ASSESSING ENVIRONMENTAL SUSTAINABILITY AND VALUE ADDITION OPPORTUNITIES FOR BY-PRODUCTS FROM AQUACULTURE

By Richard Newton

Submitted in fulfilment of the requirement for the degree of Doctor of Philosophy

Institute of Aquaculture

University of Stirling

March 2014

University of Stirling

ABSTRACT

Faculty of Natural Sciences

Institute of Aquaculture

Doctor of Philosophy

By-products and mortalities from aquaculture have often posed significant challenges to the industry because of their low value resulting in high costs and environmental impact from their disposal. However increasing interest is being expressed in their utilisation to add value to the aquaculture industry and provide synergies with industries which had previously been in competition with aquaculture.

Current and prospective processing by-product and farm mortality utilisation strategies were reviewed along with regulations and standards which aim to control their use and protect against human and animal health hazards.

The role of aquaculture and fishery by-products in the supply of fishmeal was investigated and it was found that both sectors had the potential to contribute to increasing global supply. There were significant quantities of processing by-products identified which could be directed to fishmeal manufacture but there were also significant amounts of fish production which were not being processed in some regions and could also add to supplies. Processing by-products from aquaculture species often exceed 50% of the production by mass and therefore their efficient utilisation is of significant importance to the overall performance of the value chain. Their utilisation strategies are diverse and in some circumstances offer the possibility to add significant value.

Life Cycle Assessment (LCA) is increasingly being used to inform decision makers and consumers about the environmental performance of goods and services to make choices on best practices and informative decisions on purchasing choices. Current methodology in LCA was critiqued and developed to be used for identifying disproportionate impacts from by-product industries and comparative assessment of the eco-efficiency of value chains from Thai shrimp, Vietnamese *Pangasius* catfish and Scottish salmon aquaculture. New LCA methodology was developed assessing the eco-efficiency of co-products as a whole and in relation to a tonne of edible yield. Measuring the impact of the by-product industry in relation to their edible yield gave different results to measuring their eco-efficiency between the three study species. It was found that the Thai shrimp value chain was the most eco-efficient when by-products were directed to chitosan and hydrolysate manufacture, but production of the salmon was the least impacting between the species in terms of edible yield. *Pangasius* was the most environmentally impacting of the three species value chains using both methods. It was also found that the upstream impacts of fish and shrimp production, especially feed manufacture, contributed most to the environmental impact in most circumstances, using both economic and mass allocation. Although the methodology produced interesting results, there were some drawbacks and the data sets also had several gaps which led to some assumptions, which could have skewed the results and interpretation.

The cause of mortality for five aquaculture species in five countries and their subsequent utilisation was investigated. It was found that extensive systems were more prone to mortality than intensive systems in many cases. There was a wide range of strategies for mortality utilisation. In countries where by-product industries existed, farmers were often able to sell some of their mortality losses but in other areas, disposal could create health and biosecurity hazards.

In conclusion, it was found that both by-products and aquaculture mortalities could be utilised effectively and that the additional impact from their use was low in proportion to the rest of the value chain.

Acknowledgements

I am most grateful to my supervisors, Prof. Dave Little and Dr. Trevor Telfer, for their encouragement and ideas throughout my studies. I would especially like to thank them for their help in contacting and engaging with industry in order to collect the necessary LCA data, without which this thesis would not have been possible. Thanks should also go to Dr. Kriengai Satanpornvanit from Kasetsart University, Thailand and Dr. Phuong Nguyen from Can Tho University Vietnam for their hospitality and help in arranging field visits in their countries. I would like to thank Dr. Francis Murray for his help and insights into Asian systems which proved invaluable throughout the course of this study. Also I would like to thank Dr. Darren Green for his help and advice in constructing statistical models for some of the sections in this thesis.

I would like to thank Patrik Henriksson and Dr. Jeroen Guinée for their help and advice in constructing LCA models and guidance in the use of the LCA modelling software. I would also like to thank Jintana Jeoaw, Dow Hai and Phan Thanh Lam for their help in collecting and translating survey data in Asia. Thanks are also due to Andrew Jackson from the IFFO with whom I collaborated in producing the data for global fishmeal resources. Thanks also to Steve Prescott for good discussions on LCA and proof reading of some of the sections in the thesis.

I would like to thank my father, Ms. Tori Adams and my other friends for their endless help and encouragement during the writing up of the thesis.

DECLARATION

The work described in this thesis was undertaken by the candidate and embodies the results of his own research. Where appropriate, the nature and work carried out by others has been fully acknowledged.

Richard William Newton

TABLE OF CONTENTS

CHAPTER 1: GENERAL INTRODUCTION 1
1.1 Introduction 1
1.2 Current status of by-product utilisation 5
1.2.1 European Salmon 5
1.2.2 Thai and Vietnamese Penaeid Shrimp 9
1.2.3 Vietnamese *Pangasius* catfish 11
1.3 Mortality in aquaculture 12
1.4 Current and prospective options for by-product value addition 15
1.4.1 Processing by-product utilisation 16
1.4.1.1 Fish and shrimp meals 16
1.4.1.2 Fish oils 18
1.4.1.3 Sauces, pastes and other products for human consumption 22
1.4.1.4 Collagen 24
1.4.1.5 Gelatine 26
1.4.1.6 Chitosan and glucosamine 29
1.4.1.7 Fish and shrimp peptides 32
1.4.1.8 Carotenoids (astaxanthin and canthaxanthin) 34
1.4.2 Value addition options for farm mortalities 36
1.4.2.1 Ensiling 36
1.4.2.2 Incineration and burial 38
1.4.2.3 Composting 39
1.4.2.4 Anaerobic Digestion 41
1.4.2.5 Maggots and other non-livestock animals 43
1.5 Thesis objectives 44

CHAPTER 2: LEGISLATION AND STANDARDS GOVERNING USE OF AQUACULTURE BY-PRODUCTS 47
2.1 Introduction 47
2.2 International Guidelines and Standards 49
2.2.1 Codex Alimentarius 51
2.2.2 FAO Code of Conduct for Sustainable Fisheries 53
2.2.3 European Union regulations 54
2.2.4 Industry association certification schemes 59
2.3 Private Certification 61
2.3.1 GlobalGAP 62
2.3.2 Best Aquaculture Practice (BAP) 64
2.3.3 Aquaculture Stewardship Council (ASC) 65
2.4 Organic Certification 67

2.5 Regulation and standard’s role in directing by-products within aquaculture value chains 70

CHAPTER 3: GLOBAL SUPPLY OF FISHMEAL AND ITS RELEVANCE TO THE AQUACULTURE INDUSTRY 76
3.1 Introduction 76
3.2 Global fishmeal supplies from fisheries and aquaculture processing by-products 76
3.3 Capture and aquaculture supply 79
3.4 Edible yield 81
3.5 Processing and utilisation of fishery products 81
3.6 Current production of fishmeal by region 86
3.7 Potential for extra fishmeal production from by-product processing 90
3.8 Fishmeal quality from aquaculture and capture fishery by-products for use in livestock diets 94
3.9 Projected fishmeal supplies to 2030 99
3.10 Developing by-product utilisation and directing best utilisation practices 103

CHAPTER 4: CAUSES AND DISPOSAL OF MORTALITY IN ASIAN AND EUROPEAN AQUACULTURE SYSTEMS 109
4.1 Introduction 109
4.2 Data collection 112
4.2.1 Asian integrated farm survey design and enumeration 112
4.2.2 Data collection from Scottish Atlantic salmon farms 118
4.3 Data analysis 119
4.4 Mortality in Asian aquaculture systems 121
4.4.1 Survival 121
4.4.2 Farmer perception of mortality cause 126
4.4.3 Disposal of on farm mortalities in Asia 139
4.5 Mortality in Scottish Atlantic salmon production 147
4.5.1 Disposal of Scottish Atlantic salmon mortalities 152

CHAPTER 5: LIFE CYCLE ASSESSMENT AND ITS APPLICATION TO AQUACULTURE BY-PRODUCTS 154
5.1 Life Cycle Assessment of by-products from aquaculture production 154
5.1.1 Life Cycle Assessment in aquaculture 154
5.2 Life Cycle Assessment methodology 155
5.2.1 LCA procedure 155

5.2.1.1 Goal and Scope 156
5.2.1.2 Methodological issues in LCA studies of by-products 159
5.2.1.3 Apportioning impacts in multi-functional processes 162
5.2.1.4 Choice of functional unit 169
5.2.1.5 Life Cycle Inventory 175
5.2.1.6 Life Cycle Impact Assessment 176
5.2.1.7 Uncertainty in LCA; NUSAP approach, horizontal spread and Monte Carlo analysis 178
5.2.1.8 Sensitivity analysis 180
5.3 Life Cycle Assessment of aquaculture by-products 180

CHAPTER 6: LIFE CYCLE ASSESSMENT OF THAI SHRIMP BY-PRODUCT PROCESSING 182
6.1 Introduction 182
6.2 Goal and Scope 185
6.3 Life Cycle Inventory 187
6.3.1 Chitosan plants 188
6.3.2 Shrimp meal and hydrolysate plants 192
6.4.3 Shrimp by-product hydrolysate 195
6.4 Life Cycle Impact Assessment 196
6.4.1 Chitosan plants 196
6.4.2 Shrimp meal plants 203
6.4.3 Shrimp hydrolysate 206
6.4.4 Comparing best utilisation strategies for shrimp by-products in the Thai shrimp value chain 210
6.4.4.1 Utilisation alternatives from shrimp by-products associated with one tonne of IQF shrimp directed to human consumption 212
6.4.4.2 Utilisation alternatives from shrimp by-products associated with $1000 of value from all products 217

CHAPTER 7: LIFE CYCLE ASSESSMENT OF VIETNAMESE *PANGASIUS* CATFISH BY-PRODUCT PROCESSING 223
7.1 Introduction 223
7.2 Goal and Scope 225
7.3 Life Cycle Inventory of pig feeds from *Pangasius* by-products 226
7.3.1 *Pangasius* by-product fishmeal and oil processor 227
7.3.2 Pig feeds including *Pangasius* by-product meal 230
7.4 Life cycle impact assessment of *Pangasius* by-products 231
7.4.1 Pangasius by-product meal, stomachs and swim-bladders 231
7.4.2 LCIA of the *Pangasius* catfish value chain 234

7.4.3 LCIA of pig feed formulated from *Pangasius* by-product meal 237

CHAPTER 8 LIFE CYCLE ASSESSMENT OF SALMON BY-PRODUCT VALUE CHAINS 242
8.1 Introduction 242
8.2 Goal and scope 243
8.3 Life Cycle Inventory 244
8.3.1 Salmon feed production 245
8.3.2 Scottish salmon grow-out production 246
8.3.3 Scottish salmon processing plants 249
8.3.4 Salmon protein concentrate and oil extraction plant 251
8.4 Life cycle impact assessment of Scottish salmon value chains 254
8.4.1 LCIA of Scottish salmon grow out feeds 254
8.4.2 LCIA of Scottish salmon farming 257
8.4.3 LCIA of Scottish salmon processing plants 259
8.4.4 LCIA of protein concentrate and oil extraction from salmon by-products 261
8.4.5 LCIA of the Scottish farmed salmon value chain 264

CHAPTER 9 COMPARING VALUE CHAINS 268
9.1 Comparing the environmental impacts between value chains 268
9.2 Comparison of LCAs of shrimp, *Pangasius* and salmon value chains 269
9.3 Conclusions 286

LITERATURE CITED 291

APPENDIX 1 - SPECIFIC INFORMATION RELATING TO CHAPTER 3 - GLOBAL SUPPLY OF FISHMEAL AND ITS RELEVANCE TO THE AQUACULTURE INDUSTRY 319
A1.1 Countries within study regions for the global database 319
A1.2 Edible yields of top 40 fisheries and aquaculture species by production volume 321
A.1.3 Global fish meal database results by region (screenshots) 322

APPENDIX 2 LIFE CYCLE ASSESSMENT SURVEYS FOR SHRIMP BY-PRODUCT VALUE CHAINS 331
A2.1 Thai shrimp meal manufacturers 331
A2.2 Thai chitosan manufacturers 341
A2.3 Shrimp by-product hydrolysate questionnaire 367

A3 VIETNAMESE *PANGASIUS* BY-PRODUCT PROCESSOR LCA SURVEYS 382
A3.1 *Pangasius* catfish by-product processor 382
A3.2 Vietnamese pig feed producer LCA survey 399

APPENDIX 4 SURVEYS FOR LCI DATA COLLECTION FOR THE SALMON BY-PRODUCT VALUE CHAIN 409
A4.1 Salmon feed survey 409
A4.2 Salmon grow out LCA survey 421
A4.3 Scottish Salmon processing survey 432
A4.4 LCA questionnaire for protein concentrate and salmon oil extraction 443

LIST OF FIGURES

Figure 1.1. Proportion of fishmeal used in different sectors and price per tonne 2
Figure 1.2. Distribution of farmed eviscerated Atlantic salmon produced in Norway and the UK for further processing during 2008 7
Figure 1.3. Production and number of processors of a) *Pangasius* catfish and penaeid shrimp in the Mekong delta of S. Vietnam in 2008, b) Penaeid shrimp in S. Thailand in 2007 10
Figure 1.4. EPA and DHA concentrations in the viscera of farmed Atlantic salmon (grammes of PUFA per 100g total FAs), compared with whole wild and farmed salmon and other commercially important species 20
Figure 2.1. The hierarchy of international standards and regulations from a European perspective. See below for descriptions of abbreviations and standards 50
Figure 3.1. Global capture of major fishmeal reduction species. FAO Fishstat 2013 78
Figure 3.2. Schematic of calculations and assumptions in estimating extra fishmeal potential from fishery and aquaculture by-product resources 83
Figure 3.3. Screen capture from IFFO/UoS global fishmeal database, showing major steps in estimating fishmeal potential from unutilised by-products for the top twenty capture fishery and aquaculture species from Europe as shown in figure 3.2 85
Figure 3.4 Five year average fishmeal production from nine regions a) FAO fishstat database (2013), b) IFFO/UoS database estimates 87
Figure 3.5 Contribution of fishmeal from whole fish, capture fishery and aquaculture by-products (BPs), estimated from the IFFO/UoS database 88
Figure 3.6 Estimated potential for increased fishmeal production if a) all current unutilised processing by-products and b) all current seafood production was processed and the by-products directed to fishmeal 91
Figure 3.7 potential for extra fishmeal production from marine and freshwater seafood by-product resources 92
Figure 3.8 Potential for extra fishmeal production from aquaculture and fisheries resources by region 94
Figure 3.9 historical and projected aquaculture production and growth, 1982 to 2031, fishmeal production 1982 to 2009 100
Figure 3.10 Projected growth of major aquaculture species based on 5 year annual growth rates adjusted to projected global growth rates for all species 101
Figure 4.1. Shrimp survival rates (%) in 4 Asian study areas by scale; a) Thailand, b) Vietnam, c) China, d) Bangladesh. 123
Figure 4.2. Survival in different production systems for selected species in different countries (%); a) Thailand tilapia, b) Vietnam shrimp, c) China shrimp, d) Bangladesh shrimp/prawn polyculture by scale 123
Figure 4.3. Survival rates of secondary species (%) in 4 Asian study areas by scale; a) Thailand tilapia, b) Vietnam catfish, c) China tilapia, d) Bangladesh giant freshwater prawn 125
Figure 4.4 Ranked causes of mortality in selected Asian shrimp aquaculture systems/scales, where system or scale was a significant factor for survival, percentage of farmers in a) Vietnam, b) China, c) Bangladesh 128
Figure 4.5 Ranked causes of mortality in selected Asian aquaculture systems/scales, where system or scale was a significant factor for survival, percentage of farmers in a) Thailand tilapia, b) Bangladesh FW prawn 135

Figure 4.6 Mortality cause as perceived by farmers (%) in systems/scales which were not significant for survival, a) Thai shrimp, b) Vietnamese catfish, c) Chinese tilapia system, d) Chinese tilapia scale 137
Figure 4.7 Mortality utilisation/disposal in selected Asian species by scale, % of farms in a) Thailand shrimp, b) Vietnam catfish, c) Thailand tilapia, d) Bangladesh FW prawn 144
Figure 4.8 Total mortality, months post transfer across 5 Atlantic salmon farms in Scotland attributed to cause, by a) biomass, and b) number of individuals 148
Figure 5.1 Simplified example of system expansion where 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 164
Figure 5.2 Simplified example of allocation by mass (black) and by economic value (red) to *Pangasius* by-products used in fishmeal for pig feeds 166
Figure 5.3 Simplified example of how live weights are not appropriate for species comparisons 171
Figure 6.1 Shrimp by-product value chain, showing multi-functional flows (blue arrows), alternative utilisation (brown arrows), economic and mass allocation (red and black percentages) and final products (yellow boxes with brown borders) 184
Figure 6.2 Generalised diagram of chitosan production according to LCA survey work in Thailand 191
Figure 6.3 contributions to impact categories from individual inputs to selected chitosan manufacturing plants 200
Figure 6.4 contributions to producing shrimp at Thai farms and feed at shrimp feed mills 202
Figure 6.5 contributions to impact categories from individual inputs to shrimp meal manufacturing plants in Thailand 205
Figure 6.6 contributions to impact categories from individual inputs to shrimp hydrolysate manufacturing plants, SM2 in Thailand and SHH1 in South America, adjusted to Thai conditions and input materials 209
Figure 6.7 Alternative strategies for shrimp by-product utilisation with economic values in US$ (red) and mass of products in kg (black) in relation to one tonne of product directed to human consumption; a) mixed by-product directed to shrimp meal, b) heads directed to hydrolysate with shell by-products directed to chitosan extraction 211
Figure 6.8 LCIA of chitosan (green) hydrolysate (red) and shrimp meal (blue) associated with one tonne of shrimp directed to human consumption using economic allocation 214
Figure 6.9 LCIA of chitosan (green) hydrolysate (red) and shrimp meal (blue) associated with one tonne of shrimp directed to human consumption using mass allocation 216
Figure 6.10 LCIA of IQF shrimp (pink) chitosan (green) hydrolysate (red) and shrimp meal (blue) in order to produce US$1000 of total products using economic allocation 220
Figure 6.10 LCIA of IQF shrimp (pink) chitosan (green) hydrolysate (red) and shrimp meal (blue) in order to produce US$1000 of total products using mass allocation 221
Figure 7.1 Female workers at a *Pangasius* catfish by-product processing plant sorting stomachs and swim-bladders for sale in local markets, Mekong delta 228
Figure 7.2 *Pangasius* by-product processing to produce fishmeal fish oil, stomach and swim-bladders 229
Figure 7.3 Contributions to LCIAs of *Pangasius* fishmeal, large scale *Pangasius* farms and commercial *Pangasius* feeds using economic allocation 233
Figure 7.4 LCIA of products resulting from processing activities to produce 1000kg of *Pangasius* fillets and associated by-products by economic and mass allocation 236
Figure 7.5 Contributions to LCIAs of Vietnamese pig feed including *Pangasius* by-product meal and a standard formulated Chinese pig feed (Liu et al 2012), using economic allocation 239
Figure 8.1 Farmed salmon heads for sale at a local market in Dong Thap province, Vietnam 243

