due to the highly variable mariculture production methods used globally the absolute measure of sea area cannot be calculated with any level of robustness in the current study. Further studies focussing on specific regions/areas could address this aspect more rigorously. It should be noted that because the potential changes in sea area were calculated for live weight production of fish and shellfish, the % increases in sea area required per scenario were substantially greater than the % increases in edible yield of fish and shellfish produced in each scenario.

The feasibility of the Scenarios, and the wider environmental and socio-economic risks and benefits of expanding global mariculture to the levels explored are discussed further in Sections 7.2.1 and 7.3 below.

7.2.1 Scenario Feasibility and Ability of Mariculture to Contribute to Future Seafood Demand

The above analysis has developed theoretical scenarios based on recent historical production trends and used the LCA outputs to enable relative comparison of the impacts of these scenarios on GHG emissions, land and water use. However, it is also interesting to consider how these increases in production compare to previous future projections of demand for seafood and whether such future scenarios are viable given the land and water resources available.

Section 3 provided some examples of future projections of global seafood demand, highlighting that the lower predictions of some projections for 2020 and 2030 had already been exceeded in 2012 (see Table 3.2). In the current study, the projected production of fish (fish and shellfish; live weight) in 2050 were 125mt (Scenario 1), 150mt (Scenario 2) and 250mt (Scenario 3). Hence fish production in Scenario 3 exceeds that of the demand projected by Wijström (2003) for 2050 (270mt comprising of aquaculture and wild capture fisheries, the latter presumably plateaued at 70mt as per the 2000 baseline and hence approximately 200mt relating to aquaculture production).

As noted in Section 3, future demand for seafood is influenced by numerous factors including consumption, demand and market development in addition to the availability of land and water resources. In 2012, global per capita fish supply was approximately 19kg/ per person (pp), ranging from 1kg/pp in Ethiopia to over 70kg/pp in Hong Kong). Assuming a population of 9 billion in 2050 (see Section 7.3 for the uncertainty surrounding projected population increases), global per capita fish supply from total marine and freshwater aquaculture production plus wild capture fisheries would be 22kg/ pp, 25kg/pp and 36kg/pp in Scenarios 1, 2 and 3 respectively. It is extremely difficult to assess whether the projected fish production in Scenario 3 would require a realistic consumption per capita, given that consumption per capita varies enormously at a global level (from 1kg/pp in Ethiopia to over 70kg/pp in Hong Kong in 2012; see Section 3.4.1). Regional fish consumption is influenced by numerous factors (already described in Section 3) including access to products, cost, culture and marketing and it is not possible to further assess whether such levels of per capita consumption are realistic within the current study.

In order to assess whether such fish production volumes may be viable, the absolute production volumes of feed required for each future scenario is briefly explored below (i.e. the LCA assessed the impacts on land and water use, however, this text explores whether the production required exceeds the feed resources available and the impacts of potential future developments in feed formulations).

Table 7.12 shows the increases in feed components, compared to 2012 baseline levels that would be required for Scenarios 1-3 (based on current inclusions of constituent products). The results show that increasing the proportions of mariculture (Scenario 2) and of all freshwater and mariculture production (Scenario 3) compared to meat production results in progressive reductions in the absolute amount of feed required as would be expected from the reduction in impacts on land and water use in the LCA assessment. However, there is potential for additional reductions in land and water use impacts if feed requirements can be reduced through altering the proportions of protein produced by land-based and marine/freshwater-based systems. With regard to other marine species, particularly carnivorous finfish, the fishmeal issue is of critical importance. Even in absolute best case scenarios, utilising all by-products from fisheries and aquaculture production, it is unlikely that the increase in fishmeal production could be increased by more than a factor of two. Therefore current inclusions could not be projected to meet the levels required in Scenario 3. The demands on terrestrial crop production are far less and with further advances in feed technology, more vegetable based protein could be included and better efficiencies could be obtained. Well targeted use of fishmeal is also required, utilising it as finishing diets and at critical juvenile stages rather than throughout the production cycle could also allow for further efficiency savings.

Table 7.12 Increases in major feed ingredients required for Scenarios 1 to 3, assuming current proportions

Ingredient	% increase from 2012 requirement		
	Scenario 1	Scenario 2	Scenario 3
Fishmeal	196	246	492
Soy bean	54.5	50.5	41.2
Maize	57.6	53.3	41.1
Wheat	45.7	42.1	47.6
Oilseed rape, pea, sunflower	159	357	419
Total feed increase	46.5	42.3	34.0

In Section 6, it was highlighted that by far the highest contributions to freshwater consumption and land use were from feed provision for mariculture. Recent advances in feed technology resulting in reductions in FCR have been comparatively much bigger in aquaculture than terrestrial species. Therefore, by increasing the efficiencies of major feed production crops and their use in feeds on farm, there is proportionally much more scope for improvements in aquaculture production than there is for terrestrial species.

7.3 Consideration of Wider Issues not Accounted for in the Quantitative Comparison

It is important to note that the quantitative analysis described above has necessarily been simplistic in its approach. In addition to the data and methodological limitations already described (see Sections 6 and 7.1.1), the analysis was not able to account for factors such as future gains in technological efficiencies of marine (or freshwater) production systems which are likely to improve considerably. Similarly, although a basic estimate of the potential increase in sea area required for the projected mariculture production levels was made, the scenarios could not account for the potential geographical location of the increased mariculture production and whether the challenges of production in such locations (for example offshore environments) may negate increases in production efficiencies. Similarly, the scenarios could not account for whether the environmental impacts, for example, on habitats and species may outweigh the benefits afforded to land and water resources. The purpose of the following section is to explore these issues in further detail, through discussion of the general constraints to expanding mariculture towards levels proposed in the scenarios and the wider environmental and socio-economic risks and benefits of doing so.