Figure 8.2 Typical land-based net pen salmon farm on the west coast mainland of Scotland, viewed from the office window 248
Figure 8.3 Contributions to LCIA in Scottish salmon feeds by economic allocation 255
Figure 8.4 Contributions to the LCIA of producing Scottish farmed salmon at the farm. Transport incudes the delivery of feed and the boat used for servicing the farm 258
Figure 8.5 Contributions to the LCIA of farmed salmon processing at 2 processors using economic allocation 261
Figure 8.6 Contribution analysis of producing salmon protein concentrate and salmon oil from Scottish farmed salmon viscera by economic allocation 263
Figure 8.7 LCIA of products resulting from processing activities to produce 1000kg of salmon directed to human consumption and associated by-products by economic and mass allocation 266
Figure 9.1 LCIA of products resulting from processing activities to produce US$1000kg of total shrimp, *Pangasius* and salmon products by economic allocation 271
Figure 9.2 LCIA of products resulting from processing activities to produce US$1000kg of total shrimp, *Pangasius* and salmon products by mass allocation 272
Figure 9.3 LCIA of products resulting from processing activities related to production of one tonne edible yield of shrimp, Pangasius and salmon production by economic allocation. 274
Figure 9.4 LCIA of products resulting from processing activities related to production of one tonne edible yield of shrimp, Pangasius and salmon production by mass allocation. 275

LIST OF TABLES

Table 1.1. Fillet yield, expected mortality and proximate analysis of whole carcass and entire co-product post-filleting, for farmed Atlantic salmon, striped catfish and penaeid shrimp 6
Table 1.2. Summary of costs, level of expertise and value addition from options available to mortalities falling into Category 2 of the ABPR 37
Table 2.1: EU Animal By-Product Regulations, categories and approved uses (EC, 2009) 56
Table 2.2 Selected private certification schemes, issuing body, location 62
Table3.1 Proximate analyses and amino acid profiles (where available) of key protein ingredients in aquafeeds. 97
Table 3.2 Amino acid profiles of key protein ingredients as a percentage of the ideal profile for growing pigs. 98
Table 3.3 Fishmeal and fish oil inclusion rates from different sources in Asian aquafeeds. 106
Table 4.1. Number of farms surveyed by country, species and scale for SEAT integrated survey. 114
Table 4.2. Example of farm scale criteria as used in Vietnam for catfish, shrimp and prawn pond, and tilapia cage systems 115
Table 4.3 Geographical scope of SEAT integrated survey 116
Table 4.4. Description of Asian production systems characteristics 117
Table 4.5 Mortality cause category aggregation in Asian production systems 120
Table 4.6 Percentage of farms keeping written records of mortality for each species by country and scale. 122
Table 4.7 Statistical analysis of survival to harvest using pairwise ANOVA comparisons between different scales and systems for different species in 4 SEAT study countries 126
Table 4.8 Top six utilisation methods of shrimp mortalities in Asian countries by mortality cause 140
Table 4.9 Top six (where cited) utilisation/disposal of mortalities of other species in Asian countries by mortality cause. 142
Table 4.10 Salmon farm mortality by individual site attributed to cause in % numbers of smolts stocked and % biomass of final harvest weight 150
Table 5.1 Number of farms surveyed for each species in each country for in depth LCC/LCA survey work 176
Table 5.2 Impact categories and their characterisation factor used in this thesis 178
Table 6.1 Life Cycle Inventory of four chitosan manufacturing plants in Thailand 190
Table 6.2 LCI of shrimp meal manufacture from two plants in Thailand 193
Table 6.3 LCI of shrimp hydrolysate manufacture from two plants, SM2 in Thailand and SHH1 in South America, adjusted to Thai conditions 197
Table 6.4 LCIA of four chitosan production plants per one tonne of solid chitosan using economic allocation 199
Table 6.5 LCIA of two shrimp meal production plants per one tonne of shrimp meal using economic allocation 204
Table 6.6 LCIA of two shrimp hydrolysate production plants per one tonne of hydrolysate using economic allocation 207
Table 6.7 LCIA using economic allocation showing shrimp meal in scenario a) and sub-divided impacts from chitosan and hydrolysate in scenario b) manufactured from the by-product resulting from 1 tonne of product directed to human consumption 213

Table 6.8 LCIA using economic allocation showing shrimp meal in scenario a) and sub-divided impacts from chitosan and hydrolysate in scenario b) to produce $1000 of final products 219
Table 7.1 LCI for the production of one tonne *Pangasius* catfish meal and one tonne of pig feed from *Pangasius* catfish meal in Vietnam and a comparative European diet 230
Table 7.2 LCIA of 1 tonne of *Pangasius* fishmeal and associated stomach and swim-bladder production, using economic allocation 232
Table 7.3 LCIA of 1 tonne of pig feeds including *Pangasius* by-product meal (Vietnam) and a standard formulated Chinese pig feed (Liu *et al* 2012), using economic allocation 238
Table 7.4 summary of results of statistical analysis of 1000 Monte Carlo runs, ranking the environmental performance of production of Vietnamese pig feed including Pangasius by-product meal and conventional Chinese pig feed using ANOVA 240
Table 8.1 LCI for the production of one tonne of standard grow out salmon feed produced in a UK feed mill. 246
Table 8.2 LCI of six salmon farms on the west coast of Scotland and Outer Hebrides 247
Table 8.3 LCI of two farmed Atlantic salmon processing plants in Scotland 250
Table 8.4 LCI of salmon protein concentrate and oil extraction plant in Scotland 252
Table 8.5 Proximate analysis and amino acid profile (% of protein) of salmon protein concentrate and amino acids as percentages of those in an ideal grower pig diet 252
Table 8.6 LCIA of one tonne of generic salmon feed at the mill by economic allocation 255
Table 8.7 LCIA of one tonne of live salmon at farm by economic allocation 257
Table 8.8 LCIA of products from two Scottish farmed salmon processors using economic allocation 260
Table 8.9 LCIA of salmon protein concentrate and salmon oil extracted from farmed salmon viscera by economic allocation 262
Table 9.1 summary of results of statistical analysis of 1000 Monte Carlo runs, ranking the environmental performance of production of US$1000 of Vietnamese *Pangasius*, Thai shrimp and Scottish salmon products using ANOVA 270
Table 9.2 summary of results of statistical analysis of 1000 Monte Carlo runs, ranking the environmental performance of production of one tonne of edible portions of Vietnamese Pangasius, Thai shrimp and Scottish salmon, and associated products using ANOVA 276

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

AA	Amino acid
AD	Anaerobic Digestion
ABPR	Animal By-Product Regulations
AHVLA	Animal Health and Veterinary Laboratories Agency
AIC	Agricultural Industries Confederation
ANEC	Association for the Co-ordination of Consumer Representation in Standardisation
ASC	Aquaculture Stewardship Council
BAP	Best Aquaculture Practice
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BOD	Biological Oxygen Demand
BP	By-product
BSE	Bovine Spongiform Encephalopathy
BSFL	Black Soldier Fly Larvae
BSI	British Standards Institute
CFM	Complete Feed Manufacturer standard
CIS	Commonwealth of Independent States
COD	Chemical Oxygen Demand
COP	Code of Practice
COROS	Common Objectives and Requirements for Organic Standards
DD	Degree of Deacetylisation
DDGS	Dried Distillers Grains with Solubles
DEFRA	Department for the Environment, Food and Rural Affairs
DHA	Docosahexaenoic Acid
EC	European Council
EEA	European Economic Area
eFCR	Economic Feed Conversion Ratio

EFSA	European Food Safety Authority
EMS	Early Mortality Syndrome
ENTEC	Environmental Technology Best Practice Programme
EPA	Eicosapentaenoic Acid
EU	European Union
FA	Fatty Acid
FAO	Food and Agriculture Organisation of the UN
FDA	US Food and Drug Administration
FEFAC	Fédération Européenne des Fabricants d’Aliments Composés
FEMAS	Feed Materials Assurance Scheme
FFDR	Forage Fish Dependency Ratio
FIFO	Fish In Fish Out ratio
FM	Fishmeal
FSA	Food Standards Authority
FU	Functional Unit
GAA	Global Aquaculture Alliance
GGN	GlobalGAP Number
GHG	Greenhouse Gas
GM	Genetically Modified
GSSI	Global Seafood Sustainability Initiative
GWP	Global Warming Potential
HACCP	Hazard Analysis and Critical Control Point
HCFC	Hydrochlorofluorocarbon
HOG	Head On Gutted
HOSO	Head On Shell On
HUFA	Highly Unsaturated Fatty Acid
IAA	Integrated Agriculture Aquaculture

ICES	International Council for Exploration of the Sea
IFFO	International Fishmeal Fish Oil Organisation
IFIS	IFSA Feed Ingredients Standard
IFSA	International Feed Safety Alliance
IHHN	Infectious Hypodermal and Haematopoietic Necrosis
IMTA	Integrated Multi-Trophic Aquaculture
IPCC	International Panel on Climate Change
IPNv	Infectious Pancreatic Necrosis virus
IQF	Instant Quick Frozen
ISEAL	International Social and Environmental Accreditation and Labelling
ISO	International Standards Organisation
IUCN	International Union for Conservation of Nature
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LPG	Liquid Petroleum Gas
MBM	Meat and Bone meal
MSC	Marine Stewardship Council
NGO	Non-Governmental Organisation
NUSAP	Numeral Unit Spread Assessment Pedigree
OGS	Organic Guarantee System
PAP	Processed Animal Protein
PAS	Publicly Available Standards
PCB	Poly-Chlorinated Biphenols
PD	Peeled, De-headed and deveined
PUFA	Polyunsaturated Fatty Acids
RAS	Recirculating Aquaculture System

RASFF	Rapid Alert System for Food and Feeds
SEAT	Sustaining Ethical Aquaculture Trade
SEPA	Scottish Environmental Protection Agency
SETAC	Society of Environmental Toxicology and Chemistry
SFP	Sustainable Fisheries Partnership
SM	Shrimp Meal
SPF	Specific Pathogen Free
SSPO	Scottish Salmon Producers Organisation
TFFA	Thai Frozen Foods Association
TSE	Transferable Spongiform Encephalopathy
UFAS	Universal Feed Assurance Scheme
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environmental Programme
UoS	University of Stirling
UV	Ultra Violet
VASEP	Vietnam Association of Seafood Exporters and Producers
VFA	Volatile Fatty Acid
VIFE	Vietnamese Institute for Fisheries Economics
WBSCD	World Business Council for Sustainable Development
WFE	Whole Fish Equivalents
WHO	World Health Organisation
WRI	World Resources institute
WSV	White Spot Virus
YHV	Yellow Head Virus

CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

Fish production from capture fisheries and aquaculture has been criticised for inefficiency of resource use and environmental damage. Whereas capture fishery production has remained fairly static at around 90 million tonnes, aquaculture production has steadily increased from 26.7 million tonnes in 1996 (FAO 2002a) to 60 million tonnes in 2010 (FAO 2012). Global aquaculture production is dominated by China at 61.4% by volume in 2010, largely for domestic markets, although its production continues to increase, its share of world production is decreasing (FAO 2012). The rest of the world's aquaculture industries have also experienced rapid expansion, representing significant trade and income. Globally, aquaculture continues to be the fastest food growth industry, expanding at a rate roughly four times that of terrestrial livestock species combined and now representing around half of global food fish supply (FAO 2012).

In addition to food capture fisheries, in excess of 30 million tonnes of fish are caught each year for non-food purposes, mainly for the manufacture of fishmeal and oil for use as feed and feed supplements in aquaculture, pig and poultry production (Figure 1.1). Aquaculture has often been criticised for inefficient use of fishery resources being directed to fishmeal and oil, and for putting pressure on species which can threaten ecosystems (Alder *et al* 2008), whereas more of the fishery resource could be used for direct human consumption, including extracted oil (De Silva and Turchini 2008). In addition, there is little published work on the potential for aquaculture to alleviate the pressure on resources through producing fishmeal and oil to feed other livestock through processing of by-products. By-product is not a term that is readily used in Life Cycle Assessment, but for the purposes of this thesis, by-products are defined as those parts of the animal, other than the edible fraction, which may have some value but are often under-utilised, or may be wasted. Within this definition, co-products are defined as those parts which can be readily used to add value, whereas a waste cannot be used and must be disposed of (ISO 2006a, 2006b). On-farm mortalities may be considered as co-products or wastes depending on their fate.

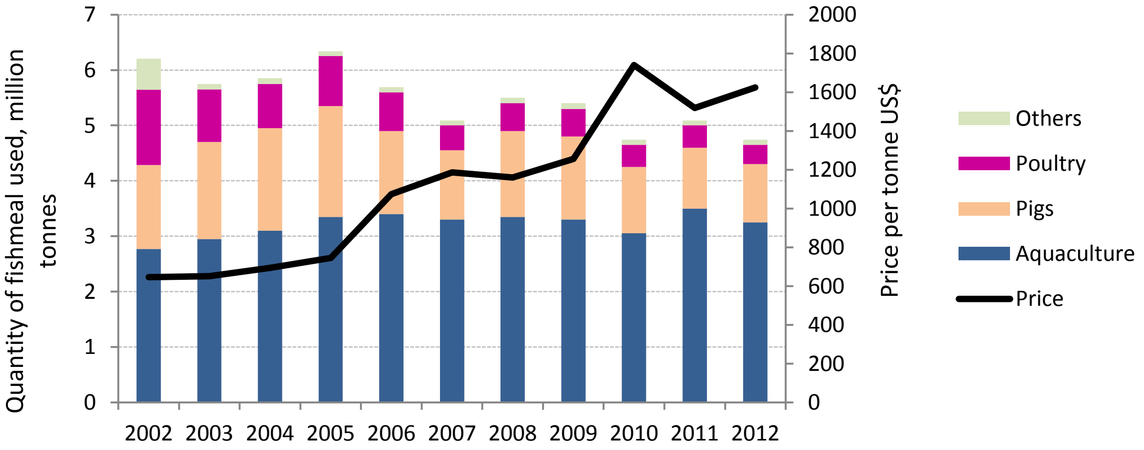


Figure 1.1. Proportion of fishmeal used in different sectors and price per tonne. Source: IFFO 2013 unpublished data. Price; International Monetary Fund 2013

In 2009 the estimated quantity of fish captured and directly used in fishmeal and oil production was 17.9 million tonnes (FAO 2012), although this is significantly lower than the estimated 30 million tonnes used in 1994 (FAO 2009), mainly due to the steady decline in anchoveta catches from 10.7 million tonnes in 2004 to 4.2 million tonnes in

2010 (FAO 2012). Declines in the global capture of blue whiting, capelin, sandeel and other minor species also contributed to the overall reduction in fishmeal supplies (Fishstat 2013). Although the quantity of fishmeal used in aquaculture has remained fairly constant for about ten years at around 3 million tonnes, the total supply has varied greatly, due to El Niño events for example, and overall has been in decline. This has resulted in fluctuating, but ultimately rising, prices for both fishmeal and oil and increasing pressure on the aquaculture industry, particularly that of marine shrimp and carnivorous fish such as salmon, which still utilise large quantities of fishmeal (Tacon *et al* 2011). The highly unstable nature of reduction fisheries, dominated by vulnerable anchoveta catches (FAO 2014), has led to the search for more stable supplies and an increasing proportion of fishmeal is now sourced from seafood processing by-products.

The reliance of aquaculture on fish oil is even greater than fishmeal, and is estimated to utilise between 80% and 90% of global supplies annually, compared to the 1970s when most was directed toward hydrogenation plants to be converted to trans-fats, used in margarines for example (Bimbo 2007). The recent promotion of omega-3 fatty acids as health promoters has seen an upsurge in the demand for encapsulated fish oil, growing at over 4% per annum between 2003 and 2007 in the US (Snyder 2010), putting further pressures on prices and supplies. As many of the capture fisheries used for fishmeal and oil production are fully exploited (FAO 2002b; Fishmeal Information Network 2008), it is becoming increasingly important to maximise the efficiency of resource use from aquaculture and fishery products. In addition, with increasing production costs and competition within the aquaculture sector and with other sectors, profit margins have been squeezed for many producers (Borch 1999; Lam *et al* 2009). It is therefore becoming more important to add value to the product wherever possible throughout aquaculture value chains (i.e. the interlinked sectors and service industries throughout production). Full utilisation of by-products can open many opportunities for the industry and there are potentially many synergies to be found between the food production industries.

While there has been some research to investigate the potential for by-products, lack of knowledge transfer, logistical barriers and the strict European Union (EU) Animal By-Product Regulations (European commission 2002a; 2003; 2009) have proven prohibitive to European products and imports to the European Economic Area (EEA, the 28 EU countries plus Norway, Iceland and Liechtenstein). Legislation will be discussed in detail in chapter 2. Many technologies are available (which are described below) that enable value to be added through by-product utilisation, and these are often used innovatively in Europe and Asia. However, there are areas where efficiency can be massively improved, by employing such technologies and a full study of the various trade-offs between them has been long overdue. In some cases scaling to commercial levels still remains a challenge with respects to purification, efficiency, documentation and verification of health claims, commercial licensing and marketability (Raghavan and Kristinsson 2009; Thorkelsson and Kristinsson 2009). There has sometimes been little progress on how to integrate the technologies and ideas for the aquaculture sector and the organisational structure to facilitate their uptake in terms of cost benefit, environmental impact and future projections. However, fish products may have particular advantages over porcine and bovine products for religious reasons, particularly in Asia and therefore, aquaculture products hold significant opportunity for value addition.

1.2 Current status of by-product utilisation

1.2.1 European Salmon

Aquaculture in the EEA is dominated by salmonid production, particularly Atlantic salmon (*Salmo salar*), the majority of which is grown in Norway. Here the combined production of salmonids was in excess of 1.3 million tonnes in 2012 (Norwegian Directorate of Fisheries 2013) and more than the EU28 marine finfish aquaculture production combined (Fishstat 2013). Estimated fillet yields from farmed salmonids, *Pangasius* catfish and *Penaeid* shrimp are shown in table 1.1. For salmon they are about 62%, with 9%, 18%, 9% and 2% wet weight, making up the viscera, head, backbone and skin, respectively (Ramírez 2007). The most significant by-product streams are viscera at the point of slaughter and then the heads, bones and often the skin after transportation to the processing plants. In some circumstances the slaughter and processing may be combined. Norway exports more than half of its product (Whole Fish Equivalents, WFE) to the EU as whole/eviscerated fish, mostly for further processing (Global Agriculture Information Network 2007) and further exportation within the EU (Figure 1.2). Despite this, according to RUBIN (2014) there was an estimated 250,000 tonnes of aquaculture by-product utilised in Norway in 2009. Recently much of the processing of eviscerated Norwegian salmon has moved from Denmark and Germany to eastern European countries, such as Poland (Norwegian Seafood Export Council 2009). The UK, specifically Scotland, is the second largest producer of cultured salmonids within the EEA at around 160,000 tonnes, the vast majority of which are Atlantic salmon and production is steadily increasing with new export markets opening (Marine Scotland Science 2013). An estimated 38% (WFE) of Atlantic salmon is exported (SSPO 2009), with the remainder of fish cultured in Scotland processed in the UK along with an additional 40,000 tonnes WFE which are imported from Norway (in 2008) (Norwegian Directorate of Fisheries 2009).

Table 1.1. Fillet yield, expected mortality and proximate analysis of whole carcass and entire co-product post-filleting, for farmed Atlantic salmon, striped catfish and penaeid shrimp

Species	Fillet yield %	Mortality %	Water %	Protein %	Lipid %	Ash %	Omega-3 FA, % total
Whole animal*							
Atlantic salmon	62[1]	5[2]	65.9[3]	18.9[3]	13.7[3]	2.6[3]	39.3[4]
Striped catfish	35[5]	30[6]	76.8[7]	12.8[7]	5.6[7]	4.0[7]	-
Penaeid shrimp	50[8]	55[9]	74.9[10]	18.0[10]	1.2[10]	3.4[10]	22.9†[11]
By-product							
Atlantic salmon	-	-	62.1[3]	16.9[3]	19.1[3]	4.7[3]	43.6[12]
Striped catfish	-	-	73.6[13]	11.8[13]	7.9[13]	5.6[13]	-
Penaeid shrimp	-	-	69.3[14]	18.9[14]	1.2[14]	5.8[14]	19.1[14]

*Whole animal figures for striped catfish were taken from fingerlings of average weight 7.6g. Atlantic salmon and *Penaeid* shrimp figures from market size animals except †whole shrimp omega-3 content is for Indian white shrimp, *Fenneropenaeus indicus* at average weight 17.6g, all others are for the black tiger shrimp, *Penaeus monodon.* Co-product figures are extrapolated from whole fish quantities, fillet yields and quantities.

Source: 1. Ramírez 2007; 2. SEPA 2004; 3. Einen and Roem 1997; 4. Stubhaug *et al* 2007; 5. Le Nguyen 2007; 6. Lam *et al* 2009; 7. Hung *et al* 2010; 8. Benjakul *et al* 2009; 9. Briggs *et al* 2005; 10. Focken *et al* 1998; 11. Ouraji *et al* 2009; 12. Higgs *et al* 2006; 13. Polak-Juszczak 2007; 14. Sriket *et al* 2007

The UK salmon processing industry has consolidated over the last ten years with the number of plants reduced from 145 to 48 between 2001 and 2008 but with a slight increase in the number of employees in the same time frame (Seafish 2009a). Consolidation has allowed some processors to produce a range of commodities, such as smoked fillet, mousses and ready meals. This trend has the potential for more efficient use of by-products. Despite opportunities for value addition from within the UK, over 25,000 tonnes of the estimated 52,400 tonnes of processing by-product from UK farmed fish in 2003 was exported (SEPA, 2004) and, with much of the production exported as whole/ eviscerated, much of the potential for value addition within the UK is lost.

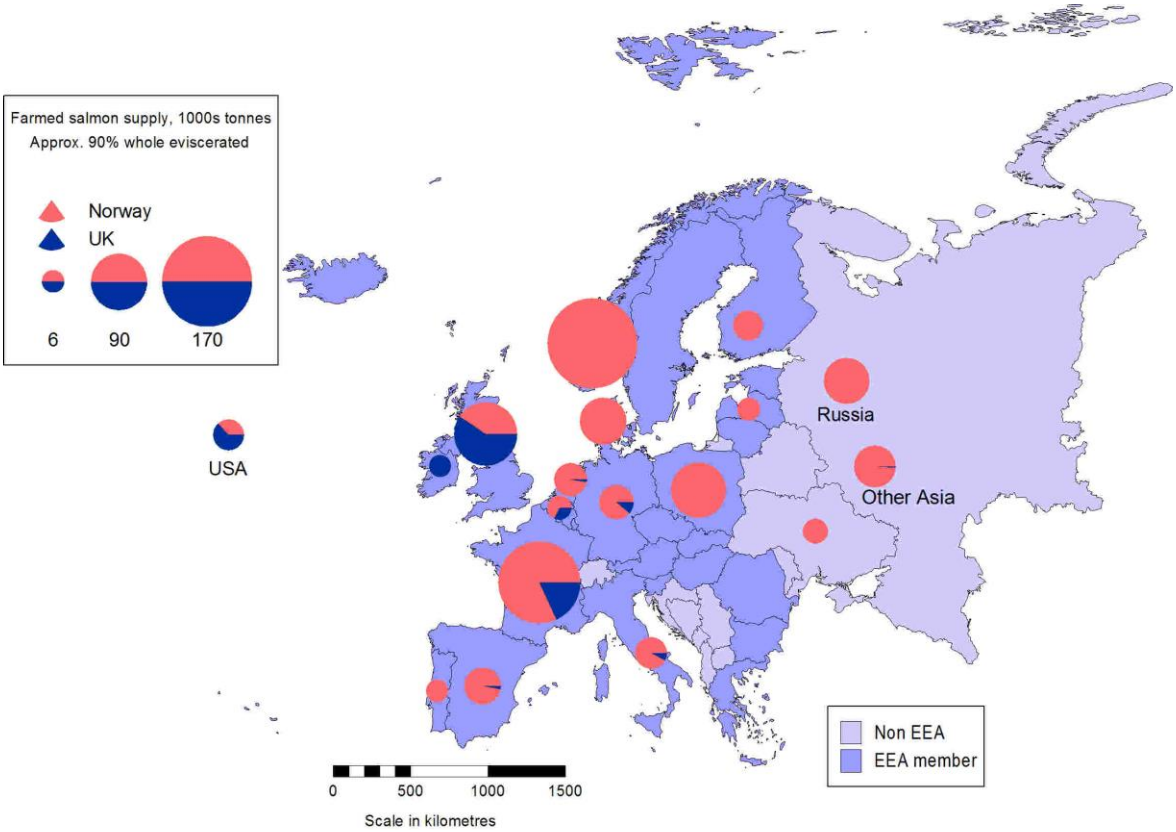


Figure 1.2. Distribution of farmed eviscerated Atlantic salmon produced in Norway and the UK for further processing during 2008. Source: Norwegian Directorate of Fisheries 2009; SSPO 2010 unpublished data

Aquaculture by-products have advantages that they are often more uniform and fresher than those obtained from capture fishery processing (Šližytė *et al* 2009), as they are often slaughtered close to the processing site and are of a uniform species, at the same stage of their life cycles. Conversely, capture fisheries products may be composed of mixed species and life stages, which vary according to season. Frequently changing socio-economic conditions and consumer attitudes have led to continual restructuring and a fractured nature of the aquaculture processing industry in the EU, resulting in excessive transportation, diffuse availability, and a potential loss in quality of by-products and potential revenue. Studies have shown that salmonid by-products not only contain significant amounts of omega-3 fatty acids (FAs) (see Table 1.1 for proximate analysis and references) but high value substances, such as collagen and peptides (see below) may also be extracted from the various fractions.

Currently, companies in Scotland (Rossyew Ltd), Norway (Scanbio AS) and Denmark (Hordafor) extract the oils from farmed salmon processing co-products, and produce protein concentrates intended for use in pig or poultry feeds (Thistle Environmental Partnership 2008). For example, Hordafor, Denmark, produces around 30,000 tonnes of protein concentrate from around 100,000 tonnes of aquaculture by-products per year and also utilises mortality waste for biogas production (see below) (Leivsdóttir, pers. comm. 2010).

Markets for some salmon processing products such as heads are well established in Vietnam and they can frequently be seen for sale commonly in major supermarkets as well as in local markets for around 30,000 VND (about US$1.45) per kilogramme. There is at least one company in the UK which exports aquaculture and fishery by-products to Asia and other locations. The import of by-products demonstrates different values attached to various animal products by different countries. More research is required to establish the demand for by-products in various locations and weigh these against other value addition options closer to the processing areas.

1.2.2 Thai and Vietnamese Penaeid Shrimp

The rapid growth of the aquaculture industry in countries such as Thailand and Vietnam (particularly penaeid shrimp and *Pangasius* catfish, mainly striped river catfish, *Pangasianodon hypophthalmus*) provides an opportunity for comparison of utilisation strategies to the European Atlantic salmon situation. In these Asian countries, producers and processors have developed in parallel and traditionally use a mixture of high and low technology solutions to utilise aquaculture production and processing by-products (according to stakeholders in the region). The relatively close co-location of production, processing and support industries in Asia (particularly Vietnam) provide excellent opportunities to formulate efficient resource use management strategies (Figure 1.3). For the reasons above, these strategies may be logistically more difficult to implement retrospectively in Europe.

Both Vietnam and Thailand are major producers and exporters of *Penaeid* shrimp. In 2013 Vietnam produced around 475,000 tonnes of shrimp (Vietnamese Ministry of Agriculture & Rural Development 2014), a ten year increase of over 700% (VASEP 2010), whereas Thailand produced 551,000 tonnes in 2011 which was an increase of 24% over five years (Thai Frozen Foods Association (TFFA) 2014). Recently, however, the global *Penaeid* shrimp industry has suffered catastrophic losses due to the Early Mortality Syndrome (EMS) epizootic, which severely curtailed production in 2012. In typical years, Thailand remains the biggest exporter of shrimp, exporting 392,000 tonnes in 2010 mainly to the USA with around 40% of this preserved or prepared as value added products such as ready meals or gourmet products (TFFA 2014).

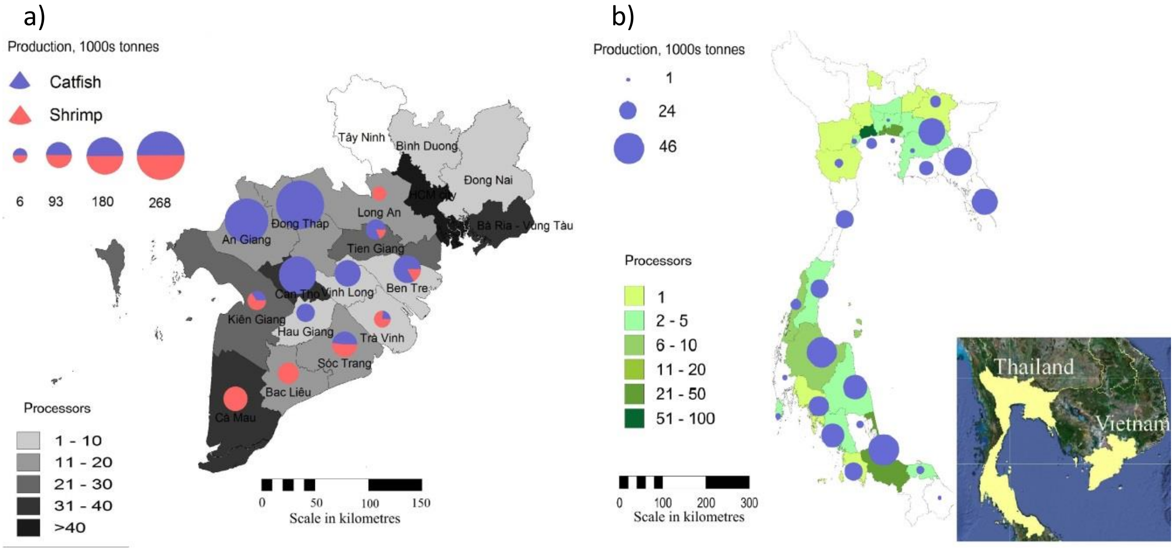


Figure 1.3. Production and number of processors of a) *Pangasius* catfish and *Penaeid* shrimp in the Mekong delta of S. Vietnam in 2008, b) Penaeid shrimp in S. Thailand in 2007. Source: (VASEP 2010, VIFE 2009, Department of Fisheries (Thailand) 2009

Evidence from processors in Thailand and the Mekong delta, Vietnam show that there is a large variety of shrimp export products ranging from whole, head on shell on (HOSO) to completely peeled, de-headed and deveined (PD), for which complete production data were not available. These products may be raw or cooked and may also include value added products such as ready meals or marinated products, for example. Evidence from VASEP (2010) suggests around half of Vietnamese shrimp is being exported whole, mainly to Japan, the USA and Europe. Estimates of fillet yields from *Penaeid* shrimp vary but most reliable figures suggest around 50% of the animal is fillet (Table 1.1) for all species (Benjakul *et al* 2009). However, the variety of shrimp products and the changing market makes the amount of by-product available difficult to assess, although for Vietnam it was estimated at over 150,000 tonnes in 2010 (Trung 2010) which is in agreement with communications with Thai processors who estimated around 30% of the shrimp raw material entering their facilities becomes by-product. Shrimp by-products have often been used to produce shrimp meals. Although these by-products provide a readily available protein supply for livestock, they could perhaps be redirected to other industries providing products of more value, both nutritionally and economically. These issues will be discussed in more detail in subsequent chapters.

1.2.3 Vietnamese Pangasius catfish

In Vietnam, production of the *Pangasius* catfish*,* grew from 23,000 tonnes in 1997 to 1.15 million tonnes in 2008 (VASEP 2010) but has since declined to around 970,000 tonnes (Vietnamese Ministry of Agriculture & Rural Development 2014) as a result of unstable prices and consolidation. As a consequence of the unprecedented growth, fish processing and service industries grew rapidly with over 90% of production processed locally for export to over 100 countries as frozen fillets (Lam *et al* 2009). However, the expanding industry has also experienced some of the same problems that the salmon industry faced two decades ago. This includes unstable prices at each node of the value chain along with production problems in terms of poor feed quality, water quality and disease issues. Fillet yield for *Pangasius* catfish is low compared to salmon, typically between 30% and 40% (Table 1.1), depending on the cut (e.g. deep skin, trimmed etc.).

According to some processors, demand is growing for products such as frozen industrial block, regular cuboid blocks which can be further processed more easily. This process results in more trimmings which could be used for many value addition options.

Key informant interviews of *Pangasius* catfish processors in Dong Thap and Can Tho provinces in the Mekong region conducted as part of the research for chapter 4, coupled with direct observation in local markets in Soc Trung, supermarkets and restaurants in several other Mekong provinces revealed that post-filleting products are commonly on sale for direct human consumption. These included the catfish stomachs and swim bladders, and sometimes heads and other trimmings. According to Nguyen (2010), this is around 5% and the rest is processed into fishmeal and oil, including viscera, heads, skins and trimmings (Le Nguyen 2007). 53% of fish meal from by-products is directed to terrestrial livestock feeds, and 45% to domestic aquaculture, with the oils separated for further sale, also usually to livestock feeds manufacture (Nguyen 2010). However, traceability can sometimes be poor in Vietnamese *Pangasius* and shrimp value chains (Le Nguyen 2007), possibly resulting in intra-species feeding (feeding of animal products to the same species) of exported products. Some unpublished feed ingredients lists from Vietnamese feed mills have shown that small quantities of *Pangasius* by-product oil is sometimes included in *Pangasius* feeds and Tacon (2002) suggested that some shrimp by-product may still be used to produce shrimp feed, and is preferred by some farmers.

1.3 Mortality in aquaculture

This section gives a brief overview of the mortality problems encountered for the three study species in typical production scenarios. More detailed analysis of mortality causes for the three species, their subsequent fate and other options for value addition will be dealt with in chapter 4. Although, according to regulations (EC 2009a), mortalities from production should not enter the human food chain, they have the potential to alleviate the impact on fish meal and oil supplies that are suitable for human food production, by directing them to feeds for pets and other non-livestock feeds. According to De Silva and Turchini (2008), around 13.5% of the global forage fish catch suitable for fishmeal inputs into human food production was directed to pets and animals farmed for their fur in 2002. Although this figure is out-of-date, it is thought that a large proportion of high quality fishmeal is still being directed to industries where other options may be available, that are not accessible to the livestock industry.

Chronic fish mortalities in European salmonid production and from other reasons such as losses following transfer to sea from freshwater etc. amount to between 5% and 10% of the total production in numbers of individuals, for Scotland and Norway (SEPA 2004; Statistics Norway 2009). On occasion acute local or widespread catastrophic mortality events occur through disease, algal blooms (Treasurer *et al* 2003), jellyfish (Fisheries Research Services 2010; SEPA 2004) or extreme weather (SEPA 2004). A weather or disease event may result in the loss or culling of an entire farm stock of several hundred tonnes. The slow accumulation of chronic mortalities means they are of little value but schemes such as ‘The Fallen Stock Scheme’ may allow for more efficient collection, lower costs and better utilisation (Bansback 2006). However, producers are reluctant to allow vehicles to move between sites for biosecurity reasons.

The vast majority of shrimp mortality occurs in the early stages when the animals are less than 1g, therefore they tend to be left in the pond and are of little value, according to farmers in SE Asia. Small amounts of chronic mortality may also occur throughout the grow-out cycle. Farmers have battled against a number of particularly costly disease problems for decades, including white spot syndrome (WSV), yellow head virus (YHV) and Infectious Hypodermal and Haematopoietic Necrosis (IHHN) amongst others. Crustaceans lack an immune memory (Arala-Chaves and Sequiera 2000) and therefore effective long-term vaccination programmes are not possible. Instead farmers rely on a diverse range of management practices to try to prevent against disease outbreaks where possible, including monitoring of broodstock and diverse extensive, integrated and polyculture systems (Bush *et al* 2010).

Disease has also been a major issue for *Pangasius* catfish production in Vietnam, resulting in high mortality and consequent use of antibiotics (Lam *et al* 2009). *Pangasius* catfish farms in An Giang province, one of the most intensive production areas on the Mekong delta, commonly report a mortality of up to 30% in the early to mid stages of the production cycle, but mortality may remain as high as around 10% in the later stages of production, despite a reliance on antibiotic based therapies (Lam *et al* 2009). Possible chemotherapy-derived contaminants in mortalities may limit opportunities for value addition, even for pet and fur animal feeds (Lam *et al* 2009; Nguyen *et al* 2006). Some farmers also revealed that fresh mortalities may sometimes be consumed by farm employees or sold to local markets. Whilst this would be unacceptable in the EU, it is commonly accepted in Vietnam but it is thought that in most cases mortalities are being buried. According to evidence from stakeholders, mortalities were reported to be occasionally fermented for fertiliser, for use on local farms or on the site itself, in small quantities for fruit production. Issues surrounding farm mortality and their disposal will be dealt with in detail in Chapter 4.

1.4 Current and prospective options for by-product value addition

The various options available for value addition to by-products are dependent on what is allowable under national and international regulations and standards. This is more fully explored in chapter 2. EU regulations are commonly regarded as the strictest and the following presents the situation under EC regulation 1069/2009 for animal by-products (EC 2009a). The regulations split animal by-products into three categories, based on their risk to humans and animals, with category 1 being of highest risk. No aquaculture products fall into category 1, by-products from processing are category 3 and mortalities from production are category 2. Generally category 2 by-products must not re-enter the human food chain, either directly or indirectly, whereas category 3 by-products can. The regulations and standards governing the international trade and utilisation of aquaculture by-products are discussed in more detail in chapter 2.

1.4.1 Processing by-product utilisation

1.4.1.1 Fish and shrimp meals

Aquaculture has often been condemned for its use of commercial fisheries products, in aquafeeds, such as fishmeal from anchoveta (Alder *et al* 2008), although fishmeal use in aquaculture has not increased significantly for the last 10 years (Figure 1.1). However, global supply of fishmeal and oil is unstable and this has led to increasing prices on the global market (FAO 2013). The impact on the high grade fishmeal industry can therefore be lessened by replacing that used in terrestrial livestock feeds with fishmeal made from the by-products from aquaculture. Pig and poultry feeds in Europe include high grade fishmeal from traditional dedicated fisheries, that contain between 6% and 10% oil (Seafish 2009b), because of the health benefits of omega-3 fatty acids (FAs) to both the livestock and human consumers (see below) and because of the high digestibility and good amino acid profile of fishmeal (Fishmeal Information Network 2001; Kouba and Mourot 2010). Though *Pangasius* catfish are naturally high in protein, they are low in omega-3 (Polak-Juszczak 2007). The lower omega-3 content results in a fishmeal that is perceived to be of lower quality. However, Nguyen (2010), showed that on a trial basis pigs fed diets containing catfish by-product performed as well or better in terms of diet intake, growth, meat quality and mortality, than pigs fed diets which included traditional fish meal sources. *Pangasius* fishmeal is now a widely available product and is commonly used within pig feeds in Vietnam. Chapter 7 investigates the environmental performance and value addition of *Pangasius* fish meal in a commercially available pig feed.

Studies have also shown that capture fishery by-products can be used in shrimp feeds with good results (e.g. Sudaryono *et al* 1996). EU regulations (which will be covered in more detail in Chapter 2) allow for aquaculture by-products to be used in the diets of other species since 2011 (EC 2009a). By-products from capture fisheries have been used in trials for aquafeeds for other fin fish species by Goddard *et al* (2008), Whiteman and Gatlin (2005) and Seoka *et al* (2008) amongst others. The results for these studies were mixed, with various by-product and by-catch meals performing well in Nile tilapia diets (Goddard *et al* 2008) but less so in red drum (Whiteman and Gatlin 2005). Seoka et al (2008) showed that pacific salmon roe phospholipids performed well in blue-fin tuna (*Thunnus oreintalis*) larval diets. These mixed results show the highly variable qualities of the by-product fractions which need to be targeted towards specific uses.