It is important to note that the relative magnitude of the risks and benefits will be influenced by the uncertainties of key factors including:

- Population increases and demographics – projections of global populations in 2050 are uncertain (e.g. ranging from 8.3 billion to 10.9 billion; UN-DESA, 2013). Population changes will not be uniform but it is expected that major increases will occur among groups for which seafood is a preferred dietary component. (e.g. Asia, and west Africa). These are also areas of rapid urbanisation and aquaculture-derived products will be needed to substitute for wild caught fish in the diets of these people, in contrast to the subsistence fisheries that sustain rural populations. Increased purchasing power might also affect preference for different types of seafood stimulating additional demand for higher value (and generally higher trophic) marine species as has been observed in China (Fabinyi *et al* 2012; World Bank 2014). This will have a significant impact on feed and other resource requirements between the scenarios as presented.
- World trade patterns – as described for population, the distribution of seafood products and waste is not uniform. Increases in regional trade as compared to further development of global value chains, are highly likely given current trajectories. For example intra-Asian trade is developing fast and is likely to be more diverse and sustained than many other types of the seafood trade. As such, there is the possibility of undersupply of aquaculture products to meet continuing growth in EU seafood needs. Furthermore there is also the issue of equitable access to nutrition, if and when the price of seafood increases;
- Consumption, related to consumer preference, is likely to change as noted above, and is highly impacted by purchasing power. However, the very large numbers of poorer rural people will ensure that demand for freshwater species is maintained. In absolute terms, production of marine species is likely to remain low compared to freshwater even though growth rates will be high.

- Technological advances and gains in production efficiency – these would be expected to be relatively large compared to terrestrial livestock production as many forms of aquaculture are relatively novel and utilise, essentially, unimproved genetic stock.

7.3.1 Key Challenges (Constraints) to Expansion of Global Mariculture

The key issues considered to influence the ability to substantially increased global mariculture production are briefly discussed below.

- Available space in the marine area – in general it is accepted that in the future, production will look to move offshore in many regions (e.g. for large fish species such as salmon) where there may be less competition for space, although offshore marine sectors will still provide some competition for available space. However, such offshore mariculture developments will only occur if larger scale production can be achieved in these more challenging environments to compensate for the high investment costs required i.e. they are economically viable. Integration with marine spatial planning is essential to ensure beneficial outcomes, especially linkages with the investment and implementation of offshore renewable energy. Concentration of production (output/length of coastline) is highly variable, partly depending on the species produced (see Section 3); where shellfish is in demand, higher levels of production can be sustained than finfish. Countries with large brackish water zones (Egypt, Vietnam, Bangladesh) also have high productivity because of their large brackish deltaic areas that are ideal for pond-based production. However, there are potential threats to biodiversity, for example, through destruction of habitats, such as mangrove forests if such development is not managed responsibly (including through mitigation measures such as marine protected areas, conservation zones, mangrove/seagrass restoration etc.). Marine engineering constraints aside, high costs and risk prevent the greater development of offshore aquaculture. Examples of potential areas for mariculture development that may provide opportunities if various constraints can be overcome include:

    - Scope for the development of coastal ponds for shrimp and fish production in tropical Africa (East and west coast) and parts of South America (Brazil) although there are potential threats to biodiversity and ecosystem services (e.g. mangrove destruction). However the economic models are well established providing disease risk can be reduced. Issues of lack of infrastructure, investment capital and know-how are gradually being overcome especially with increased Chinese investment in Africa. There is also scope for further intensification of production in many coastal pond systems (SE Asia and Egypt), particularly if reliable power supplies can be secured;
    - Cage-based culture in African lakes and reservoirs is developing fairly rapidly as technology is developed and relatively cheap. The main constraints relate to the cost of feed inputs and general infrastructure (transport and power) problems. Freshwater recirculated aquaculture faces much of the same problems as marine RAS but with technology cost and power cost issues addressed it could expand according to market demand for produce;

  - Integration of shellfish production with offshore energy production schemes (e.g. offshore wind farms, tidal lagoons) to maximise productivity from available marine space, although such integration faces challenges (e.g. incentives for integration with offshore renewable developers) and is likely to require legislative support to ensure consideration of co-location of such activity is a condition of the consents process (e.g. see Syvret *et al*. 2013). This opportunity will only occur in countries where offshore renewable development is occurring/expanding in relation to policy drivers;
- Technological advances to enable adequate scale production in more challenging offshore environments. Very large scale production will be required to achieve viable economies of scale and this has not yet been proven to be economically viable;
- Sources, availability and cost of feed ingredients (for fed species) – linkages with land-based crop production may not be a major constraint providing plant-based alternatives with amino acid supplements are acceptable to consumers (see opportunities section below). Closer integration with terrestrial livestock, and in particular the use of non-bovine Processed Animal Proteins (PAPs) in the form of by-products from meat processing as feed ingredients will need to be encouraged subject to chain of custody and market development (see Section 6);
- Lack of social support for mariculture expansion in some regions (generally developed regions) - for example relating to visual impacts and concerns regarding 'environmental' impacts (particularly pollution and impacts on wild populations/communities). Strategies to further develop social licence will be multidimensional including Corporate Social Responsibility (CSR), aesthetically improved infrastructure and public education. It remains a negative issue in the EU and North America rather than in the major areas of global production;
- Economics relating to market demand and consumption patterns – particularly for 'low unit value' products (e.g. mussels, seaweed) – especially if looking to expand in challenging (e.g. offshore locations) where production costs will be higher. There will be a need to develop value added opportunities local to production that reduce the cost of production and for significant increases in scale of production. Shellfish and algae remain small-scale enterprise in much of the world but meeting the production targets implicit in the scenarios will require wholesale change in these sectors;
- Water quality for shellfish production – good water quality is a key requirement for shellfish culture in countries in which food hygiene and safety regulations are applied. The unexpectedly high GWP associated with both oyster and mussel production in the LCA analysis related to the energy required for on-farm operations for oysters and depuration for both oysters and mussels (although as noted above the on-farm operations GWP data was based on one study). Again technology development to reduce such costs is likely given market incentives. Currently demand for such products is greatest in areas where water quality is often most likely to give rise to public health constraints. Paradoxically these are the areas where shellfish often perform well given high levels of background fertility from man-made pollution and their production in such areas offer an environmental service (i.e. a beneficial ecosystem service, currently not considered in the limited number of published shellfish LCA).

7.3.2 Wider Environmental Impacts (Risks and Benefits) of Expanding Global Mariculture

There are a number of potential environmental impacts associated with mariculture systems that are not accounted for in the LCA analysis presented in Section 6. It is outwith the scope of the current study to provide a comprehensive review of the literature relating to environmental impacts of mariculture, however, the main impacts which are not accounted for in the LCA analysis are briefly described below.