Shrimp by-product meal has been shown to perform less well than fishmeal when included in aquafeeds (e.g. Whiteman and Gatlin 2005, Hardy *et al* 2005) and in pig feeds (Fanimo *et al* 2006). This is attributed to poor availability of protein (Coward-Kelly *et al* 2006; Sachindra *et al* 2006), and higher fibre and ash content due to the high chitin and mineral levels (Fanimo *et al* 2006). Although shrimp by-product has protein levels of 35 to 50% (dry weight), much is bound to highly indigestible chitin (15 to 25% dry weight) (Edwards 2004; Sachindra *et al* 2006) and 10% to 15% mineral content (Sachindra *et al* 2006). Digestibility can often be improved by separation of the chitin by hydrolysis or fermentation to break the protein-mineral-chitin complex (Coward-Kelly *et al* 2006; Nwanna 2003). Autolysis at ambient temperatures has generally given low yields of usable products., according to Cao *et al* (2009) who showed, however, that autolysis of shrimp heads using gradual increase in temperature up to 70°C could give protein recovery rates of 88.8% which can then be used for animal feeds or flavourings for human consumption (see below).

1.4.1.2 Fish oils

In recent years there has been much emphasis on the health benefits of consuming oily fish as part of a balanced diet, not least because of high omega-3 highly unsaturated fatty acid (HUFA) contents, eicosapentaenoic acid (EPA) and docosohexaenoic acid (DHA) which are limited to marine sources (Erkkila *et al* 2006). Studies have shown that maintaining a level of omega-3fatty acids (FAs) to be important in reducing factors associated with heart disease (Domingo 2007; Holub and Holub 2004), strokes, thrombosis, mental health problems and arthritis (Sun *et al* 2002). More recently a high ratio of omega-3 FAs (including EPA and DHA) to inflammatory omega-6 FAs, common in many plant oils, has also been shown to be important in human health, particularly in preventing coronary heart disease (Holub and Holub 2004). This is because omega-3 FAs can block the enzyme binding sites responsible for conversion of omega-6 FAs to inflammatory prostaglandins (Araujo *et al* 2014)

In animal nutrition, inclusion of long chain omega-3 FAs in pig diets has been shown to improve survival substantially for weaning and suckling pigs and is therefore an important dietary component (Fish Information Network 2001). At present, much of this omega-3 FA comes from commercial fishmeal and fish oils (Seafish 2009b). However, if necessary, fishmeals with low omega-3 FA content from *Pangasius* catfish by-products, for example, could be supplemented with oils extracted from salmonid by-product or other high omega-3 product such as from marine capture industries, depending on the formulation strategies of the feed producers.

Concentrations of lipid and in turn of EPA and DHA in farmed salmon viscera are higher than those of the fillet, and many whole wild captured fish (Figure 1.4), although whole salmon have lower levels than whole Atlantic herring (Sun *et al* 2006). Concentrations of EPA and DHA will depend on the diet of the farmed salmon. A proportion of Scottish salmon, perhaps 10%, are fed higher levels of fishmeal and fish oil than in other locations to meet consumer demand but overall fishmeal and fish oil inclusion levels have been dropping in farmed Atlantic salmon diets (Tacon and Metian 2008).

Consumer fears over contamination of farmed salmon with persistent organic pollutants (Hites *et al* 2004) and heavy metals (Domingo 2007) may lead to further fears over bioaccumulation of PCBs if oils are concentrated for health supplements or recycled for animal feeds. Mercury is mostly found as methyl mercury but methylation does not reduce the polarity sufficiently so that it is readily dissolved in oil fractions (Gong *et al* 2011) and is therefore more of a problem for accumulation in fish meals. Contaminant levels are generally regarded as being below levels considered to be dangerous to human health (COT 2006; Fernandes *et al* 2009) and often the refining process removes many persistent contaminants (Muggli 2006), especially the deodorisation process using steam distillation, but this may destroy valuable fractions such as carotenoids (Hilbert *et al* 1998). Salmonid visceral oil is of lower quality than that of muscle in terms of lower phospholipids, anti-oxidants α-tocopherol and total carotenoid concentrations (Zhong *et al* 2007) but despite this, visceral oil is less subject to oxidation than muscle oils (Sun *et al*

2006) and aquaculture by-products can often be supplied fresh (Šližytė *et al* 2009). Oils are already extracted from salmon by-products by simple heating, decanting and clarification by centrifuge, in Denmark by Hordafor, Norway by Scanbio Ltd. and the UK by Rossyew Ltd. who also filter the oil for a purer product (Wright 2011, pers. comm.). However, the full potential is not being met. More research is required to determine markets for the products and where oils can best be directed. Also, yields can be improved and the omega-3 FA fraction separated to higher purity (Sun *et al* 2002) although this may not be cost effective. Production of oils for direct human consumption requires that certain requirements are met regarding the production facilities and possible contaminants as laid out in EC Regulation 853/2004. Regulations and standards regarding aquaculture by-products are discussed in more detail in Chapter 2.

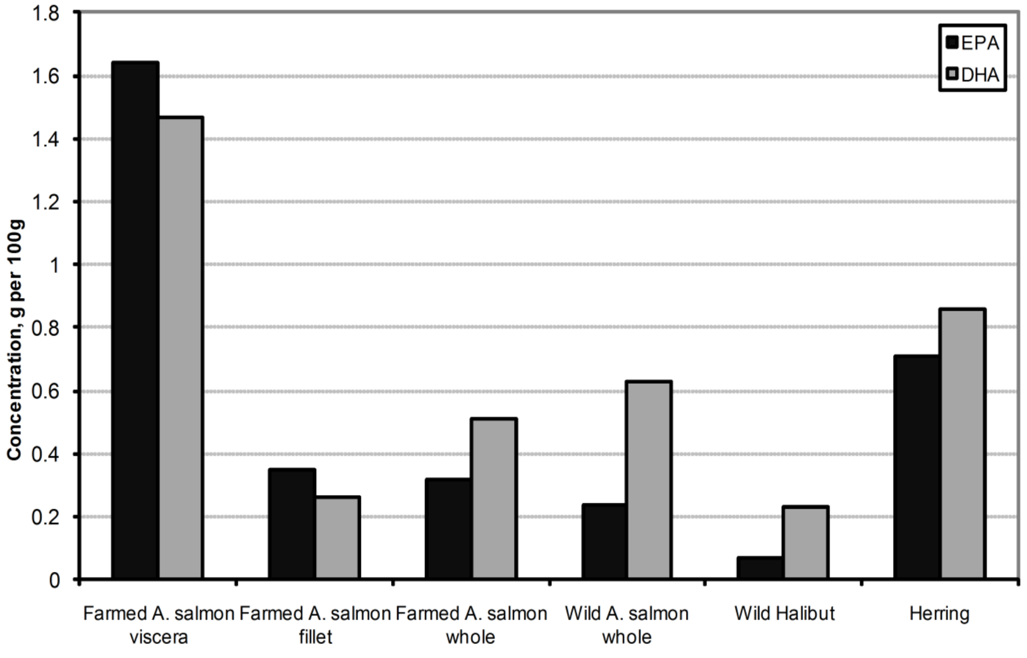


Figure 1.4. EPA and DHA concentrations in the viscera of farmed Atlantic salmon (grammes of PUFA per 100g total FAs), compared with whole wild and farmed salmon and other commercially important species. (See table 1.1 for total lipid and omega-3 contents in the studied species). Adapted from Sun *et al* 2006.

Whereas it is important to maximise the use of omega-3 FAs to relieve impacts on commercial fishmeal and oil reduction industries, by-products from species which are low in omega-3 FA content such as *Pangasius* catfish may be better used for other uses. If cost effective, these applications can also contribute to resource efficiency of fishmeal and other global inputs within and without the *Pangasius* catfish value chain.

Fish oils have traditionally been used in the tanning industry, for the production of high quality leather such as chamois and this is a possible route for oils produced from low grade by-products and mortalities (Thistle Environmental Partnership 2008). Worldwide, there has been increasing interest in biofuels as an alternative to fossil-fuels, but this has been tempered with concerns over deforestation and diversion of food products towards the biofuel industry (Piccolo 2009; Sachs 2007). Recent activities have shown catfish by-products in Vietnam and tilapia by-products in Honduras to produce excellent biofuels. Research into using fish by-products and mortalities from the *Pangasius* catfish industry has been gathering pace (Nguyen. *et al* 2009a; Nguyen *et al* 2009b; Piccolo 2007). Fish oils have been reported to be excellent fuels because they can be used in unmodified diesel engines and a high yield can be obtained from the raw product (Piccolo 2007). Initial attempts produced fuels which released emissions which were harmful to human health, but the quality has now improved (Nguyen *et al* 2009a).

Fish fat can be broken down into functional biofuels by simple processes on small or large scales with glycerol as a further by-product that has applications in a number of industries e.g. cosmetics (Piccolo 2007). The oils may be further purified into fuels of more specific character and use as outlined by Wiggers *et al* (2009), Wisniewski Jr. *et al* (2009) and Preto *et al* (2007) and which may meet European Quality Standards for biofuels, although this needs further attention. According to Nguyen (2009a), between 2005 and 2007 the price of *Pangasius* catfish fat increased from between 2000 and 3000 VND (US$0.10 to $0.14) per kg to about 6000 VND ($0.28) per kg due to interest in producing biofuels and there are now established processing plants in An Giang and Can Tho. The Can Tho plant has a capacity of around 50 tonnes per day of raw material and was exporting its product to Singapore at 11000 VND (about US$0.60) per litre in 2005 (Agriviet.com 2009). Although there is no specific mention of using mortalities or fish by-products for biodiesel production in the EU regulations, the allowance for biogas production and industrial uses should permit this route which could be of particular interest to remote or small scale fish-farms and processors in the EU.

1.4.1.3 Sauces, pastes and other products for human consumption

In Europe and other Western countries, direct consumption options for humans are likely to be limited because of customer perception, compared to Vietnam and other Asian countries which import processing by-products from the West for human consumption. It is difficult to trace the by-products which are available for value addition from European salmon because of the diffuse nature of processing and subsequent trade has led to uncertainty over the quantities of various fractions in each of the major processing countries. Surveys conducted as part of the LCA work in chapter 8 indicated that the value of by-products was extremely low in Scotland and that apart from the viscera, the remaining by-product was being exported to Russia, where its further utilisation could not be traced. The acceptability of products to European consumers may differ to their Asian counterparts and the nature of value-added products will depend on the quality of the flesh which can be obtained from the trimmings etc. and may only allow for commodities such as fish-balls, mousses or pâtés to be produced (Young 2010 pers. comm.). In Vietnam, Thailand and other Asian countries, there is also a market for fish sauces, pastes and surimi to which some by-products, such as trimmings and undersize fish, are directed (Le Nguyen 2007). However, the flesh quality of certain species such as *Pangasius* is still an issue for these products. Gelman *et al* (2001) and Glatman *et al* (2000) described possible techniques for fermenting fish, using strains of lactic acid bacteria, similar to the traditional small scale techniques, common in the region, to produce novel "meat-like" products which could be acceptable to consumers.

Technology is readily available which allows a significant increase in edible yield through recovering fish scraps from frames, which may not be economically attractive to remove manually (Bibwe *et al* 2011). Whereas this is commonly practiced for high value species such as salmon and some marine whitefish (Kim and Park 2007), for species such as *Pangasius*, the value of the recovered flesh may be low (Young pers. comm. 2010). According to *Pangasius* by-product processors in the region, the value of the by-product was around 6500VND/kg (US$0.35) but the removal of the flesh from frames may lower the value of the by-product, ultimately resulting in more waste if fishmeal producers can no longer produce a product of high enough quality to be of interest to livestock feed producers. These trade-offs need much further exploration from a resource efficiency and value addition perspective and will be investigated further in Chapter 7.

In Thailand, Vietnam and many other Asian countries, utilisation of shrimp co-products from small capture fishery species such as krill is fairly well established as fermented goods for human consumption (Sobhi *et al* 2010). There is also an established market for *mungoon*, a shrimp paste made from the cephalothorax (Binsan *et al* 2008). Mungoon is a highly nutritious and healthy food because of high omega-3 FAs, essential amino acids and calcium ions according to Binsan *et al* (2008). Despite this usage, the yield of mungoon using traditional production methods is low, reported at 21.5% of raw material (Benjakul *et al* 2009), leaving substantial amounts of further by-product that requires processing into useful products or disposal. Mungoon, remains a relatively niche product, being produced by traditional processes (Benjakul *et al* 2009). Most shrimp processors reported that the vast majority of their by-product is either directed to shrimp meal in the form of heads, or to chitosan manufacture as shells.

1.4.1.4 Collagen

Collagens are the most abundant proteins in vertebrates, commonly found in connective tissues, especially of the skin but also bones. There are at least 26 forms (Li *et al* 2005) of which the most abundant and most useful for biomedical and cosmetic applications is type I (Li *et al* 2005, Lee *et al* 2001). Its usefulness stems from the ease of its extraction in solution and that it can be shaped into many forms containing tensile fibres which are biodegradable, biocompatible and non-antigenic (Lee *et al* 2001). These can be used in many applications including multiple medical uses such as drug delivery and wound dressings, cosmetics and edible food coatings (Lee *et al* 2001; Singh *et al* 2011). Collagen extracted from fish swim-bladders, commonly called isinglass, has traditionally been used to clarify beer (Regenstein and Zhou 2007; Hickman *et al* 2000). Extraction from terrestrial animals is well established, however fish skins also provide excellent potential for extraction and this has been described by Singh *et al* (2011), Sadowska and Kolodziejska (2005), Muyonga *et al* (2004), Aidos *et al* (1999), Eckhoff *et al* (1998) amongst others. Although yields from fish skins are generally higher than from mammalian skins (Yunoki *et al* 2003), there are differences in structure and amino/imino acid sequences which can change the properties of fish collagens compared to those from higher vertebrates. Denaturation temperatures are generally lower for fish collagens which may affect their uses, particularly for human biomedical applications (Saito *et al* 2009; Nagai and Suzuki 2000; Yunoki and colleagues 2003, 2004), but more work is needed to investigate how the different properties can best be applied. The thermal stability of collagen is generally higher in tropical species and according to Singh *et al* (2011), *Pangasius* catfish collagen has a maximum temperature threshold of around 39.5°C, similar to that of commercial porcine collagen. Collagen with lower thermal stabilities, such as that from salmon, reported as about 19°C for chum salmon, can be improved by techniques such as UV irradiation without risking the toxicity that chemical techniques may encounter (Yunoki *et al* 2003).

In most extraction studies, fish collagen was split between acid and pepsin soluble fractions. Singh *et al* (2011) described methods to extract collagen from *Pangasius* catfish skins that were similar to other collagen extraction techniques, using NaOH to first extract non-collagen proteins followed by neutralisation and dissolving in acetic acid. The acid soluble collagen can then be precipitated using NaCl and the further fractions obtained from the filtrate using pepsin hydrolysis to give a combined yield of 12.8% (wet skin weight).

1.4.1.5 Gelatine

Gelatine is a mixture of proteins prepared from the breaking of cross-linkages and denaturation of collagen but otherwise is similar in amino/imino-acid composition to the parent collagen (Regenstein and Zhou 2007). Although less valuable per unit weight, fish gelatines have considerable opportunities for halal food applications, most commonly in various sorts of gels for texture, stabilisation, emulsification and alternatives to fats (Karim and Bhat 2009). There are certain trade-offs between gelatines from cold or warm water fish, or terrestrial sources. The lower melting points of fish gelatines are an issue, and therefore those from warm water fish with higher melting points may be of more value, possibly due to higher imino acid content (Muyonga *et al* 2004; Karim and Bhat 2009; Shahiri Tabarestani *et al* 2010). However, a major application of gelatines has been in chilled desserts which could perhaps favour lower melting point fish gelatines because of better release of flavours and aromas (Choi and Regenstein 2000; Boran *et al* 2010) and offer alternative product options because of different textures and properties (Zhou and Regenstein 2007). Some additives such as neutral salts (Sarabia *et al* 2000), sugars (Choi and Regenstein 2000), egg albumen (Badii and Howell 2006) or treatments with transglutaminase (Yi *et al* 2006) may improve properties but uncertainty exists over the halal status of enzyme treatments (Karim and Bhat 2009).

Thermal stability is of importance in the manufacture of drug and food supplement capsules, which has been suggested as another possible application for fish gelatines with lower melting points (Karim and Bhat 2009). Other applications include possible biomedical uses such as biocompatible films and fibres with similar properties to collagen, possibly combined with other biopolymers such as chitosan, described below (Yi *et al* 2006). The most desirable qualities for all applications are high gel strength, viscosity and rheological properties, given particularly by the amino/imino acid contents and lower content of low molecular weight fractions (Karim and Bhat 2009; Eysturskarð *et al* 2009; Badii and Howell 2006) but also higher gelatine concentration and maturation temperature, i.e. that at which the gel is allowed to set (Choi and Regenstein 2000). The intrinsic physical properties also tend to be inferior for (especially cold water) fish compared to mammalian sources, but the extraction process can also have a significant influence over the quality of the gelatine (Shahiri Tabarestani *et al* 2010; Boran *et al* 2010).

Generally gelatine is extracted by one of two processes, the acid or the alkaline process, referring to the pre-treatment phase, to produce type A or type B gelatine respectively. Low storage and pre-treatment temperatures are generally thought to preserve the integrity of fish gelatine and provide better yields, especially for gelatines of cold water fish origin which are subject to quicker degradation than mammalian gelatine (Giménez *et al* 2005a; Karim and Bhat 2009; Regenstein and Zhou 2007). Pre-treatment is usually followed by hydrolysis in mild organic acids at moderate temperatures of around 45°C

(Karim and Bhat 2009; Giménez *et al* 2005b). The alkaline process has advantages in removing more non-collagenous protein and the following acid neutralisation allows for a weak acid extraction which minimises damage and gives high yields of good quality gelatine (Regenstein and Zhou 2007; Shahiri Tabarestani *et al* 2010). Barriers to the production of fish gelatines cited by Karim and Bhat (2009) were possible fishy off-flavours and odours in some species, and problems with availability of large amounts of consistent raw material, therefore economy of scale. If any problems of fishy flavour and odour are sufficiently addressed, there is considerable potential for collagen and gelatine extraction from the *Pangasius* catfish industry within the Mekong delta which produces large amounts of consistent by-product and has the infrastructure to provide fresh material and overcome economy of scale difficulties. In Europe, niche markets for cold water fish gelatines may be less interesting and may not be able to compete with porcine or bovine sources. Despite the large potential for *Pangasius* collagen and gelatine, scoping activities revealed that there was little evidence of commercialisation within the Mekong Delta, itself until recently. *Pangasius* skins had been widely available for sale on international markets but their level of utilisation could not be ascertained. Vinh Hoan, has recently become the first company to commercialise collagen and gelatine from *Pangasius* skins, in Vietnam (http://www.vinhhoan.com.vn/en/products/1668/1751 accessed 12/5/2013).

1.4.1.6 Chitosan and glucosamine

Chitosan is a polysaccharide which is most commonly made from the deacetylisation of chitin from crustacean shells but must first be separated from the protein and mineral complex. Chitosan is an attractive material because it is biodegradable, biocompatible, exhibits anti-microbial and haemostatic properties, binds protein and fats, and is soluble in weak acids (Shahidi 2007). Chitosan has many commercial applications depending on the properties provided by the raw material, the processes used to achieve different degrees of deacetylisation (DD), the molecular weight of the product and polyectrolytic properties (Synowiecki and Al-Khateeb 2003). Applications include disease resistant coatings for agriculture and maintaining freshness of produce, in industrial polymers used for paper and textiles, halal cosmetics, and medical purposes such as wound dressings, slow release drug and encapsulation technologies. It is also commonly marketed as a slimming aid (Lallemont 2008; Aye and Stevens 2004; Coward-Kelly *et al* 2006; Percot *et al* 2003; Synowiecki and Al-Khateeb 2003).

Commercial processes for chitosan production from aquaculture by-products are already well established and usually involve treatment of shrimp shell with acids to demineralise the calcium content, alkalis to separate the chitin from the protein and finally deacetylisation of the chitin to produce chitosan (Synowiecki and Al-Khateeb 2003). Properties given by high DD are considered more valuable as outlined by Lertsutthiwong *et al* (2002) and Synowiecki and Al-Khateeb (2003) amongst others, but this requires several deacetylisation steps with washing and drying between each, and high levels of control at each point (Lallemont 2008). The quantities of chemicals used have caused environmental concerns (Trung 2010; Aye *et al* 2004; Pacheco *et al* 2009) and can adversely affect the product (Arment and Guerrero-Legarreta 2009). Therefore interest is directed towards techniques such as enzymatic hydrolysis which are potentially more predictable, less damaging to the product and environment, and that separate protein and carotenoid fractions for further use (Aye *et al* 2004; Coward-Kelly *et al* 2006; Synowiecki and Al-Khateeb 2003). More research is required to weigh the various advantages and disadvantages over traditional methods on economic and environmental bases (Percot *et al* 2003; Synowiecki and Al-Khateeb 2000).

The growth in shrimp culture has led to an increase in the availability of raw material for chitosan production making it more economically attractive (Coward-Kelly *et al* 2006). Chitosan production is low in Vietnam because of environmental concerns and technological barriers relating to the quality of the product (Trung 2010). However, Vietnam exports a small proportion of chitin and shell from shrimp processing to China for chitosan production which is then further exported world-wide. Evidence from interviews with Vietnamese shrimp processors also suggests a growing chitin industry in Vietnam but it is losing the potential to create huge revenues, as the price for chitosan is between US$30 and US$150 US per kg, compared to US$3.60 and US$6 per kg for chitin (Pichyangkura 2010). Thailand has a well-established chitosan industry and dedicated research into its applications (Lallemont 2008), though more work is needed to establish these markets and assess how they may compete with alternative products such as collagen for some applications. Currently around 70% of the chitin produced is transformed into less valuable glucosamine products, 10% into oligosaccharides and only 20% into chitosan (Lallemont 2008). However, markets for chitosan are growing, especially within the agriculture and food industries for prevention of spoilage. The seed coating market is particularly well developed in Asia and interest is growing in chitosan and derivative products that can be used directly in food or within food packaging applications in order to lengthen shelf life (Jeon *et al* 2002, Leceta *et al* 2013). The interaction of proteins with chitin in complexes in crustacean shells has led to concerns over seafood allergens, which may not be completely removed during synthesis of chitosan (Muzzarelli 2010) and rigorous testing is required to allay consumer fears over this issue before full commercial adoption can occur (Parry pers. comm. 2013).

Glucosamine is a health supplement which is widely available in several forms in the USA and Europe. It is marketed for alleviation for osteoarthritis as it is thought to promote the formation and repair of cartilage (Lallemont 2008). It is formed from the hydrolysis of chitin usually by the action of acids. The process does not require the same level of control as chitosan production, though it follows the same initial steps to produce chitin which is then hydrolysed by the action of acids. The accessibility of the technology and the developed international markets result in it being more favoured by industry than chitosan, but this may change as more applications for chitosan become apparent, particularly for valuable medical and anti-spoilage applications mentioned above (Lallemont 2008).

1.4.1.7 Fish and shrimp peptides

Hydrolysis techniques are well established in other industries and are gaining interest in the aquaculture and fisheries industries for the derivation of peptides from marine products. The resulting mixture of peptides is referred to as a protein hydrolysate. Peptide production by ensiling is unpredictable (Cancre *et al* 1999) because of many different endogenous enzymes and the low pH may destroy some valuable nutritional elements (Lian *et al* 2005) leading to bitter tasting peptides with unpredictable properties that may be unsuitable for many applications (Hevrøy *et al* 2005). Therefore more predictable and controllable forms of hydrolysis are required for the production of peptides of particular size and character which determine specific properties (Bourseau *et al* 2009; Hevrøy *et al* 2005; Vandanjon *et al* 2009). This requires commercially available enzymes in controlled conditions which can give more predictable results than endogenous enzymes.

There are a huge number of applications for fish protein hydrolysates including bio-active supplements, health food supplements, food additives (e.g. emulsifiers and foaming agents), animal feeds and cosmetics outlined by Thorkelsson and Kristinsson (2009), Kristinsson and Rasco (2000) amongst others. Valuable peptides can be extracted from fish heads, trimmings, bones and viscera, shrimp shells and heads. The processes have been well studied, but documentation and verification of health claims, with regards to rigorous *in vivo* investigation and many marketing aspects to achieve full commerciality still need to be addressed (Raghavan and Kristinsson 2009; Thorkelsson and Kristinsson 2009).

The range of properties of various peptides is huge and beyond the scope of this thesis, but smaller peptides (of high degrees of hydrolysation) are generally more desirable for flavourings and larger peptides for foaming agents and emulsifiers (Kristinsson and Rasco 2000; Šližytė *et al* 2009). The effect that various conditions have on the size and character of final products of some fish hydrolysates and their uses is outlined by Bourseau *et al* (2009), Cancre *et al* (1999), Kristinsson and Rasco (2000), Thorkelsson and Kristinsson (2009) and Kim and Mendis (2006). Human health benefits of fish peptides are generally attributed to high anti-oxidative properties (Dong *et al* 2008) and are given by He *et al* (2007), Hong and Secombes (2009), Je *et al* (2004), Marchbank *et al* (2009) amongst others. Methods of filtration and separation for purifying hydrolysates are given by Bourseau *et al* (2009), Vandanjon *et al* (2009) and Thorkelsson and Kristinsson (2009).

There are many publications which investigate the feasibility of feeding hydrolysates from fish and seafood by-products to fin-fish aquaculture species (Aksnes *et al* 2006; Gildberg *et al* 1995; Hevrøy *et al* 2005) amongst others and shrimp (Córdova-Murueta and García-Carreño 2002) with varying success. This poses many opportunities for value addition, but strict biosecurity and traceability measures would be necessary that meet the regulations of producing nations and those to which producers may wish to import their goods, particularly with regards to intra-species feeding. Salmon hydrolysates are already produced commercially in conjunction with oils, by the companies mentioned in section 1.2.1, for use in the animal feed industry and there is increasing interest in producing hydrolysates from other fin-fish and from shrimp head by-products. Salmon and other fish by-product hydrolysates are commonly used in the *Penaeid* shrimp feed industry as attractants and are valued for their high digestibility (Hernández *et al* 2011; Grey *et al*

2009). They have the ability to increase performance by improving feed conversion ratios and reduce mortality (Hernández *et al* 2011; Nguyen *et al* 2012). They may also be able to reduce the overall "fish" inclusion within diets by achieving the same performance with much reduced levels of conventional fishmeal resources (Anon, unpublished data 2013). These issues will be investigated more fully in chapters 6 and 8.

1.4.1.8 Carotenoids (astaxanthin and canthaxanthin)

Shrimp and salmonid by-products both contain carotenoid, mostly astaxanthin or canthaxanthin at around 24g per tonne in cultured *P. monodon* (Babu *et al* 2008) and up to 7.5g per tonne in salmon viscera (Czeczuga *et al* 2005). Carotenoids are powerful anti-oxidants and therefore have many beneficial properties in human and animal nutrition (Lorenz and Cysewski 2000; Pacheco *et al* 2009). They are also used as a pigment in cosmetics (Armenta and Guerrero-Legarreta 2009).

Synthetic astaxanthin is used as a pigment in animal feeds, particularly for salmonids (Lorenz and Cysewski 2000; Sachindra *et al* 2006) at about 5kg per tonne (Synowiecki and Al-Khateeb 2003) as flesh colour is important for salmonid marketing. However, no significant difference was found between uptake and deposition of synthetic astaxanthin and natural astaxanthin in salmonid feeds (Lorenz and Cysewski 2000). Therefore, natural astaxanthin has no advantage within aquafeeds and is unlikely to be able to compete with synthetic ingredients, although there could be a niche in the organic aquafeed market. However, concentrations are far less in salmon and crustaceans than in the alga

Haematococcus pluvialis, which commercially grown can contain as much as 30kg per tonne (Guerin *et al* 2003). Therefore extraction of astaxanthin from shrimp and salmonid by-products is only likely to be cost-effective if it is removed during the processing of other valuable products, but it may be able to add value to salmon oil health supplements if retained during the extraction process.

Extraction of astaxanthin from shrimp by-products can be combined with chitosan production (Armenta-Lopez *et al* 2002) and some studies have shown that acids, commonly used in the chitosan industry, may increase the yield of astaxanthin because of reduced oxidation. However excessively aggressive acid and alkali treatments can adversely affect the carotenoid (Armenta-Lopez *et al* 2002; Pacheco *et al* 2009; Sachindra *et al* 2005; Sachindra *et al* 2006). The most promising methods, both economically and environmentally, therefore, are those which can combine mineral, chitin, protein, oil and carotenoid separation and extraction in the various processes outlined above (Armenta-Lopez *et al* 2002; Coward-Kelly *et al* 2006; Pacheco *et al* 2009; Synowiecki and Al-Khateeb 2003).

Capsules of “natural” astaxanthin containing around 4mg per capsule from *H. pluvialis* commonly sell for around US$20 for 60 on the internet, therefore there is commercial potential for a natural substance from a number of aquaculture sources including shrimp and salmon by-product (Pacheco *et al* 2009; Synowiecki and Al-Khateeb 2000).

1.4.2 Value addition options for farm mortalities

1.4.2.1 Ensiling

Until a few years ago in the EEA, mortalities had commonly been minced and ensiled in large plastic containers, using organic acids (usually formic) at about 2 to 3 % v/v to encourage autolytic hydrolysis, for interim storage before further treatment or disposal (Thistle Environmental Partnership 2008). It is now less common to ensile within the European salmonid industry as more sites have been using on-site incineration as a disposal route with little or no need for storage. However, ensiling is still relevant where quick disposal methods are not an option as it prevents spoilage and odours, and avoids attracting vermin (Arason *et al* 1990; Carswell *et al* 1990; Lückstädt 2008).

Although ensiling will deactivate many commercially important fish pathogens, infectious pancreatic necrosis virus (IPNv) can survive long periods at ambient Scottish temperature and requires heating to 80 °C for deactivation (Smail *et al* 1993) which could have implications for biosecurity if the product is to be transported. Ensiled product using organic acids can be used as a feed for pigs and other livestock (Carswell *et al* 1990; Lückstädt 2008; Pérez 1995) but acceptance from these industries can be low (Arason *et al* 1990) and is not permissible in the EU for farm mortalities. Ensiled mortalities can also be used as a fertiliser if used with other ingredients (Prescott *et al* 1997) but the disease risk from run-off into water courses could be an issue. Ensiling is also often used to store post-filleting by-product before transportation for further processing. Organic acids are generally preferred in all countries, not only because they can be fed to animals but because they are less corrosive to equipment and less dangerous to handle than inorganic acids (Carswell *et al* 1990). Ensiling is not generally used as a storage method for shrimp but Cao *et al* (2009) showed that it could be used to extract protein from by-products for further use (see above). Table 1.2 gives a summary of options available for mortality utilisation and disposal under EU ABP regulations.

Table 1.2. Summary of costs, level of expertise and value addition from options available to mortalities falling into Category 2 of the ABPR

Method	Level of capital investment	Level of expertise	Operating costs	Value of product	Pathogen deactivation	Comments
Ensiling[1]	Low	Low	Low	Very low	Some	Interim storage
Feeding to animals[2]	Low	Low	Low	Low	If cooked	Quality can be too poor
On site incineration[3]	Low	Low	Medium	None	Yes	High air pollution
Landfill[3]	None	Low	High	None	No	Biosecurity risk
Composting[4]	Low	Medium	Low	Low	Yes	Unsuitable for large numbers
Anaerobic digestion[5]	High	High	Low	High	Thermo-phillic only	Markets not well established for liquid products

Source: 1. Arason *et al* 1990; Carswell *et al* 1990; Smail *et al* 1993; Lückstädt 2008, 2. Thistle Environmental Partnership 2008 3. Glanville *et al* 2006; Thistle Environmental Partnership 2008; Local Government association 2008, 4. Glanville et al 2006; Smail et al 2009; Intertrade Ireland 2009, 5. Seafish 2008; He 2010; Méndez-Acosta *et al* 2010; Intertrade Ireland 2009

1.4.2.2 Incineration and burial

Recently in Scotland, there has been a trend towards onsite incineration of fish mortalities, whereas in the past they were collected to go to energy recovery incineration plants or landfill. Onsite incineration reduces transport costs and negates the need for storing waste through ensiling (Thistle Environmental Partnership 2008). Both methods of disposal are seen as inefficient and unsatisfactory because the wet nature of fish mortalities means incineration requires more energy input than produced SEPA (2004). However, according to salmon producers, onsite incineration is still highly inefficient in terms of fuel required to adequately dispose of the material, is highly polluting, unpleasant for farm staff and still represents a loss of nutrients that could be valuable to other production systems outside of the human value chain, such as fur farm or zoo animals. Disposal to landfill, especially of large numbers of mortalities due to catastrophic events, is problematic in being potentially a reservoir for disease, an attraction for vermin, a contamination risk to land and water courses, can release methane and takes a considerable time to fully decompose (Glanville *et al* 2006; 2009). Escalating pressure has been applied by the EU to reduce waste to landfill for several years, partly through levying higher taxes, causing increased costs to producers and processors in remote areas who still use this method for disposal (Local Government Association 2008). According to many producers in Vietnam and Thailand, burial is the most common disposal method for small amounts of mortalities (see chapter 5).

1.4.2.3 Composting

Composting is regarded by many as being a more environmentally sound solution to mortality disposal than incineration or burial (Glanville et al 2006, 2009; Wilkinson 2007). However, this must be in accordance with EU regulations and most often requires disposal at an approved site in closed systems which may not be able to cope with a catastrophic event. The physico-chemical processes involved in composting (and its environmental impacts) are reviewed in Peigné and Girardin (2004) and the feasibility of composting mortalities and by-products, from terrestrial and aquatic sources, has been reviewed and studied in several reports and articles notably by Glanville *et al* (2006) Wilkinson (2007) and Frederick *et al* (1989). Unlike ensiling, composting can deactivate most pathogenic organisms including IPNv (Smail *et al* 2009) due to temperature and other antagonistic factors generated by the compost. Although ABP regulations state that mortalities and by-products must be heated to 70°C for 1 hour (EC 2011), Glanville *et al* (2006) Wilkinson (2007) Laos *et al* (2002) and Liao *et al* (1997) all reported temperatures in excess of 55°C combined with other factors were sufficient for pathogen deactivation but optimum conditions needed to be maintained. However, Wilkinson (2007) reported that temperature and antagonistic factors did not deactivate prions and this may explain the EU requirement for pre-treating, although this is largely irrelevant for fish waste as there have never been any reported prion infections of fish or seafood species (FAO 2002b).

Glanville and colleagues (2006; 2009) showed harmful emissions to air and water from composting to be less than incineration and burial respectively. However, Peigné and Girardin (2004) warned that if composting systems are badly maintained e.g. with inadequate oxygen or poor feedstock balance, methane could be a significant pollutant if anaerobic conditions develop. In terms of fish and other livestock mortality disposal, this may mean significant quantities of carbon rich material to balance the high nitrogen content of the animal products, which might not be feasible in some locations. Therefore efficient composting requires a certain amount of expertise and labour intensity that may not be achievable on site, even if regulations did allow for it. There are now commercial composting facilities that accept fish by-products, and meet the EU ABPR such as Gray Composting Service in Aberdeenshire, UK. Salmon producers, particularly, are very reluctant to allow vehicles to travel between production sites for biosecurity reasons (Thistle Environmental Partnership 2008) and would be especially unwilling to allow vehicles that are carrying high risk material such as mortalities from other sites, according to several site managers. Therefore it is likely that on-site solutions to disposal will remain most favoured in the short to medium term. However, fish composts can be highly valued and commercial grade composts can be achieved within 6 months (Frederick *et al* 1989; Inter Trade Ireland 2009; Irish Sea Fisheries Board 2002; Laos *et al* 2000). According to Inter Trade Ireland (2009), agricultural compost can be sold from €30 per tonne up to several hundred euros per tonne for speciality composts.

1.4.2.4 Anaerobic Digestion

Anaerobic digestion (AD) is the microbiological decomposition of liquid or solid organic matter in the absence of oxygen to produce a biogas (about 60% methane and 40% carbon dioxide) which can be used as a multi-purpose fuel, plus solid and liquid fractions used as fertilisers (Gomez *et al* 2010; Seafish 2008). AD has already been developed for many industries across the world, from household to large industrial scales (Friends of the Earth 2007; He 2010; Seafish 2008). In Europe AD has been used in agriculture for the treatment of slurry, for sewage treatment and for the breakdown of municipal household waste that would otherwise be put to landfill (Garcia and Angenent 2009). AD initiatives have been increasing across Europe in an effort to increase efficiencies and reduce wastes going to landfill, (BSI 2010). With composts, wet materials can have problems because the moisture prevents bacterial access to air, therefore AD has an advantage over composting for aquaculture wastes (Inter Trade Ireland 2009), however, widespread uptake for aquaculture has been low due to difficulties in controlling the process which includes several biological reactions. Only thermophilic AD, which requires heat input, deactivates all pathogens (Smith *et al* 2005) although the EU ABPR requirement for pre-heating will also achieve this and certain antagonistic factors of competitive bacteria in mesophilic processes may inactivate a proportion of pathogens (Smith *et al* 2005). The composition of gases and digestate produced from AD depends on the composition of the feed-stocks and the conditions of the reactions, and more research is required to determine the optimum criteria for typically high N containing aquaculture products. The system must be fed adequately and high C:N ratios maintained (He 2010; Méndez-Acosta *et al* 2010), which may be more difficult in remote areas as for composting. The high fat content of certain fish species such as farmed Atlantic salmon may also prove problematic as a build-up in volatile fatty acids (VFAs) has been shown to hinder the anaerobic digestion process, and requires increased monitoring and control such as pH adjustment to counter these effects (Méndez-Acosta *et al* 2010). Overall the high level of expertise required to operate AD systems is likely to be a severe hindrance, although small community projects could take fish farm waste as part of a feed stock sourced from other local municipal and agricultural waste to supply fuel in remote areas. There are several thousand farm-based community AD projects in Germany and there is a government initiative for such projects in the UK (Local United 2011).

In the UK, quality control for the digestate is indicated by the (PAS) 110[1] (BSI 2010), adopted in response to issues raised by the EU Waste Framework Directive (European Union 2008) which specifies that biodegradable waste should be directed away from landfill and recycled or reused where possible. The main aim of PAS 110 is to provide a benchmark by which digestates can be assessed to provide more uniformity and encourage a market (BSI 2010). It specifies which feed-stocks are within its scope and certain operating procedures for Hazard Analysis and Critical Control Point (HACCP) procedure (see chapter 2). Markets for digestate are not well established in many parts of the EU at this time, although some initial trials have been encouraging for using anaerobically digested fish waste as fertilisers (Ward and Slater 2002; Inter Trade Ireland 2009).