In general, potential environmental impacts of mariculture may include the following:

- Smothering of benthic habitats and associated communities through the deposition of particulate waste. In finfish farming the particulate waste comprises fish faeces and uneaten food pellets. In shellfish farming the particulate waste comprises faeces and pseudofaeces excreted by the shellfish;
- Organic enrichment and subsequent deoxygenation (anoxia) of seabed sediments leading to changes in benthic communities. This pressure arises when deposited particulate organic matter (described above) starts to breakdown and form a source of nutrient inputs for the natural fauna both within the sediments and the overlying water column. On and within the sediments, aerobic respiration and other oxygen dependent microbial processes fuelled by the waste, impose extra oxygen demands on the system potentially leading to deoxygenation and anoxia;
- Nitrogen and phosphorus enrichment of the water column and potential subsequent effects on pelagic communities and water quality. This pressure arises from the release of dissolved nutrients including ammonia, nitrate, nitrite and phosphate arising from fish excretory products and dissolution from feed pellets and/or faecal particles. Where the addition of these nutrients leads to harmful effects the system is described as ‘eutrophic’[29] (see also Section 6.2.1.7);
- Exceedance of ecological carrying capacity and subsequent impacts on ecological processes, services, species, populations or communities in the environment (e.g. FAO. 2013);
- Chemical pollution arising from the application of veterinary medicines and sea lice treatments in finfish farming and biocide boosters in antifoulants (if used on mariculture infrastructure) and their subsequent release into the water column and/or underlying sediments (e.g. Roberts *et al*. 2014);
- Introduction of invasive non-native species (INNS), for example, transferred accidently with the broodstock or juveniles of species for culture or through the introduction of new non-native species for culture. Subsequent impacts on local biodiversity may arise through competition for food or other resources (e.g. habitat), predation on native species, transfer of disease (see also below) or modification of habitats;

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[29] Marine eutrophication is defined in the OSPAR Eutrophication Strategy as “the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned, and therefore refers to the undesirable effects resulting from anthropogenic enrichment by nutrients as described in the Common Procedure“.

- Transfer of pathogens (viral, bacterial or fungal) and/or parasites from cultured stock to wild populations. As noted in Section 3.4.5.3, diseases tend to spread initially from the wild to farmed populations, however, the farmed stock then act as a reservoir and a source of infection back to wild populations. Examples include white spot syndrome in shrimp, infectious salmon anaemia, oyster herpes virus (OsHV-1) and *Bonamia ostreae* which also affects oysters;
- Genetic interaction between escaped farm fish and wild populations;
- Degradation of coastal habitats and subsequent loss of ecosystem services with land use transformation for marine or brackish aquaculture (e.g. for example through conversion of mangrove forest to shrimp farms) (see Section 6 for introduction to this issue);
- Disturbance or displacement of other fauna (e.g. birds or seals) by scaring devices designed to discourage predation of stock;
- Impacts on wild resources i.e. fish and shellfish, arising from harvesting for use as seed (in the case of shellfish farming) or fish stocks harvested for use in aquaculture (see Sections 3 and 6).

Some of the above impacts are well researched and documented (e.g. the impacts of finfish farming in sheltered sea lochs), however, there is a lack of knowledge around the dispersion of wastes and impacts in higher energy and more offshore sites. Such impacts will need to be better understood to enable large scale production offshore.

With regard to fish farming, implementation of fallowing, often requiring changes in governance (site licencing etc.) is an effective approach already used in some contexts to reduce environmental impacts. In general shellfish farming is considered to have less environmental impacts due to the lack of feed (hence the low land use impacts in Section 6) and chemotherapeutants required. However, introduction of invasive non-native species, disease and exceedance of biological carrying capacity with subsequent effects on biological communities and mariculture yields are still potential issues.

Increasing mariculture production may be achieved through increasing the productivity (yields) from farms and/or increasing the number and size of farms. As such, cumulative impacts of such expansion will also pose environmental risks (as described above). Potential cumulative impacts can only be assessed at a local level as they will relate to numerous issues including the prevailing physical conditions, the ecological carrying capacity of water bodies, the sensitivity of the biological communities in the vicinity of farms, other marine activities activity occurring in the area and other sources of pollution relating to other marine activities or land use.

Potential environmental benefits of mariculture relate to the beneficial ecosystem processes and services (beyond food provision) which may be provided by cultivated algae and shellfish, including in IMTA systems as described in Section 4. For example, numerous laboratory studies have investigated mechanisms of nutrient uptake by seaweed species including *Laminaria/Saccharina* spp., *Gracilaria* spp., *Porphyra* spp., *Ulva* spp., *Euchema* spp. and *Codium* spp. In addition to providing information on the function of nutrient uptake, they help identify species suitable for integration in IMTA systems, although observations from laboratory experiments are not necessary reproducible in open-water. The ability of macroalgae to remediate dissolved nutrients from finfish and shellfish has been demonstrated in land-based IMTA systems, where bioremediation can be optimised through the selection of the appropriate densities and culture sizes, and by controlling the supply of nutrients to the seaweed. However, this level of control is not possible in open-water systems where nutrient are released into an environment of variable, complex hydrography. As a result, it can be difficult to locate an area where the direct uptake of nutrients would be optimised. Despite this, the cultivation of seaweed does remove dissolved nutrients from the environment, and in some cases improved seaweed growth and reduced nutrient concentration has been demonstrated when seaweed culture is located in proximity to higher trophic aquaculture. However, environmental impacts may occur through the cultivation of seaweed itself, for example shading, sedimentation, introduction of INNS, depending upon the environment.

With regard to shellfish, there is evidence that naturally occurring oyster reefs provide beneficial ecosystem processes such as biogeochemical cycling, nutrient removal, turbidity reduction (with subsequent habitat improvement), provision of habitat for other species and supporting juvenile fish populations (e.g. see Herbert *et al*. 2012). In some locations, restored oyster reefs (using cultured oyster seed) have been created to improve water quality (e.g. see the Billion Oyster Project, New York Harbour, USA[30]); although in these instances the oysters are not suitable for human consumption. As noted in Section 4, it has been proposed that filter feeders, such as oysters, can be used as 'biomechanical filters' in intensive fish or shrimp aquaculture, as an inexpensive option to improve water quality by removing particulate organic matter and dissolved nutrients from effluent waste water. The ability for bivalves to intercept fish faecal and waste food particles has been demonstrated in laboratory experiments, for example, Lefebvre *et al*. (2000) indicated that Pacific oysters are capable of filtering most of the faecal particles in effluents from land-based fish farms and that detrital waste from intensive fish-farming can contribute to the growth of the oysters. However, when such wastes are released in pulses from fish farms they surpass the concentration at which the bivalve can effectively intercept, and often a significant proportion of particles are deposited below the finfish area. Furthermore, where planktonic organisms such as microalgae are present, they may be preferentially selected as a source of food. Beyond laboratory experiments, empirical evidence demonstrating bioremediation of particle wastes is limited, but positive observations have been made. Bivalves have also been considered for their potential to feed upon algae that has proliferated due to dissolved nutrient emissions from aquaculture, thus resulting in indirect bioremediation. Although there is not strong evidence of microalgae blooms resulting as a direct result of marine cage aquaculture activities in western countries, in enclosed bays with high fish biomasses and restricted water exchange, the occurrence is possible. Although these considerations imply that the remediation of fish waste through bivalve cultivation may only be feasible in some circumstances, ecological models incorporating the balance of nutrient emissions and extraction have showed that bivalve co-culture might result in a net removal of nutrients.