---

[1] Publicly Available Specification

1.4.2.5 Maggots and other non-livestock animals

Foods for pets have historically taken up a large share of the available reduction fishmeal industry for omega-3 supplementation (De Silva and Turchini 2008). The EU ABPR allow for pets, zoo and fur animals to be fed on mortality waste (EC 2009), however, the quality of mortalities can be low and the supply may be inconsistent, leading to poor acceptance from some of these industries. Alternatively the oils can be extracted to provide valuable omega-3 FA inclusions, if cost effective.

Maggots and other insect larvae can be used to dispose of waste in low-tech systems. In addition to maggots for fishing bait, which is a well-established route, interest has been gathering in the black-soldier-fly larva (BSFL), *Hermetia illucens*. BSFL are well known to be voracious feeders on organic material including vegetable matter, manure and carcasses (Bondari and Sheppard 1987). St-Hilaire *et al* (2007) showed that the BSFL could be used for breaking down fish offal and the larvae retained omega-3 fatty acids at levels similar to the feed material in the short term. Although the EU ABPR do not allow for BSFL grown on fish farm by-products or mortalities to be fed to fish species, it is possible that meal produced from BSFL could be used in feed-stuffs for other animals, such as pigs and poultry although clarification on the regulations would be required. Newton *et al* (1977) showed that young pigs would feed readily on diets supplemented with dried BSFL meal but no comparative growth performance or mortality study was conducted. There is also a growing market for BSFL in the live feeds for the exotic pet trade, such as for lizards and this is one possible route which could prove of interest. As a low input system, it has the potential to substantially reduce costs, environmental impact and to be more pleasant for workers, but depends largely on the possible markets that are achievable for BSFL and full acceptance under EU and other regulatory schemes. *H. illucens* is widely found in tropical countries all over the world but would need to be artificially bred in temperate conditions as they are unable to breed successfully in the wild. However, this is also an advantage in that there is no risk of exotic introductions. BSFL currently retail for around US$3 per one hundred grubs in pet food suppliers the UK.

1.5 Thesis objectives

The objectives of this thesis were to assess the current by-product value chains and utilisation strategies for three of the major aquaculture species and their role within global food production. The major part of the thesis was to evaluate the environmental impact of processing by-product technologies and their eco-efficiency in terms of the trade-offs between value addition and impact on a global value chain level. This thesis also investigates the possible use of mortalities as a major by-product at the farm level. These utilisation strategies have an element of risk attached to them, in terms of biosecurity, human and animal health and this thesis also addresses these issues by identifying the risk of certain by-product and mortality utilisation. The final objective is to identify how decisions regarding the use of by-products affect interactions between competing global value chains from a farm and producer level to a regulatory and government level.

Chapter 2 seeks to establish if current legislation is a barrier to efficient utilisation and if current utilisation is meeting the appropriate regulations for the intended markets. It also discusses whether there is chain of custody throughout the industry in global markets where imports from 3rd nations to the EU may have lower standards and whether consequently, where standards are lower regarding access to certain by-product commodities, they have a competitive advantage over European producers.

As a major concern of the aquaculture and other livestock industries, chapter 3 investigates the current and future scenarios regarding the global supply of fishmeal. It looks at the role aquaculture by-products may have in alleviating the pressure on fishmeal and other feed commodities which aquaculture and other livestock rely on and how synergies may be improved between some sectors in continuing the sustainable supply of feed ingredients in global value chains.

The major part of the thesis assesses how efficiently by-products are being utilised from three major aquaculture species production systems; Thai shrimp, Vietnamese *Pangasius* and Scottish salmon from an environmental and economic perspective. It investigates what trade-offs are apparent between these two objectives using Life Cycle Assessment (LCA) methodology (in chapters 6, 7 and 8).

Life Cycle Assessment is an ISO accredited environmental impact accounting methodology (ISO 2006a, 2006b). It measures impacts of producing products which can perform a particular function, which is standardised by a functional unit to which all impacts are related via reference flows. Reference flows trace the impacts associated with different processes and inputs throughout a production chain from the acquisition of raw materials to final disposal of wastes. This type of life cycle approach, avoids problem shifting (Ayer and Tyedmers 2008) which has sometimes been an issue with other assessments and also allows for identification of areas within the production that contribute disproportionately to the overall impact (Hospido *et al* 2006). For these reasons, LCA was chosen as the major impact assessment tool for this thesis.

Chapter 5 assesses standard methodologies for LCA, how they have been applied to aquaculture and if they adequately evaluate the environmental efficiencies of by-product utilisation in diverse production systems. It subsequently defines the novel LCA methodology which will be used in chapters 6, 7 and 8 to assess by-product utilisation and which can allow for a common denominator to compare between the systems. Mortalities from aquaculture are not included in the LCA component because of the very varied approaches to their utilisation and the data requirements required to investigate them. However, chapter 4 seeks to investigate the causes of mortality for some of the major aquaculture species in Asia and Europe (*penaeid* shrimp in Bangladesh, China, Thailand and Vietnam; tilapia in Thailand and China; Vietnamese *Pangasius* catfish; Bangladeshi freshwater prawn (*Machrobrachium* spp.) and Scottish salmon) and the subsequent efficiencies and sustainability issues concerning disposal and utilisation techniques of the mortality. The environmental impact is not measured in absolute terms but assessed qualitatively to evaluate whether biosecurity, traceability, human and animal health issues are of concern for the varied approaches in the different countries.

CHAPTER 2: LEGISLATION AND STANDARDS GOVERNING USE OF AQUACULTURE BY-PRODUCTS

2.1 Introduction

The use of animal by-products in aquaculture feeds is a centuries old practice with early trout production in Scotland using horse and oyster meat as major ingredients, for example (Maitland 1887). However, human health fears, typified by the Bovine Spongiform Encephalopathy (BSE) crisis, and ensuing media and public outcry of the 1990s led to stringent legislation controlling the use of many animal by-products in livestock feeds in the EU (EC 2002, Atkinson 2000). In the UK, the crisis resulted in hundreds of thousands of livestock being culled, all exports of UK beef products being banned by the EU and domestic consumption falling by 40% costing the industry £980 million in the first year (Atkinson 2000). In addition, the EU Animal By-Product Regulations (ABPR) and subsequent amendments (EC 2002, 2003, 2009a) were established that laid down strict traceability measures and forbade the use of all mammalian by-products in feeds, and especially the intra-species feeding of any animal by-products, leading to large restructuring of the feeds commodities industry in the EU (Atkinson 2000). However, increasing pressure on ingredients for livestock feeds has led to continuous relaxation of EU legislation through the various amendments, culminating in the reversal of the ban on mono-gastric animal proteins for use in aquafeeds (EC 2013). There are fears, particularly from consumers and some retailers, that traceability of by-product utilisation is still low, that the quality may be poor and the potential human health risks out-weigh the possible economic and environmental benefits of utilising these materials (Sanver, Pers comm. 2014). This is especially the case as international trade in seafood and seafood commodities has increased in recent years (Fishstat 2013). Therefore, there may be significant resistance to the renewed adoption of these protein sources in aquafeeds in the short term.

Globally, there are many other regulations, guidelines and standards which aim to govern best practice for food safety, traceability and efficiency of resources for the various sectors of the aquaculture industry. The scope of the various regulations and their detail on required practices is very varied from specific technological requirements in some of the EU regulations to vague references to best practices in some of the private certification standards. In addition, documents are partly laid down in law, for example in the case of the EU ABPR, which may result in criminal proceedings if contravened. However, they may also be in the form of producer certification or simply guidelines aimed at better production practices, e.g. on animal or social welfare or product quality, that producers may adopt to give consumer confidence and provide a premium on a particular product or range of products. However, the strictness of national regulations varies between countries and regions leading to confusion and difficulty for producers in terms of adhering to the laws of international markets which they wish to target. This complexity may be added to as regulations are constantly up-dated, especially in the EU, and the various standards which need to adhere to them are slow to react. International third party certification schemes may help to standardise practices for producers which may wish to conform to the regulations of these markets, although the specific agendas of these schemes can sometimes be led by entrenched popular perception and political motivations, rather than strict scientific evidence (Little *et al* 2012). Therefore, despite changes in over-arching regulation allowing for the use of certain previously banned by-product ingredients, popular perception, which may be swayed by the popular press and the agendas of NGOs, may ultimately control what is actually practiced as large retailers respond to consumer attitudes.

This chapter explores the legislation, guidelines and certification standards controlling the use of by-products and mortalities within the aquaculture industry, particularly from a European stand point, including products traded into the EU. This mostly affects the feed industry but also processors and producers which may have to dispose of by-products or on-farm mortalities, which are included in both the EU ABPR and many of the private certification standards. The implementation of standards and legislation for by-products can be regarded from three perspectives. Firstly, how consumer fears regarding food safety are managed, secondly, do they allow for the most environmentally efficient use of the resource and finally, can industry add value to the cultured product effectively? It is clear that there are potential trade-offs between these factors and therefore a scientific evidence based approach must be adopted which can manage all criteria most effectively.

2.2 International Guidelines and Standards

International guidelines and standards for production of animal feeds are mainly concerned with human safety issues regarding contaminants and produce a hierarchical

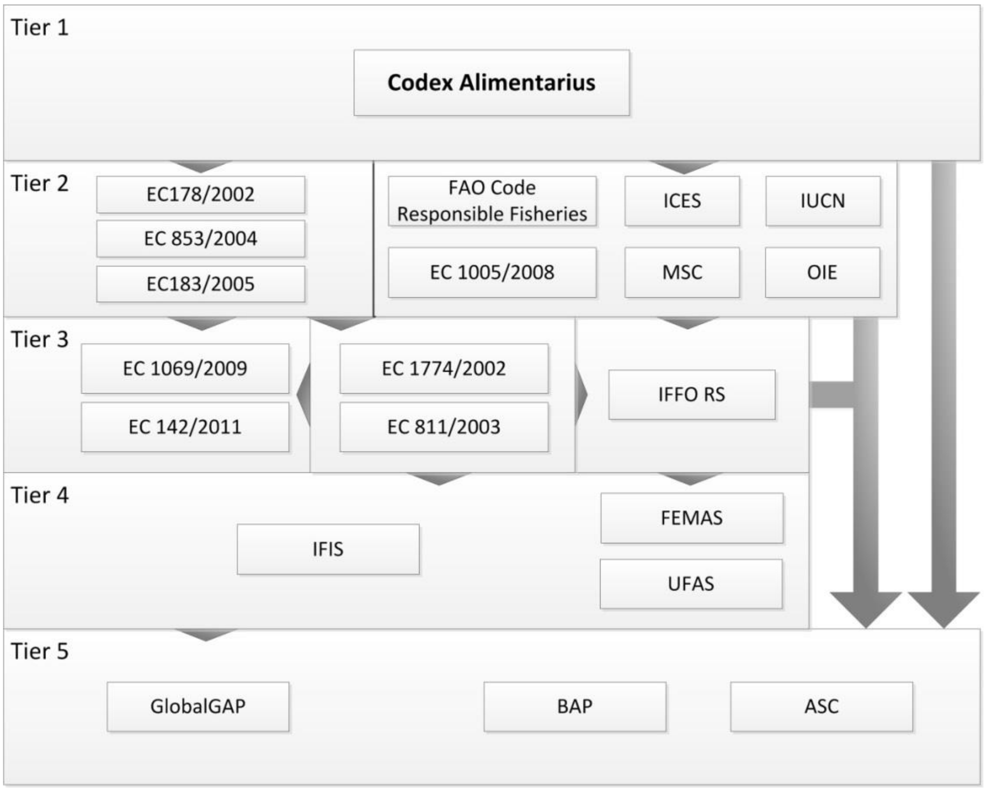


Figure 2.1. The hierarchy of international standards and regulations from a European perspective.

Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety

Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific hygiene rules for on the hygiene of foodstuffs

Regulation (EC) No 183/2005 of the European Parliament and of the Council of 12 January 2005 laying down requirements for feed hygiene

Regulation (EC) 1005/2008 establishing a Community system to prevent, deter and eliminate Illegal, Unreported and Unregulated fishing, amending Regulations (EEC) No 2847/93, (EC) No 1936/2001 and (EC) No 601/2004 and repealing Regulations (EC) No 1093/94 and (EC) No 1447/1999

Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation)

Commission Regulation (EU) No 142/2011 of 25 February 2011 implementing Regulation (EC) No 1069/2009 of the European Parliament and of the Council laying down health rules as regards animal by-products and derived products not intended for human consumption and implementing Council Directive 97/78/EC as regards certain samples and items exempt from veterinary checks at the border under that Directive

Regulation (EC) No 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption

Regulation (EC) No 811/2003 Implementing Regulation (EC) No 1774/2002 of the European Parliament and of the Council as regards the intra-species recycling ban for fish, the burial and burning of animal by-products and certain transitional measures

ICES = International Council for Exploration of the Sea, MSC = Marine Stewardship Council, IUCN = International Union for Conservation of Nature, OIE = World Organisation for Animal Health, IFFO RS = International Fishmeal and Fish oil Organisation Global Standard for Responsible Supply, IFIS = International Feed Safety Alliance (IFSA) Feed Ingredients Standard, FEMAS = Feed Materials Assurance Scheme, UFAS = Universal Feed Assurance Scheme, BAP = Best Aquaculture Practice, ASC = Aquaculture Stewardship Council framework to be adopted by national and regional regulators. The hierarchy of how regulations and standards are structured from a European production and trade perspective is shown in figure 2.1.

2.2.1 Codex Alimentarius

Overarching international and regional guidelines are provided by the Codex Alimentarius (www.codexalimentarius.org), published jointly by the Food and Agriculture Organisation of the United Nations (FAO) and World Health Organisation (WHO). The Codex Alimentarius, established in 1965, provides standards on the production of food raw materials and commodities for trade and further processing in value chains for human consumption, directly and indirectly. It covers topics such as drug residues, contamination, labelling and traceability as well as sampling protocols. In many cases, especially in regards to food processing, it incorporates a Hazard Analysis Critical Control Point (HACCP) approach, developed by the US Food and Drug Administration (FDA). HACCP offers a scientific framework for identifying and acting upon specific points within a production facility which may pose health risks and does not form a standard in its own right. A summary of how it can be implemented for seafood production and processing is given by the Codes of Practice (COP) for fish and fishery products (WHO, FAO 2003). While the Codex Alimentarius does not provide actual law with regards to permissible production and utilisation practices, it provides COPs which act as unifying standards in consultation with the FAO and WHO, to which many legislators can turn. The HACCP framework is also widely adopted by processors at all stages of food and feed processing.

Meetings are held among the regional and international members of the Codex commission, along with expert observers, to provide the framework for new standards to be adopted within the Codex on a regional or global level for particular commodities. The standards included within the Codex Alimentarius may then be implemented within national or regional legislation, which are enforceable by law (WHO/FAO 2010a).

Feed safety is covered by the Codex Alimentarius COP on Good Animal Feeding (WHO/FAO 2004) and COP for Fish and Fishery Products (WHO/FAO 2003), which include traceability of feed ingredients and correct labelling. There is also a standard related to contaminants in animal feeds (WHO/FAO 2010b). However, within these guidelines there is little reference to the inclusion of by-products. Instead feed safety issues focus on contamination from microbes, pesticides and toxins, although the COP for Fishery Products (WHO/FAO 2003) points to proper heat treatment of fish silage and offal. There are no references to intra-species feeding although avoidance of the use of ingredients that could be a source of BSE agents is advocated.

The World Organisation for Animal Health (OIE) also works in collaboration with Codex Alimentarius, WHO and FAO for maintaining the health and welfare of animals, worldwide. As it is not strictly related to human health issues, it will not be dealt with in detail here. However, it does issue standards related to aquaculture feeds (OIE, 2013). While in general it advocates the use of fishery and aquaculture by-products, it warns against the use of by-products for species which are closely related, e.g. between salmonids. This is not because of the risk of transferring Transferable Spongiform Encephalopathies (TSEs), of which BSE is one, but because of the risk of spreading other pathogens between susceptible species. It actually acknowledges that cannibalism is a reality in the aquatic environment and that there is no evidence of prion transfer in aquatic species to date. It also advocates the need for more research on the risk of terrestrial animal proteins in aquafeeds, which are banned in feeds for all terrestrial species, so that the pressure on marine feed ingredients may be relaxed. In general, however, it points to HACCP measures for feed processing as laid out by Codex Alimentarius (OIE 2013).

2.2.2 FAO Code of Conduct for Sustainable Fisheries

The FAO Code of Conduct for Sustainable Fisheries (FAO 1995) was developed mainly for capture fisheries although it does also refer to the development of aquaculture, regarded as a sub-set of fisheries by the FAO. It particularly encourages the maximisation of fisheries resources for human consumption and reduction of waste through better use of by-catch and by-products for value addition. It also refers to the Codex Alimentarius for ensuring good food safety standards throughout production and processing, and to appropriate disposal of wastes such as dead fish in order to avoid human health risks and the spread of disease. However, no detail is given on these practices.

2.2.3 European Union regulations

EU regulations apply to all countries within the European Economic Area (EEA), (the 28 EU countries plus Norway, Liechtenstein and Iceland) and any product that is produced or passes within the EEA. The overarching regulations on food and feed safety, and traceability for all products produced or traded within the EU are given by Regulation (EC) No 178/2002 (subsequent reference to EU regulations will be by their number only for ease of reading, e.g. EC178). It also lays the foundations for the establishment of the European Food Safety Authority (EFSA) and Rapid Alert System for Food and Feeds (RASFF). EFSA is responsible for giving scientific and technical support to Commission regulations including identifying risks and analysing the data from RASFF, which is responsible for notifying the authority of possible human health risks. Regulation (EC) No 183/2005 points to the proper registration and approval of feed producers by competent national authorities, following site visits to ensure compliance with the regulations. Neither of these documents directly refers to by-product use but both are mostly concerned with general safety, cleanliness, traceability and risk assessment. They point to HACCP principles and also harmonisation with other international standards and guidelines such as Codex Alimentarius.

The general regulations on the use of animal by-products in the EU were first given by Regulation (EC) No 1774/2002, including the safe disposal of mortalities as well as the allowable uses of by-products for feeds and industrial purposes. This was drawn up following the BSE and foot-and-mouth crises of the 1990s and 2000s, and largely deals with measures to ensure safety, traceability and biosecurity. Specific regulations to prevent the spread of TSEs are given by Regulation (EC) No 999/2001 and subsequent amendments (EC 2013). EC1774 and amendments have been repealed since March 2011 by Regulation (EC) No 1069/2009, although many of the principles of the original regulation were carried forward, but clarified or updated to account for new technology or scientific evidence. Some older standards still refer to the original EC1774 and Regulation (EC) No 811/2003, which gives details concerning the utilisation of fishery and aquaculture by-products, both of which are now covered by EC1069. The regulations stress the importance of traceability through adequate labelling, health certification and record keeping at each point of transfer, and include by-products and their derivatives imported from outside the EEA.

Principally, different animal by-products are separated into three categories based on their risk to human and animal health with category 1 having the highest risk. These categories have different allowable options concerning their utilisation or disposal. The specific details of these operations are now given in detail in the annexes of Commission Regulation (EU) No 142/2011 and specific hygiene requirements for foodstuffs manufactured from category 3 by-products are given by Regulation (EC) No 853/2004. The specific directions on the use of animal by-products in EU142 include parameters for feed production, disposal by incineration, composting and biogas generation, and industrial uses such as biodiesel. The different categories and the utilisation/disposal options relating to aquaculture and fisheries products can be seen in Table 2.1.

There are no fish by-products which fall into category 1. Category 2 materials include farm mortalities, diseased and contaminated processing by-products. Processing by-products from aquatic organisms, fit for human consumption, fall into category 3, which also includes fish caught for reduction into fishmeal and fish oil. Generally, category 2 materials may not be fed to animals which will enter into the human food chain but may be fed to other animals such as pets or zoo animals. Where category 2 products are used for feed, there must be adequate biosecurity measures to prevent the possible spread of

Table 2.1: EU Animal By-Product Regulations, categories and approved uses (EC, 2009)

Category	By-product	Allowable uses under ABPR
1.	• No fish by-products in Cat. 1	Not applicable
2.	• Fish farm mortalities irrespective of cause • Fish parts collected from the effluent of Cat. 2 processing plants • Fish parts that contain excessive amounts of veterinary residues • Cat.3 material that may have been contaminated with Cat. 2 material.	• Incineration on site or at approved facilities • Processed in accordance with other ABPR provisions but not for livestock feeds, cosmetics or medicinal uses • Feeds for fur, zoo and circus animals • Ensiled, composted or used in biogas plants at approved sites, meeting hygiene and biosecurity measures in the annexes of the ABPR • Disposed of in landfill if special derogations are applicable
3.	• Parts of slaughtered animals considered unfit or not intended for human consumption • Fish caught for fishmeal production • By-products from fish processing plants	• Incineration on site or at approved facilities • Ensiled, composted or used in biogas plants at approved sites, meeting hygiene and biosecurity measures in the annexes of the ABPR • Processed in accordance with other ABPR provisions including “technical purposes” such as pharmaceuticals and cosmetics • Used to make fishmeal feeds but must be clearly labelled with taxonomic name if from aquaculture, to avoid intra-species feeding

pathogens, otherwise they may be used for industrial purposes or must be disposed of in an appropriate manner such as incineration at an approved plant. Certain remote sites, such as those without easy access to approved plants, may receive a derogation to be permitted to dispose of category 2 material in landfill or incinerate on site which has become the preferred method for fish farm mortalities (Thistle Environmental Partnership 2008).

Category 3 materials include the processing by-products from capture fisheries and aquaculture facilities which are fit for human consumption. They may be used in the same way as category 2 materials but can also be used in livestock and aquaculture feeds as long as there is no risk of intra-species feeding and appropriate biosecurity measures have been followed, including pressure sterilisation, proper storage and transportation. The previous regulations EC1774 and EC811 stated that fishmeal for feeding livestock should only be sourced from wild fish and their by-products. EC1069 and EU142 now state that fishmeal derived from farmed fish must be labelled clearly with the taxonomic name of the species from which it is derived to ensure against intra-species feeding. The ban on intra-species feeding of by-products originating from wild fish does not apply to dedicated reduction fisheries or by-products from wild fish as the species may be mixed, there are sometimes identification problems but the risk to human and animal health is thought to be low. However, aquaculture products have a clear advantage in this respect in that their species is easily determined and uniform. Legislation outlined in EC999 forbade the use of terrestrial processed animal proteins (PAPs) in livestock feeds of any description. This has now been amended by Commission Regulation (EU) No 56/2013, which now allows for the use of PAPs originating from mono-gastric animals in aquaculture feeds, provided that all other regulations have been adhered to, particularly regarding traceability.

Category 3 materials may also be used for the production of gelatine, collagen and medicinal products for human consumption as well as cosmetic uses following appropriate treatments as laid out by EC1069, EU142 and EC853. Specific requirements for the production of cosmetics are given by Council Directive (76/768/EEC). Generally, operations for the further processing of by-products must be in a separate building to the slaughtering and processing of food products.

In addition to the general regulations covering all food production and its derivatives, there are also specific regulations that deal with organic food production which will be covered below.

Member states or interested parties may apply to the EFSA to employ alternative methods other than those stipulated by the regulations. Plants which perform the operations listed in table 2.1 must be approved by the competent national authority, including those outside of the EEA which seek to export derived products to the EEA. A list of approved plants must be made available to the Commission and the public. For example, in the UK, the Animal Health and Veterinary Laboratories Agency (AHVLA) and the Food Standards Agency (FSA) are responsible for the approval, registration and inspection of animal by-product processors and also give these facilities guidance on meeting the requirements of the regulations. The export of animal by-products outside of the EEA is also controlled so that those of higher risk are not exported for purposes for which they are deemed to be unfit.

2.2.4 Industry association certification schemes

Following various food safety scares, in Europe particularly, several feed ingredient quality assurance schemes have evolved initiated by industry associations. Although several schemes run within Europe, many are recognised and benchmarked between the different trade associations for different countries. For example the Agricultural Industries Confederation (AIC) of the UK is responsible for producing the Universal Feed Assurance Scheme (UFAS) for compound feeds and the Feed Materials Assurance Scheme (FEMAS) for feed ingredients. One of the main criteria for UFAS accreditation is that feed ingredients are sourced from assured sources such as FEMAS or other recognised schemes. The AIC recognises schemes produced, primarily in European countries such as by Productschap Diervoeder (PDV) in the Netherlands, Ovocom in Belgium and Qualität und Sicherheit GmbH (QS) in Germany, with an aim of standardising assurance schemes. Further attempt to standardise were made by the International Feed Safety Alliance (IFSA); the four associations above plus Fédération Européenne des Fabricants d'Aliments Composés (FEFAC), comprising 22 national associations. FEFAC is a long running organisation with observer status on Codex Alimentarius, therefore many of its principles have been adopted based on an HACCP approach. In addition, many national associations, being EEA members, must comply with the EU regulations, particularly, EC178 and EC183 (Figure 2.1). These schemes commonly recognise the standards from the other companies within the group for sourcing of assured ingredients. IFSA introduced the IFSA Feed Ingredients Standard (IFIS), which brought together the schemes from the different associations, although it has not been widely adopted (Pers.

Comm. Williams 2012). The main aim of IFIS is to provide a benchmark for the mutual recognition of individual schemes within the group (Pers. Comm. Bouxin 2012). FEMAS has also produced specialist sector notes for fishmeal (AIC 2009) which were produced in conjunction with the International Fishmeal and Fish Oil Association (IFFO). These focus on traceability and safety aspects with HACCP principles and forbid the intra-species feeding of aquaculture by-products. They also specifically draw attention to EC1774 and EC811 for products being produced and traded within the EEA.

The IFFO has also produced its own assurance scheme known as the Global Standard for Responsible Supply (IFFO RS) for sourcing fish ingredients (IFFO 2011). This standard is commonly adopted by major fish feed manufacturers in Europe. In addition to the usual traceability and safety measures that are found in other standards for feed ingredients through certification from IFIS or a recognised equivalent, they also focus on responsible sourcing of fishery ingredients. This includes attention to the FAO Code of Conduct for Responsible Fisheries (FAO 1995) and Regulation (EC) 1005/2008 to promote sustainable fishing practices. Moreover they encourage the use of Marine Stewardship Council (MSC) certified fisheries product. The IFFO RS standard has specific sections related to the use of by-products from fisheries and aquaculture. In addition to conforming with EC1774 and EC811, by-products must not be sourced from endangered species according to the International Union for Conservation of Nature (IUCN) Red List or be captured using destructive fishing practices.

2.3 Private Certification

There is a huge range of private certification schemes which run nationally and globally for aquaculture production. Some are more concerned with welfare issues or labour conditions, whereas some are specifically for organic production. However, most are concerned with environmental issues, including those concerning the feeding of fish and disposal of farm mortalities, although animal and public health issues are also important criteria.

Many schemes incorporate standards on feed ingredients and the disposal of mortalities at the farming stage but generally only a few international standards cover the processing and feed manufacture stages in detail. Major international certification schemes such as GlobalGAP, Aquaculture Stewardship Council and Best Aquaculture Practice require that the producer meets all national regulations in addition to those of the particular scheme. As the number of certification schemes grows, official recognition between these major international schemes is also increasing by necessity, to provide wide agreement for benchmarking and avoid dilution of their impact in the market place. Private certification schemes are usually developed in close collaboration between various stakeholder groups and technical committees, before being adopted by the certification body, on the recommendation of their steering committees. Many of these standards are now being adopted by Asian countries seeking to provide consumer and seafood-buyer confidence in their products for export oriented markets. Table 2.2 shows the location and scope of selected private schemes with most relevance to global production.

Table 2.2 Selected private certification schemes, issuing body, location

Scheme	Issuing body	Value chain scope	Use of fishery by-products	Intra-species feeding
GlobalGAP	GlobalGAP	Value chain – feed to processor	Encouraged	Prohibited
Best Aquaculture Practice	Global Aquaculture Alliance	Value chain – feed to processor	Encouraged	Prohibited
Aquaculture Stewardship Council	World Wildlife Fund	Primarily farm focussed	Encouraged	Prohibited for *Pangasius*
Soil Association Organic	Soil Association UK	Organic farming and production	Permitted	Prohibited
Naturland	Naturland	Organic farming and production	Encouraged	Prohibited
Debio	Debio	Organic farming and production	Encouraged	Prohibited

2.3.1 GlobalGAP

GlobalGAP is an international certification scheme available for adoption in many aquaculture centres for several species. It is widely adopted throughout major aquaculture producing countries in Europe, Asia and S. America. It incorporates a wide set of standards covering environmental, social and ethical issues, throughout the value chain, from hatcheries to processing and other service industries (GlobalGAP 2012a). Most importantly, with regards to by-products, it includes a set of standards for feed production and has a traceability scheme that allows different parts of the value chain to be linked via a GlobalGAP Number (GGN) (GlobalGAP 2012a, 2012b). Feed use in GlobalGAP certified farms is covered by the Compound Feed Manufacturing Standard (CFM). Therefore all feed must be certified either by the CFM or a CFM recognised scheme, such as IFSA, and adoption of national assurance schemes is encouraged (GlobalGAP 2012b). GlobalGAP are also trying to promote the harmonisation of these national assurance schemes so that they may be internationally recognised, providing a level playing field for major exporting regions (GlobalGAP 2011). The CFM requires HACCP principles to be implemented and refers to the Codex Alimentarius as a guideline. All feeds must be traceable to the batch of fish linked by the GGN and internal records kept by the feed mill for feed batches and ingredients. All fishmeal that is used in the preparation of feeds must conform to the FAO Code of Good Practice, sourced from sustainable stocks in a responsible manner as laid out in the rest of the document. Maximum efficiency is encouraged including the use of by-products in feeds conforming to national legislation but intra-species feeding is generally prohibited by the standards unless it is allowable under specific national legislation (GlobalGAP 2012b). There are no specific standards regarding the disposal of mortalities except that biosecurity measures must be implemented.

2.3.2 Best Aquaculture Practice (BAP)

BAP certification is coordinated by the Global Aquaculture Alliance (GAA). Similarly to GlobalGAP, it audits the major nodes of aquaculture production and supporting services value chains, and incorporates environmental, social and ethical issues. Similarly to GlobalGAP, BAP includes a mandatory on-line traceability scheme that links feeds used to the production facilities and ultimately the processed product (GAA 2010a). BAP recognises the challenging status of fishmeal and fish oil supplies which must be sourced from sustainable sources, recognised as such by the International Council for the Exploration of the Sea (ICES), the IUCN, FAO or other regional conservation groups. As of June 2015, the majority of reduction fishery sources will need to comply with the MSC, Environmental Standard for Sustainable Fishing (ISEAL) or IFFO RS. This includes the use of by-products and trimmings from capture fisheries, which are otherwise actively encouraged. The standards for *Pangasius* (GAA 2010b) tilapia (GAA 2008) and salmon (GAA 2011) include calculations for recording the fish inclusion within the feeds and the "fish in: fish out (FIFO) ratio" (Jackson 2009) from production, which do not include inputs from fishery or aquaculture by-products. Thus a feed containing only fishery by-products from compliant sources has a FIFO of zero. The FIFO target ratio for salmon is 2.0 (GAA 2011) but it had not been defined for *Pangasius* at the time of publishing the standards (GAA 2010b). Standards for tilapia state that low inclusions of fish inputs in the diets should result in FIFO ratios of less than 1.0 although a definite target has not been defined for this species either (GAA 2008). BAP standards for all species prohibit intra-species feeding, irrespective of national legislation (GAA 2010a). BAP refer to the sanitary disposal of mortalities within the salmon standards (GAA 2011) and for tilapia, and *Pangasius* (GAA 2008, 2010b) they go further, especially in the event of catastrophic mortality, recommending incineration, burial, composting or removal by a contractor.

2.3.3 Aquaculture Stewardship Council (ASC)

The ASC was set up jointly by the WWF and Dutch Sustainable Trade Initiative (IDH) to produce a globally recognised certification scheme for several species. It encompasses some sociological aspects regarding workers' rights as well as environmental and animal welfare issues. Although the ASC standards are currently focussed on farm production only, they include feed components and an ASC feed standard is under development through their "Responsible Feed Project". It is expected that ASC and other major international certifiers will attempt to harmonise their standards in the future with mutual recognition between them (ASC 2010) as part of the Global Seafood Sustainability Initiative (GSSI). The GSSI is a consortium of representatives from the seafood industry, academia and NGOs, which aims to develop a benchmarking initiative between major standards for aquaculture and fisheries that will require that all schemes cover the same major nodes of the value chain (Vogel 2010).

Similarly to GlobalGAP and BAP, the ASC standards for *Pangasius* (ASC 2010), salmon (ASC 2012) and tilapia (ASC 2012) also encourage the use of fish by-products in feeds as do the draft standards for *Penaeid* shrimp (WWF 2011). The final shrimp standards were expected in late 2013, however, they have yet to be published and they are still at draft level. In addition, ASC standards also point to compliance with ISEAL, IFFO RS, IUCN and FAO standards and guidelines for responsible sourcing of marine ingredients, including by-products, as well as being required to score above 6 points on the Sustainable Fisheries Partnership (SFP) online "FishSource" scoring system (Sustainable Fisheries Partnership 2010). The efficiency of fish inclusion is given by their Forage Fish

Dependency Ratio (FFDR) which is equivalent to FIFOs but can be separated for meal or oil. The ASC FFDR calculations exclude sources from by-products, as long as they meet the other sustainability requirements above. Intra-species feeding is not specifically mentioned in the standards for the species mentioned above except the *Pangasius* standards prohibit the intra-species feeding of by-products on the precautionary principle, related to unknown health risks from the practice (ASC 2010). This may be because the *Pangasius* by-product industry is very well established within the Mekong Delta and the chances of intra-species feeding are considered greater for this species. Shrimp are naturally cannibalistic to some degree (Cruz-Suarez *et al* 1993, Abdussamad and Thampy 1994) but although in the past it has often been common practice to include shrimp meal in shrimp diets because of better performance (Cruz-Suárez 1993), it is not encouraged by ASC or other standards.

Disposal of on-farm *Pangasius* and tilapia mortalities includes the usual methods of burial, incineration, fertiliser etc. but they can also be used for feeding to other livestock except for intra-species feeding (ASC 2012, 2010). This contravenes the EU ABPR and therefore could not be fed to animals intended for human consumption within the EU. It is also possible that dead fish could represent a biosecurity risk if fed to other aquatic organisms. The salmon and shrimp standards do not give any specific directions on disposal but refer to “proper methods”.

2.4 Organic Certification

The International Federation of Organic Movements (IFOAM) is widely recognised as the umbrella organisation for organic food value chains and is responsible for the IFOAM Family of Standards (IFOAM 2012). It seeks to harmonise the standards between regional and national organic production certification schemes via the Organic Guarantee System (OGS). The OGS is endorsed by conforming to the Common Objectives and Requirements of Organic Standards (COROS), developed jointly between IFOAM, the FAO and the UN Conference on Trade and Development (UNCTAD). Aquaculture is a relatively new addition to organic production schemes and IFOAM standards for aquaculture are yet to be covered by COROS but are presented separately. COROS also does not include cosmetics or industrial products (IFOAM 2012) which are possible routes for some aquaculture by-products such as chitosan, manufactured from shrimp shells or gelatine, from the skins and bones of fin-fish as described in chapter 1. The IFOAM standards and those laid out by COROS are presented in the IFOAM Norms for Organic Production and Processing document (IFOAM 2012). It sets out the principles of organic food production and defines standards for arable and livestock farming and processing, including aquaculture.

Organic standards usually include economic, social and ethical responsibilities as well as those for the environment. From an environmental perspective, the major underlying principle of organic production is that food should be produced in harmony with the ecosystem, emulating natural systems as far as possible, in such a way that enhances or at least does not damage the surrounding environment (IFOAM 2012, Soil Association 2010, Debio 2009). This also involves reducing waste via reuse and recycling, and the prohibition of synthetic and genetically modified substances in pesticides, feeds, fertilisers and processing techniques (Soil Association 2010, Debio 2009). This includes the use of synthetic astaxanthin in salmonid feeds, leaving opportunities for the use of shrimp or other aquaculture by-products, although other organic sources are more common, as mentioned in chapter 1. The Soil Association recommends the use of shrimp by-products, provided they are of organic origin, except for feeding to shrimp*, Phaffia* yeast or other natural, organic sources (Soil Association 2010). The prohibition on intra-species feeding of shrimp by-products could be regarded as contradictory, considering the cannibalistic nature of shrimp and the organic movement's intention to emulate natural systems. Within the IFOAM standards for aquaculture, there is no specific mention of by-product use in feeds and it only states that feed ingredients must be sourced from organic products. Considering IFOAM animal welfare and processing standards, it is unclear what status fishmeal from conventional reduction or from fishery by-products might have. The USA's National Organic Program (NOP) for aquaculture currently recognises organic fishmeal as that derived from the by-products of organic fish production (NOP 2008). However, their aquaculture standards are under development and the information here is from draft documents which are under consultation. The IFOAM standards also have no mention of rules related to intra-species feeding at this time (IFOAM 2012). A number of large organic certifiers have published standards for aquaculture which are much more detailed than IFOAM. As these become more established, the IFOAM standards may be more developed with eventual integration into

COROS, allowing for international recognition and harmonisation. Most notable amongst the organic aquaculture standards are the Soil Association (UK), Debio (Norway) and Naturland (Germany). A summary of organic standards related to by-product use in aquaculture can be seen in Table 2.2.

The EU regulations on organic production within and imported into the EU largely embody the motivations set out by IFOAM above and are set out in Council Regulation (EC) No 834/2007. This refers to the Codex Alimentarius and other EU regulations above for general food production principles and also recognises equivalent regulations in countries outside of the EU. More specific rules on organic aquaculture production are given by Commission Regulation (EC) 710/2009. In general they advocate the recycling of by-products between production systems to encourage efficient use of natural resources. They point to the use of sustainable fish stocks for the provision of fishmeal, however, wider regulations on intra-species feeding and use of by-products, including mortalities, are covered in other EU regulations outlined above (EC 2001, 2007, 2009). All organic producers in the EEA must meet these standards through their national authorities, although some have added further regulations such as DEFRA in the UK, to which the Soil Association conforms. Some national certifiers have issued standards for producers wishing to export to their country, such as Naturland and the Soil Association which have standards for *Penaeid* shrimp, *Pangasius* and tilapia amongst others. Others such as Bioland (Germany) only advocate the culture of fresh water fish in ponds which should be fed predominantly on feeds of plant origin. Almost all certifiers encourage the use of fishery by-products although some, such as the Soil Association, prefer the use of organic fish inputs (farmed organically). All organic certifiers state that wild fish inclusions should be from well-managed, sustainable stocks such as those recognised by ICES, MSC, ISEAL etc.