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30 The Billion Oyster Project website: http://www.billionoysterproject.org/

7.3.3 Wider Societal Impacts (Risks and Benefits) of Expanding Global Mariculture

The societal importance of aquaculture (mariculture and freshwater) varies significantly across the world in line with the distribution of production and consumption of farmed aquatic animals. Although the growth of aquaculture has been strong in the last decades, its comparative importance relative to wild stocks remains uneven globally; ranging from contributing less than 20% of fish consumed in Europe to more than 50% in Bangladesh and China.

Aquaculture remains spatially concentrated in the Asia Pacific; sub-Saharan Africa despite significant areas of high consumption, contributes a very small proportion of global aquaculture crop (<5%). In general aquaculture is concentrated in low and medium income countries (LMIC) and the net value of seafood traded internationally from developing countries exceeds all other agricultural commodities (Bene *et al*, 2010). Trade between neighbouring countries is also traditional for many aquatic products, especially for processed products, and aquaculture is increasing the importance and value of such trade. The impacts of aquaculture and the broader fisheries sector on poverty are difficult to unpack (Arthur *et al*, 2013) but many will occur through the value chain as a whole rather than on farm.

Figure 7.18 Shrimp processing, Soc Trang, Vietnam (Source © Richard Newton)

Many of the benefits occur as employment opportunities and the sector as a whole has a significant beneficial impact on poorer sections of societies in both LMICs and Organisation for Economic Co-operation and Development (OECD) countries[31]. In Bangladesh the notion that

[31] OECD countries comprise 34 Member countries which span the globe, from North and South America to Europe and Asia-Pacific. They include many of the world's most advanced countries but also emerging countries like Mexico, Chile and Turkey.

aquaculture mainly benefitted the better off (Lewis, 1997) has been revised (Belton *et al*, 2014). The Scottish salmon industry supports poorer urban livelihoods through processing and value addition in Central Scotland in addition to supporting isolated and vulnerable farming communities in the Highlands and Islands (Alexander *et al*, 2014). Undoubtedly exploitative practices remain within the sector, especially among those with weak bargaining power and few livelihood alternatives such as women seaweed growers in poor coastal communities that remain trapped in unfavourable patron-client relationships with buyers and processors.

A key claim is that improved diets are often a key outcome of aquaculture development. In this respect, even in poorer countries, subsistence-level aquaculture has often been less important than commercial entities where higher incomes through employment lead to greater discretionary income and strategic purchase of fish and other nutritionally dense foods. Even smallholder systems have been found to enhance household diets directly and, through increased income flows from sales and the value of a pond on the homestead can return benefits through the irrigation of vegetables in addition to fish (Karim *et al* 2011). Access to, and affordability of, fish has generally increased as aquaculture has become established. Post-2008 global food shock, prices of aquaculture products often trended well below other key dietary items and the major farmed fish often become the cheaper seafood choices as the abundance and quality of wild species decline.

These trends are increasingly important as LMICs become more urbanised and the poor become consumers rather than exploiters of seafood. Aquaculture as a livelihood option for poorer groups is unequally distributed and subject to dynamic change. In Asia those involved in the sector are often of low social status, migrants and/or ethnic minorities. Some studies have shown that participation in farmed seafood value chains can enhance such people's autonomy and strengthen their position.

The role of fish and other aquatic products in diets is the focus of current research in both the developed and undeveloped world with a consensus emerging that in addition to high quality protein, micronutrient, and particularly fats, are often critical. The comparative dietary value of cultured and wild fish has become an issue of concern in some quarters, especially as marine ingredients are declining in most fed species in favour of plant-based ingredients. Essential fatty acid levels tended to be optimal in small indigenous fish in Bangladesh for example (Bogard *et al*, 2015) and one approach is their incorporation into polycultures. Studies on farmed salmon fed with 'eco-diets' lower in marine ingredients indicated that they can still comfortably meet most nutritional requirements (de Roos *et al*, 2014).

Emergent issues are the scale of aquaculture (household, small to medium enterprise (SME), corporate) that delivers the most development benefit, and the associated levels and rate of consolidation occurring in certain aquaculture industries globally. Trends towards more technology-dependent and resource efficient systems potentially exclude smallholders from production as do the demands for transparent and traceable value chains. These requirements appear to be exacerbated by the spread of third party private standards that are becoming a *de facto* governance system in many contexts, potentially undermining local food sovereignty.

7.4 Summary

The results indicate that increasing the proportion of mariculture does contribute to an overall reduction in GHG emissions, land and water use, although making substantial changes to the impacts of future global food production will likely require strategies to expand freshwater as well as mariculture production and reduce the impact from formulated feed in addition to substantial changes in other sectors such as renewable energy. Key opportunities to maximise the benefits of increasing mariculture production could include the following, although further assessment of the feasibility and likely benefits would need to be made:

- Reduce the impact from formulated feed - primarily through reducing the amount of feed used in production systems but also through replacing some crop-based feed inclusions with more efficient ingredients and improving the efficiency of the feed production process (see technology related mitigation below). This will require continued research into the development of alternative protein and oil sources for livestock and aquaculture feeds (for example, from insect larvae, algae) and into maintaining the nutritional attributes of farmed seafood as feed composition changes. Improve FCRs to reduce the impacts associated with feed production for fed marine and freshwater aquaculture species to further reduce the footprint of farming aquatic fish species;
- Increase both mariculture and freshwater aquaculture, a scenario which is more likely based on the fact that freshwater culture currently dominates production and is the area of largest growth;
- Improve the efficiency of on-farm energy use and depuration (where required) to reduce the GHG emissions associated with shellfish (oyster, mussel) production, which have minimal land and freshwater requirements. Increase production of shellfish species (oyster, mussel) in areas of good water quality to reduce the requirement for depuration and hence the associated GWP impact. The ability to do this would depend on the availability of space in coastal or marine areas with good water quality, the economic viability of production in such areas and the ability to transport the product to consumers without negating the GWP impact reductions achieved;
- Substantially reduce the proportion of beef production and increase the proportion of pork and chicken production which had a relatively similar magnitude of impact as fish in this study (see Section 6);
- Increase production of freshwater species with relatively high saline tolerance (e.g. tilapia) in brackish water where competition for water is lower (i.e. to further decrease associated water use impacts of this production). Such areas may include higher coastal ground (as opposed to coastal habitats such as mangrove forests) to which brackish water can be supplied;
- Potential for development of brackish water production in coastal fringes where saline intrusion occurs (as this land is not suitable for crops);

Potential opportunities for technology to mitigate against any impacts of increasing global mariculture production include the following:

- Future improvements in feed technology to reduce the reliance of formulated feed on land-based crops (and hence lower the land and water impacts of feed production) and

minimise waste through the inclusion of all agricultural, fisheries and aquaculture by-products;
- Further development of IMTA, with the use of extractive species (macroalgae, shellfish) to reduce the impact of production of higher trophic species with the subsequent production of additional products for the food production system (e.g. for feed even if not for human consumption);
- Advances in biotechnology, for example selective breeding of finfish species to increase growth (yields), disease resistance and tolerance to a wider range of dietary ingredients (to optimise feed ingredients and minimise impacts as above);
- Land-based RAS could reduce potential impacts on the marine environment and the nutrient rich effluent can be further used in the food production system, for example, for aquaponics (integrated systems in which fish and plants are grown together with the fish waste providing an organic food source for the plants). However, economic analysis currently indicates this technology is uncompetitive and liable to fail commercially unless the product is a high value and/or niche species. In addition such systems also require high capital costs and energy requirements. However, such systems may offer more potential opportunity with any future technological advancements in energy production. Offshore self-contained systems also have potential and may have significant advantages over both RAS and conventional and off-shore cage systems.

In addition to the LCA methodology and data limitations already described in the report, a further limitation of this study relates to the regional influences which cannot be accounted for in the global assessment. For example:

- Environmental impacts, which may be site-specific, need a zonal approach to assessing carrying capacity and managing impacts. The 'eutrophication potential' impact assessed in Section 6 would potentially be a better indicator of more local impacts.
- Socio-economic impacts will vary by location and region as described in Section 7.3.3;
- Consumption and culture vary greatly between regions, for example, there are areas in both Asia and Africa that have very high and very low consumption and cultural norms affect the level of waste (eaten whole, eaten as a processed product); and
- Local feed ingredients often have higher environmental impacts than those sources from global markets.

For this reason it is extremely difficult to assign a relative ranking to the constraints, risks and benefits of increasing global mariculture. It is recommended that a similar approach to that presented in the study could be applied to more region/site specific assessments.

Table 7.13 summarises the key constraints, risks and benefits of expanding global mariculture to help meet future projected demand for seafood. The relative magnitude of the constraints, risks and benefits has been assessed based on the judgement of the project team.

Table 7.13 Summary of key constraints, risks and benefits of global mariculture expansion

Summary of Key Constraints, Risks and Benefits		
Constraint	Relative Constraint Level	Further Comment
Coastal and marine space	Medium - High	High e.g. UK/Europe where there is a high level of competition for space. In these areas it is essential that future space requirements for industry development are considered within marine spatial planning for example through spatial models to assess areas of 'aquaculture potential' (e.g. MMO, 2013). However, the benefits to the industry of inclusion in marine plans is yet to be tested in the UK. Integration of mariculture with infrastructure associated with other offshore marine sectors (e.g. renewables) provides a good opportunity for maximising efficient use of available space, although incentives and/or legislation are likely to be required for such co-location. Further constraints may arise in relation to the social and political acceptability of increasing the size and/or density of mariculture facilities in coastal/marine areas in the UK, Europe or North America, for example, in relation to landscape and visual impacts and subsequent effects on amenity value. High – Asia where coastal space likely already being fully utilised. Medium – Africa and Latin America – possible potential for further development in coastal waters
Technology – offshore mariculture	High	Competition for space is likely to be reduced offshore, however, the technical and economic feasibility of large scale mariculture production offshore is yet to be proven.
Technology – feed	High	The production of feed ingredients is the key driver of GHG emissions, land and water use for fed aquaculture species. The reliance on land-based crops for feed ingredients needs to be reduced, primarily through reducing the amount of feed used in production systems but also through replacing some crop-based feed inclusions with more efficient ingredients and improving the efficiency of the feed production process. This will require continued research into the development of alternative protein and oil sources for livestock and aquaculture feeds (for example, from insect larvae, algae) and into maintaining the nutritional attributes of farmed seafood as feed composition changes. Improve FCRs to reduce the impacts associated with feed production for fed marine and freshwater aquaculture species to further reduce the footprint of farming aquatic fish species Fishmeal and fish oil availability and cost have been highlighted as potential constraints to future expansion of mariculture, despite the potential for increased input from fisheries and aquaculture processing by-products. Research on alternative protein sources/supplements for use in feed that do not further impact land and water use (as well as resulting in a nutritionally adequate product) is required.
Market demand	High	Demand is a function of market price. Aquaculture competes against other food products, often in global markets. Expansion of aquaculture to more costly locations (e.g. more remote or more marginal areas) may therefore not be profitable if there is insufficient demand at that price
Pollution (water quality) - shellfish	Medium / High (e.g. Europe)	Water quality can influence economic viability in countries with food safety legislation for protection of public health. In 2014, 56% of food alerts for bivalve shellfish in Europe related to pathogen contamination

Summary of Key Constraints, Risks and Benefits		
		(e.g. norovirus) and 35% were related to biotoxins from harmful algal blooms (HABs). The frequency and intensity of HABs have increased worldwide (e.g. Fu *et al*., 2012), although risks can be reduced through biotoxin monitoring.
Lack of social licence to operate	Medium	Some countries (e.g. Europe, USA) - perceived and/or real environmental impacts relating to some forms of mariculture (predominately finfish culture) can result in general opposition from the public. Other objections can relate to visual impacts (and hence loss of amenity value) even though there does not appear to be any direct evidence for the latter.
Consumption patterns	Medium	Regional differences in culture and consumption make this extremely difficult to assign a ranking to. Marketing and education may have some influence on consumer choice in some regions.
Risk	Relative Risk Level	Further Comment
Disease	Medium - High	Expansion of mariculture has the potential to introduce and/or spread disease to wild populations (impacts on biodiversity) and also poses a potential risk to the economic viability of aquaculture initiatives.
Impacts on biodiversity	Low-High	Dependent on species cultured, method and location. Technological advances (e.g. land-based RAS, offshore production, biological parasite control etc.) may help to mitigate impacts as production is expanded. Risks relating to the introduction and spread of invasive non-native species (INNS) and disease may be harder to mitigate, especially in relation to climate change induced sea temperature changes (although advances in biotechnology e.g. in relation to disease resistance or biological containment through induced sterility may help to mitigate impacts). The general integration of the ecosystem approach in fisheries and aquaculture management may further reduce potential impacts through more effective management at least in some regions.
Impacts on ecosystem services	Low - High	Any impacts of mariculture on marine habitats, flora and fauna, if of a sufficient magnitude, could potentially impact on the beneficial ecosystem processes and services provided by those features.The magnitude of this impact will depend on the type of marine or brackish aquaculture undertaken, the location, the method and the intensity.
Impacts on animals welfare	Medium-High	Increasing intensive production of animals, including marine species, may pose a risk (real and/or perceived) to animal welfare. Increasing awareness of provenance and sustainability amongst consumers and within supply chains may help mitigate this risk to some degree in some parts of the world.
Impact on livelihoods	Low-High	Development of aquaculture could impose price pressures on fisheries products which would undermine fishing-related livelihoods, which may be locally highly significant. However, in general the contrary is true i.e. the lower cost basis of fishing undermines the potential for aquaculture unless the catch per unit effort (CPUE) of the fishery falls to the point where aquaculture can be an economically viable substitute. In some regions, aquaculture may provide a diversification opportunity for fishermen. Access to capital to establish aquaculture initiatives is very variable between countries and regions. Co-operatives, associations, unions and agricultural banks may provide a source of capital in some countries/regions with a relatively low level of risk of loss compared to that presented by loans from other financial institutions.

Summary of Key Constraints, Risks and Benefits		
Benefits	Relative Benefit Level	Further Comment
Socio-economic – employment	Medium-High	Positive impacts occur through employment throughout mariculture value chains. Employment opportunities have had a significant impact on poorer sections of society in both low and medium income countries (LMICs) and Organisation for Economic Co-operation and Development (OECD) countries, although exploitative practices remain within the sector.
Socio-economic – health	Medium	Access to and affordability of fish has generally increased as aquaculture has become established, with likely dietary benefits (although the comparative dietary value of cultured and wild fish has become an issue of concern to some in relation to changes in feed formulation).
Climate change (related to GHG emissions)_	Low-High	The current study suggests that increasing mariculture production may contribute to a reduction in the footprint of global food production, although it has highlighted that there are currently intrinsic links between terrestrial and aquatic food production systems which influence the level of benefit which may be achieved. Future technological advances in feed technology and energy production (i.e. with reduced GHG emissions) would maximise the benefits of increasing mariculture production.
Land use	Low-High	This study indicates that increasing the proportion of mariculture products in total global food production will help to reduce pressure on land resources. However, with respect to land use, the impacts of fed marine aquaculture species are intrinsically linked to feed production and proportional to feed conversion ratio (FCR) in intensive and semi-intensive aquaculture systems. Hence the level of benefit achieved will relate to future advances and efficiencies in feed production and nutrition
Water use	Low-High	This study indicates that increasing the proportion of mariculture products in total global food production will help to reduce pressure on freshwater resources. However, with respect to water use, the impacts of fed marine aquaculture species are intrinsically linked to feed production. Hence the level of benefit achieved will relate to future advances and efficiencies in feed production and nutrition
Environmental – beneficial ecosystem services	Low-High	Food provision - mariculture provides a means of food provision which may help to reduce GHG emissions, land and water impacts. However, further assessment of this potential needs to be made when additional more robust data are available, and at a more regional level to help further quantify the potential benefits. Water purification and bioremediation - potential for these beneficial ecosystem services from shellfish and macroalgae culture e.g. in IMTA systems. However, the majority of IMTA systems have arisen through coincidence as mariculture has expanded in coastal regions and the feasibility and economic viability of IMTA needs further exploration.

8. Conclusions and Recommendations

The current study has sought to assess the environmental and socio-economic impacts of expanding the contribution of global mariculture to future food and energy demands in 2050, as a way of reducing pressure on limited land and water resources and GHG emissions.

With regard to food production systems, the environmental impacts of producing meat and fish products were compared through LCA and the outputs were used to compare the relative magnitude of GWP, land and freshwater use impacts of theoretical future scenarios in which the proportions of meat and cultivated fish products were varied. The study considered the major constraints to expanding mariculture in the future, the wider environmental and socio-economic risks and benefits of doing so and how technological advances may help mitigate against any such risks.

With regard to energy production systems, the study reviewed the technologies via which macro- and microalgal biomass may be used as feedstock for biofuel production and the current status and efficiencies of these biofuel production processes. The review also considered the technical and economic feasibility of commercial scale production of biofuels from algal biomass.

The main conclusions are presented in Section 8.1 and recommendations regarding further research required to further assess this subject are provided in Section 8.2.

8.1 Conclusions

The results of the current study must be viewed as indicative only and interpreted in the light of the significant data and methodological limitations described in Section 6. However, in general the following conclusions can be made:

Algal mariculture for production of bioenergy

- The LCA analysis indicated that production of biofuel from microalgae is currently an inefficient process. The energy balance and GWP associated with the use of macroalgae for the production of energy is more comparable to land crops with the benefit of negligible land use requirements. However substantial economic and some technical and logistical uncertainties remain. Current challenges to energy production from algal biomass include:
  - Technical Processes – some algal components are inhibitory to conversion; scaling up of technology is required;
  - Production volumes – production of sufficient biomass for efficient conversion;
  - Anaerobic digestion of macroalgae may require the addition of other feedstocks to balance N:C ratios, therefore would need to form part of a broader waste management strategy;

- Some opportunities may exist to utilise the by-products from macroalgae production that is intended for human consumption and phycocolloid production. However, this is largely supposition as no studies have been performed on commercially operational algal biofuel production systems;
- Harvesting natural (wild) algal stock has the potential to affect coastal productivity and habitat availability and hence can have ecosystem implications. Cultured seaweed is much less problematic in this regard.

LCA of terrestrial and marine and freshwater aquaculture derived products

- Increasing mariculture can contribute to reducing the footprint of global food production. However, relatively substantial increases in the production of mariculture species (e.g. 300% increase in shellfish and 100% increase in salmon production), only resulted in a small overall reduction in the global footprint of food production. This relates to the intrinsic link between land and water use for the production of aquaculture feed (see below) but also because mariculture currently provides only a small proportion of overall protein consumption and thus even large percentage increases in mariculture production have only a small impact on global totals;
- With respect to land use, the impacts of fed marine and freshwater aquaculture species are intrinsically linked to feed production and are proportional to FCR in intensive and semi-intensive aquaculture systems. Similarly, with respect to water use, fish species fed higher amounts of vegetable based feed, compared to fishmeal, usually have a higher water use impact due to the higher water requirements for growing agricultural crops (i.e. water use is also linked to aquaculture feed production). As the largest contribution of mariculture to most impact categories arises from production of feed ingredients, improvements in feed technology could further reduce the pressure on land and water resources and hence further reduce the footprint of mariculture production (see recommendations);
- Although fishmeal and fish oil showed low GWP, land and water use impacts, there are serious concerns over long term sustainability of marine ingredients for the production of fishmeal/oil, including the use of trash fish and unregulated supply. Emphasis should be on maintaining well regulated, sustainable and responsible supplies of fishmeal and any expansion in fishmeal/oil supply should focus on the full utilisation of by-products from fisheries and aquaculture processing operations;
- Some feed ingredients which are considered to be viable replacements for fishmeal, such as gluten (secondary processing products) from wheat and maize, are very energy intensive. Others, such as sunflower, are water intensive. There are also major concerns regarding other terrestrially derived feed ingredients, such as soy and palm oil, in relation to habitat loss. Hence the environmental benefits of replacing fishmeal with vegetable ingredients should not be taken for granted as there are many trade offs with respect to the global footprint of food production;
- The key to reducing impacts in almost all categories is the efficient use of feed from all sources. Efficiency improvements can be made across all sectors of feed provision including ingredient supply, feed delivery (on farm) and animal nutrition (see recommendations);
- The diverse range of mariculture production systems for some species (e.g. shrimp) can result in highly variable impacts with regard to the use of terrestrial resources and

GHG emissions. The unexpectedly high GWP of shellfish (oyster, mussel) production represented the on-farm operations and depuration requirements in the studies included in the analysis. Given that the land and freshwater impacts for shellfish such as oyster and mussel are minimal (relating to the processing), if production of these species could be increased in areas in which depuration was not required (i.e. in areas of good water quality), the impact of increasing shellfish production could presumably be lowered further through reduced depuration-related energy usage. Unfortunately, areas where the growth of shellfish has been largest, and where demand is likely to increase further such as in East Asia, are areas of poorer water quality. However, there are policy drivers and the potential to substantially increase shellfish production, particularly in offshore areas where it is assumed that water quality will be good for example in the UK (e.g. Syvret *et al*, 2013; Welsh Government, 2015), if technical and economic feasibility can be proven (see key constraints below); and

- Future food production scenarios in which production of low impact mariculture species are increased in combination with freshwater fish, chicken and pork (which had similar impacts to fish in the current study) and a substantial decline in beef production is likely to provide greater overall reductions in the footprint of future food production. The current study provides a basic framework in which multiple scenarios can be explored to provide indicative estimates of the environmental impacts.

Key constraints to expanding global mariculture:

- Production of lower impact feeds with adequate nutrition for both product and consumer;
- Fishmeal and fish oil availability and cost. Whilst there is significant opportunity to continue to increase the supply from both capture fisheries and aquaculture processing, it is unlikely that fishmeal production could be increased by more than a factor of two; hence based on current feed inclusions, there would be insufficient fishmeal and oil resources to meet the levels required for the theoretical projected Scenarios 3, 4 or 5 (see Section 6). As such, careful direction of these resources to where they are most nutritionally efficient, in terms of both the cultured aquatic and terrestrial animals and for the humans who ultimately consume them should be a priority;
- The availability of coastal and marine space (e.g. in relation to competition with other sectors). Estimates of the increase in sea area required for the theoretical future scenarios, suggested that doubling the 2012 baseline production of all marine, brackish and freshwater species assessed (which only comprised approximately 25% of global fish production in 2012), may require an increase in sea area for production of approximately 450%. However, given the regional variation in production intensities (i.e. extensive, semi-intensive and intensive production systems), and the variable capacity for increases in production between different regions (relating more to the length of coastline in the short term given that economically viable offshore production is not yet proven), it is suggested that assessing the sea area requirements for low impact mariculture species should be undertaken for similar intensity production systems at a more regional/site specific level. Intensive production systems result in higher yields per unit area, albeit with higher energy use, indicating the potential

benefit of future technological advancements in energy production in helping to reduce the global footprint of food production;

- The technological and economic feasibility of offshore mariculture. The feasibility of offshore aquaculture is currently unknown; the harsher the environment and deeper the sea etc. the higher the costs of developing and running sites (e.g. in terms of resilience to the weather, accessibility for husbandry, health and safety) and from an economic point of view. Large scale production would be needed to ensure economic viability but in the immediate future that is unlikely to be enough to compensate for the higher investment costs required;
- Market demand and price for mariculture products;
- Pollution (water quality) which can influence the economic viability of bivalve shellfish production in countries with food safety legislation for the protection of public health.

Wider environmental and socio-economic risks and benefits of increasing global mariculture production

- The wider environmental impacts of mariculture on habitats and associated biological communities depend on the species being farmed, the production system and intensity, the local physical conditions, the ecological carrying capacity of the water body, the sensitivity of the biological communities in the vicinity of farms, other marine activities activity occurring in the area and other sources of pollution relating to other marine activities or land use. Therefore the risk of expanding mariculture can only be assessed on a more regional or site by site basis;
- Macroalgae and shellfish can provide the beneficial ecosystem services of water purification and hence there is the potential for the use of extractive species to provide bioremediation services whilst providing additional biomass for food consumption or other uses;
- Mariculture provides positive social impacts through consumption and employment throughout mariculture value chains; in general, aquaculture has been found to beneficially impact on poorer sections of society;
- Increased globalisation of farmed seafood trade is ensuring social and economic impacts occur in both LMIC and OECD countries. Significant trade is also developing at the regional scale in Asia and Africa;
- Transformative social and economic outcomes provided through aquaculture have been related to commercial rather than subsistence-orientated activities. Although smallholders engaged in aquaculture, particularly in LMIC remain numerically dominant, their share of production is often falling relative to larger scale enterprises; Comparably high entry costs, uncertainties and risks probably explain the lag in mariculture development compared to that inland (freshwater) and some of its mixed social and economic outcomes;
- Nutritional impacts of increasing aquaculture for the poorest groups, both rural and urban are often indirect. As production grows, a focus on maintaining the nutritional attributes of farmed seafood, compared to wild caught seafood, needs to be prioritised.

Potential opportunities for technology to mitigate against any impacts of increasing global mariculture production include the following:

- Future improvements in feed technology to reduce the reliance of formulated feed on land-based crops (and hence lower the land and water impacts of feed production) and minimise waste through the inclusion of all agricultural, fisheries and aquaculture by-products;
- Advances in biotechnology, for example selective breeding of finfish species to increase growth (yields), disease resistance and tolerance to a wider range of dietary ingredients (to optimise feed ingredients and minimise impacts as above);
- Further development of IMTA, with the use of extractive species (macroalgae, shellfish) to reduce the impact of production of higher trophic species with the subsequent production of additional products for the food production system (e.g. for feed even if not for human consumption);
- Land based RAS could reduce potential impacts on the marine environment and the nutrient rich effluent can be further used in the food production system, for example, for aquaponics (integrated systems in which fish and plants are grown together with the fish waste providing an organic food source for the plants). However, economic analysis currently indicates this technology is uncompetitive and liable to fail commercially unless the product is a high value and/or niche species. In addition such systems also require high capital costs and energy requirements. However, such systems may offer more potential opportunity with any future technological advancements in energy production. Offshore self-contained systems also have potential and may have significant advantages over both RAS and conventional and off-shore cage systems.

8.2 Recommendations

This exploratory study has developed a framework for testing the hypothesis that increasing global mariculture production contributes to reducing GHG emissions, land and water use in global food and energy production systems. This study has highlighted numerous limitations in the availability of LCA data for farmed aquatic species, the consideration of wider socio-economic issues within LCA methodologies and the limitations of applying such analysis at a global level. As such, one of the main recommendations of this study is to use the current framework to investigate optimal proportions of terrestrial meat, marine and freshwater fish species at a more regional or site specific level to minimise risks and maximise benefits of expanding mariculture. In addition, the study makes the following recommendations:

8.2.1 LCA Methodology and Improving Future Assessments of the Global Footprint of Food Production Systems

- Further improvements in LCA data availability for a greater range of farmed aquatic species, and general improvements in LCA methodology (see below) will help to enable a more accurate assessment of global impacts of mariculture and aquaculture in the future;
- LCAs should be rigorously reviewed by industry experts as well as LCA experts so that the technology and assumptions within the study are representative;

- Where possible, LCAs should be conducted on primary data from several operational sites rather than combined literature sources and/or computer models;
- Include Biological Oxygen Demand (BOD) and/or Chemical Oxygen Demand (COD) as impact factors;
- Only include toxicity potentials where the chemicals used are well characterised;
- Utilise recent uncertainty methodology (developed by Henriksson *et al*, 2014a), which allows for inherent uncertainty, representativeness and horizontal spread of secondary literature data to be incorporated into individual LCA studies;
- Describe all allocation, system boundary, functional unit and other decisions and assumptions clearly;
- More inclusive LCA studies which investigate all co-products instead of partitioning, especially when the functions of co-products are the same or similar e.g. providing energy through biofuels;
- Include water use within LCAs based on requirements of green, blue and grey water separately;
- Include land use and consequences for land use change separately; and
- Use the framework developed in this study to investigate optimal proportions of terrestrial meat, marine and freshwater fish species at a more regional or site specific level to minimise risks and maximise benefits of expanding mariculture

8.2.2 Improving Environmental Impact Savings in the Food and Energy Production Systems

- Encourage governments to invest in site suitability assessment for crops and livestock, including land use change and water availability;
- Discourage deforestation for crops and livestock;
- Reduce the impact from formulated feed through reducing the amount of feed used in production systems, replacing some crop-based feed inclusions with more efficient ingredients and improving the efficiency of the feed production processes;
- Continued research into the development of alternative protein and oil sources for livestock and aquaculture feeds (for example, from insect larvae, algae);
- Continued improvements in feed conversion ratios (FCR) of fish species to further reduce the footprint of farming aquatic fish species;
- Encourage synergistic solutions between the arable, livestock and aquaculture (marine and freshwater sectors) to conserve resources;
- Use legislative and regulatory solutions to drive the better use of resources;
- Discourage waste from processing and direct by-products to recycle effectively into livestock feeds, anaerobic digestion and composting;
- Reduce municipal waste through providing sorting for household, market, catering and retail outlet food waste. Direct waste to feeds, fertilisers and biogas; and
- Direct appropriate feed resources to most efficient industries/species for those ingredients based on nutritional requirements. For example, reduce high quality fishmeal inputs to tilapia diets and direct to marine species.
- Improve water quality to reduce bivalve shellfish depuration-related energy usage and costs;
- Use legislative and regulatory tools to encourage co-location of mariculture with other offshore marine sector activities, for example, offshore renewables or disused oil rigs, to facilitate development of offshore mariculture and increased scale production;

8.2.3 Technological Advancements and Research to Reduce Impacts of Food Production Systems and Contribute to Global Food Security

- Continue investment in improving crop yields per unit, land, water and energy use;
- Continue research into the optimal production systems for mariculture species with highly variable impacts (e.g. shrimp) to minimise the requirements for terrestrial resources and GHG emissions;
- Link research into nutrition with breeding programmes;
- Improve on farm energy use and depuration efficiency in bivalves;
- Improve feed delivery for finfish species, e.g. automatic feeders;
- Increase research into flocculation and wet lipid extraction from micro-algae biomass;
- Prioritise research into maintaining the nutritional attributes of farmed seafood as production continues to increase and feed composition changes;
- Further research into the nutritional value of macroalgae (for human and livestock/aquaculture feed) and its potential to contribute to global food security and implications for poverty;
- Research into the potential to utilise by-products from macroalgal production for human consumption and phycocolloid production in algal biofuel production systems; and
- Find better markets for co-products of algae production.

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Appendix A

Life Cycle Assessment (LCA) Studies Used to Develop the Model

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