2.5 Regulation and standards' role in directing by-products within aquaculture value chains

The regulations concerning the use of by-products are generally robust and particularly so in Europe which should allay consumer food safety concerns if they are adequately enforced. However, as recent events regarding the incidents of horse meat being miss-sold have shown ((https://www.food.gov.uk/enforcement/monitoring/horse-meat/timeline-horsemeat, accessed 28/3/2014), the enforcement of correct labelling and traceability can break down if unscrupulous processors, producers or traders are sufficiently determined. However, if it were not for the regulations, it could be said that the scandal may never have been uncovered and subsequent investigations into the source of the miss-selling could not be conducted. Following the discovery, all contaminated products were withdrawn from sale and affected suppliers ceased trading. However, no prosecutions have been made to date and there are still problems regarding cross-border responsibility for enforcement from the various agencies and attaching culpability to those directly responsible for the miss-selling in complex supply chains.

Seafood products have recently been discovered to be miss-sold in Europe also, possibly as much as 28.4% of seafood products in the Republic of Ireland (Miller *et al* 2012). Prices for some species which were miss-sold may have been substantially lower than the species which they were labelled (Miller *et al* 2012), and although some of the miss-selling may have been fraudulent, it is possible that some may have been due to genuine error in labelling similar species. In any case this is more of a problem of adequate application and enforcement, not the scope and robustness of the regulations themselves.

On a global level, there is a clear hierarchy of regulations as can be seen in figure 2.1, where many regulations regarding animal by-products lead back to Codex Alimentarius, the EU regulations and the US FDA. GlobalGAP, for example, must use feeds which are recognised by IFSA and have used HACCP in their mills. IFSA standards must follow EU regulations, therefore any aquaculture product that is certified by GlobalGAP, anywhere in the world, ultimately should adhere to EU regulations and when there is mutual recognition, this will carry across all of the major global certifiers. The question still remains, how well is it enforced? If traceability can break down in Europe, then it can do so elsewhere. Where farms are still permitted to manufacture their own feed, this may be more of a risk because it is more difficult to monitor. Having said this, the major health scare related to by-product use has been the BSE crisis of the 1990s. There has never been any case of TSE related to aquaculture production (FAO 2002b) and evidence that fish could become sources of TSE material is low (Salta *et al* 2009). Evidence has shown that the mechanisms related to infection between different species is impaired by inter-species barriers (Salta *et al* 2009), which is a reason for continuing the intra-species ban on feeding, long suspected to have been involved in causing the original crisis. However, many aquaculture species exhibit very different life strategies to cattle and sheep for which the regulations were targeted. Brown trout (*Salmo trutta*), pike (*Esox lucius*), other carnivorous fish species (Vik *et al* 2001, Hawkins *et al* 2005 , Klemetsena *et al* 2002) and *Penaeid* shrimp (Abdussamad and Thampy 1994, el Hag 1984) are often cannibalistic either in the wild or in culture conditions, and shrimp often consume moulted shells (El Hag 1984). Tacon (2002), suggested that shrimp meal was still being used in shrimp diets at that time and was preferred by many farmers, as it has shown to give good performance (Cruz-Suárez *et al* 1993). There seems little reason, based on current scientific evidence, why intra-species feeding should not be allowed for invertebrate aquaculture species and perhaps fish species too, where there is no disease present. However, most certifiers and legislators will probably continue to prohibit the practice on the precautionary principle (e.g. ASC) and because consumer acceptance is likely to be low, even if robust scientific evidence was presented that the risk was low. This may prevent the most environmentally and economically advantageous use of resources from a life cycle perspective, in some circumstances. However, if there is sufficient enforcement and regular audits by certification schemes, there is no reason why consumers cannot have absolute confidence in imported products, as well as those produced locally as there is clear provision of chain of custody from producer to retailer. Little *et al* (2012), showed that on the basis of RASFF notifications, the safety of farmed Asian seafood being imported into the EU was at least as good as that coming from capture fisheries, and communications with Asian aquafeed producers showed their awareness of the rules on intra-species feeding.

Generally, the legislation on processing by-products from fisheries and aquaculture is clear and allows for many options within the various feed industries that compete for global resources. There are good opportunities for the by-products to be further sold for value addition and good efficiency. This is demonstrated in Vietnam where the majority of *Pangasius* by-products are reduced to fishmeal and fish oil for inclusion in several livestock industries, domestically and for export, described in chapter 1. Issues concerning the various quality issues of aquaculture by-product meals are discussed in chapter 3 and some of their sustainability issues are investigated in chapters 6 and 7.

The recent change in the EU regulations regarding PAPs (EC 2013) from terrestrial monogastric animals has opened many opportunities for aquafeed producers which could much improve the situation in European aquaculture and for those wishing to export to the EU. However, this is very much reliant on customer and retailer acceptability of these protein sources. Currently, there is significant resistance to their use from supermarket chains (Sanver 2014, pers. comm.). The pressures on fishmeal resources and the associated increase in prices have led to sourcing more vegetable protein sources. Although this is often regarded as beneficial to forage fish ecosystems (Alder *et al* 2008), the replacement proteins, such as soy, are often sourced from South America which has sometimes been criticised for sensitive habitat destruction to provide these materials (Fearnside 2008). This is also the case for fish oil substitutes such as palm oil. Effective distribution of oil from aquaculture and fishery by-products could help to reduce the pressures on lipid ingredients in animal feeds as will be discussed in chapter 3.

The standards and regulations on treating mortalities from production facilities may be less clear, possibly preventing resource efficiency and value addition. The combination of strict legislation and producer fears over biosecurity have proven restrictive on the further use of mortalities in Europe, leading to the unsatisfactory practice of on-site incineration and direction to landfill. The most complete regulations are given by the EU, however, they are not totally clear and are very strict. Many private standards must conform to these, whereas other regulations are considered less strict and not discussed in detail here. The situation on European salmon farms may also partially be due to logistical problems in collecting enough material of economic significance in remote locations. Although mortalities cannot be fed to livestock intended for human consumption, there is provision for feeding to pets, zoo animals, or maggots for bait. These options may be considered to be the most environmentally attractive, as currently the pet food market takes up a significant proportion of available protein supplies, including fish meal (De Silva *et al* 2008). Other options may include feeding to insect grubs which can then be sold as exotic pet feeds, for significant economic return. However the EU regulations do not specifically state this as a possible route, as currently maggots for fishing bait are the only one mentioned, although it is probable that this would be permissible as mortalities may be directly fed to pet animals (EC 2009).

The EU regulations also allow for certain industrial uses of mortalities as described in chapter 1 but the market opportunities are likely to be very low in having enough raw material to be of economic interest. The fat content may be of some limited economic interest for use in leather tanning, in machine lubricants and paints and could partially displace fossil fuel based products. This is likely to be an extremely niche market, though. The skins have also been used for manufacturing leather items and there is currently market for fish leather goods in parts of Asia and South America. This could also be an option for mortalities in Europe, although partial decomposition may limit this option.

Finally, other options for mortalities include various disposal alternatives where a return may be achieved; environmentally, economically or both. However, this is likely to be the least efficient in terms of recycling nutrients and energy and with the least economic return for the producer. In the past mortalities were often sent to incineration plants with energy recovery and this is still a permissible route. However, plants were reluctant to accept them as their wet nature resulted in more energy input than was recovered (SEPA 2004). This led to more being sent to landfill but increasing taxes eventually led to the increased use of on-site incineration with no energy recovery. Other options for disposal include composting and anaerobic digestion which may give an economic return or provide a usable on-site product such as gas for heating. Although these options are available, there are still certain barriers to their effective up-take. Both composting and anaerobic digestion must be carried out on approved sites following regulation EC142. This lays out the specific conditions for these activities, including prior sterilisation of the by-product. The stringent conditions laid out in this document, effectively negate the ability for fish-farms to use these measures on-site and therefore are unlikely to be an option for most European fish farmers where biosecurity measures are paramount. Anaerobic digestion and composting of fish mortalities may be especially difficult to implement because of their nature as discussed in chapter 1.

CHAPTER 3: GLOBAL SUPPLY OF FISHMEAL AND ITS RELEVANCE TO THE AQUACULTURE INDUSTRY

3.1 Introduction

Aquaculture of carnivorous species, especially, such as Atlantic salmon has often been highlighted in the popular press and academia as being inefficient in its use of global fishery resources (Naylor *et al* 2009, Tacon and Metian 2008, Alder *et al* 2008). However, little attention has been made to the potential for aquaculture to be a net producer of fishmeal and to supply livestock sectors that compete with aquaculture for quality protein resources.

The aim of this section is to identify; firstly how much fishmeal is available in different global regions and how much of it is derived from fisheries and aquaculture by-products. Secondly, how much by-product is available for reduction into fishmeal but not being used and how much more by-product could potentially be made available from global fisheries and aquaculture production. Finally, what is the outlook for fishmeal supply and what role can aquaculture play in future scenarios.

3.2 Global fishmeal supplies from fisheries and aquaculture processing by-products

The supply of quality fishmeal to aquaculture has been of concern since the El Nino event of 1972, not only from an aquafeed supply perspective but also from an environmental impact perspective and has been highlighted by several authors, notably Naylor *et al*

(2009), Tacon and Metian (2008), Alder *et al* (2008). The ever increasing competition for fishmeal, not only in aquaculture industries, but also other livestock (figure 1.1), has led to increasing substitution of fishmeal with other protein resources in aquafeeds. Although this is considered more sustainable by some, the protein resources which are replacing fishmeal, often have their own sustainability issues such as soy from South America, which has been linked with environmental damage, habitat destruction and loss of biodiversity (Fearnside 2001). It has also resulted in a nutritionally lower quality product in some cases. Atlantic salmon, for example, is marketed as being a healthy, oily fish, high in beneficial omega-3 fatty acids. Although most of this originates from omega-3 rich fish oils in the salmons' diet, fishmeal from marine sources is also high in omega-3 fatty acids (see chapter 1) and these two ingredients together contribute to the high levels found in farmed Atlantic salmon flesh. However, over the last ten years, the ratio of omega-3 to other fatty acids in farmed salmonid diets, especially omega-6, has declined so that now the overall omega-3 fatty acid inclusion found in farmed salmon flesh is around half of that of ten years ago (Shepherd, unpublished work 2013). Omega-6 fatty acids, despite having positive health claims in being polyunsaturated, are considered to be inflammatory, can cause cell damage and eventually lead to cardio-vascular diseases (Wang *et al* 2009). Therefore a ratio higher in omega-3 to omega-6 FAs is reported as being fundamental to a healthy nutritional intake (Holub and Holub 2004). It is consequently becoming increasingly desirable to maximise the potential for fishmeal and fish oil production from current sources and to direct them to where they are most needed. The global supply of fishmeal from wild resources has been in decline for ten years and is subject to massive fluctuations mainly because of the dominance of vulnerable stocks of Peruvian anchoveta within the supply chain (figure 3.1).

Increasingly, the global supply of fishmeal has been sourced from the by-products of capture fisheries and to some extent aquaculture by-products. This includes a small contribution from crustacean production such as *Penaeid* shrimp to shrimp meal manufacture. It was estimated by IFFO (2011) that around 25% of the global supply was currently sourced from by-products, however, this figure was based on many assumptions and unreliable data. This has since been amended so that it was estimated, previous to this study, that around 33% of fishmeal originates from by-product resources (Jackson pers. comm. 2013).

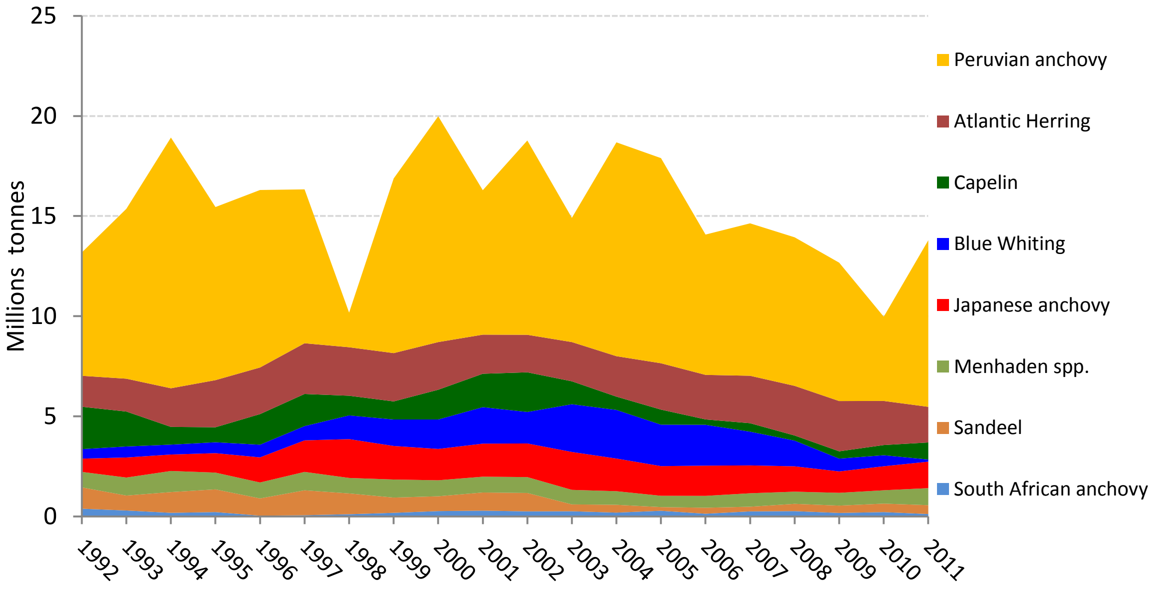


Figure 3.1. Global capture of major fishmeal reduction species. FAO Fishstat 2013.

In collaboration with IFFO, a global database of fishmeal supply was initiated in an attempt to identify areas, geographically and on an industry level, where by-products from fisheries and aquaculture could be further exploited for the production of fishmeal.

The ultimate purpose being that the IFFO and its members could use it as a tool to identify viable markets and implement improvements in resource efficiencies for acquiring fishmeal raw materials. The database included individual data from the countries within nine regions: Europe (including Greenland), South and Central America (all of the Americas except the USA and Canada), North America (USA and Canada), Commonwealth of Independent States (CIS), Africa, Middle East, China, rest of Asia, and Oceania. The individual countries which were included in each of these regions can be seen in Appendix 1.1. The database was produced using Microsoft Excel 2010. It was designed to be as fully automated as possible so that it could be updated easily as new data became available. Therefore a number of linked functions were set up to tables of data as described below.

3.3 Capture and aquaculture supply

All production and commodity data were obtained from FAO's Fishstat database (2013) which included fisheries and aquaculture production data up to 2011 and commodities trade data up to 2009. The top twenty species in terms of a five year average of production volume were identified for each of the nine regions, for each of capture fisheries and for aquaculture production. This included all fish and crustacean species, and cephalopods, but not plants, amphibians, reptiles, mammals, bivalve or gastropod molluscs, because it was assumed that they make little or no contribution to global "fishmeal" supplies (for the purposes of this section, fishmeal will refer to any meal that is obtained from fishery or aquaculture activities, including the crustacean and cephalopod groups mentioned above, unless otherwise stated).

In many cases, processing of seafood products occurs in countries other than that to which the fishing vessel belongs (for the purposes of this chapter, “seafood” will be defined as all fish, crustacean and mollusc species, whether marine or fresh water). The production of whole fish may be recorded as being in the country where the vessel is registered, but the processing occurs elsewhere. China, particularly, is a major processor of seafood commodities such as salmon, tuna and whitefish which originate from vessels which are registered in other countries such as Russia (Clarke 2009). The supply of each species was adjusted according to the five year average trade figures in whole fish commodities for each species group. Trade in fillets and other processed commodities was not counted. The supply of each species was calculated by assigning each species from the production data to commodities groups within the Fishstat trade data and using linked “LOOKUP” and combinations of “INDEX” and “MATCH” functions to total the amount of trade in that commodity and adjust it to the proportion of production that the species contributed to that particular commodity group. This produced a figure for the total supply of a particular whole fish or seafood species which was available in the region for processing. In a few cases, where production was low, for some Oceanic species for example, this resulted in a small negative production for a species, because the five year production and five year trade statistics were two years apart. In which case the production was set to zero. There was also some ambiguity as to which commodity group to assign to some species, such as some shrimp and salmonid species and it appeared from the trade data that different countries may have assigned certain species to different commodity groups. The largest two capture production “species” for both China and Asia, for example were from “marine fishes nei” (not elsewhere included) and “freshwater fishes nei”. Some error in total production may also come from the trade in frozen products which may have contained more water than the fresh product. There are more than a thousand species in Fishstat (FAO 2013) and therefore the species groups to which they were attributed cannot be presented in this thesis.

3.4 Edible yield

To determine the quantity of by-product available, it was first necessary to ascertain the edible yield for each species. The quantity that was left over from this was assumed to be the by-product that could be made available for manufacture into fishmeal (or other value added products). All figures for edible yields came directly from FAO (1989), except edible yields from anchoveta and sand-eels were assumed to be 100%, where consumed directly. A table of edible yields was linked to the production data via “INDEX” and “MATCH” functions so that it would update automatically if the raw data were changed. The edible yields of the top 40 species by global production volume can be seen in Appendix 1.2.

3.5 Processing and utilisation of fishery products

It is very simplistic to assume that all by-products from fisheries and aquaculture production are available for manufacture into fishmeal. There are many varied practices from region to region which determine this, e.g. the various shrimp products discussed in chapter 1. In many cases in capture fisheries, much of the by-product does not even make it ashore because significant levels of processing occur at sea, with guts and trimmings often discarded overboard (Be-Fair 2007). There may be many different reasons for this which vary by location, but the low value of the highly perishable by-products taking up valuable space on-board is likely to be the main reason. National restrictions which limit by-product use for human consumption, such as in France, which limits their use to the extent that fishmeal is the only viable option, so that there may not be enough value in the by-products to justify the expense required to keep them fresh (Be-Fair 2007). The Be-Fair project (2007) identified up to 3800 tonnes of discards per annum from Spanish fishing activities. Significant discards of whole, low-value species have also occurred historically, such as Atlantic horse mackerels from bass and hake fisheries, although attempts have since been made to reduce these (Be-Fair 2007).

As well as discards at sea, other sources of potential wastage are apparent. In Asia, it is much more common for fish to be sold live or unprocessed. In China for example, it is estimated that around half of tilapia production is for domestic markets with the majority being sold live in southern Chinese states (Hanson *et al* 2011). However “edible yields” are somewhat subjective and it is more common for more of the animal to be consumed in many Asian countries than it is in the West, as demonstrated by the Vietnamese markets for *Pangasius* catfish stomachs and swim-bladders, for example (Nguyen 2010). Sechena *et al* (1999) reported high levels of consumption amongst ethnic Asian groups in the US of heads, roe, bones and organs. Therefore, there are potentially large amounts of seafood that are not processed in Asia and the by-product is neither available from the processor or at the household level. Although even in these countries, 100% consumption is not likely and there will be a certain quantity of “plate waste”, which is difficult to measure. Hence, certain assumptions needed to be made regarding the amount of available supply that was processed and how much of the by-product resulting from processing was then made available for further processing into fishmeal. These assumptions were made in cooperation with IFFO with expert contributions to these assumptions being made by Andrew Jackson, technical director, IFFO.

Following assumptions on quantity of seafood supply that was processed and the amount of by-product from processors that was further processed into fishmeal, assumptions were made on the potential yields of fishmeal from by-product. The standard yield was set at 26.5% by IFFO, however, the yield of fishmeal from *Pangasius* catfish was set at 20% and shrimp meal at 23%, determined from industry responses to LCA survey work (see appendices for blank questionnaires) carried out as part of the SEAT project and described in more detail in chapters 6 and 7 respectively. Ultimately, two figures were estimated of the quantity of fishmeal that could be realised from unutilised by-product. The first figure was the quantity of fishmeal that could be obtained if all by-products from current processing activities were manufactured into fishmeal. The second figure was the quantity of fishmeal that could be realised if all seafood production was processed to the assumed edible yields, and all of the subsequent by-product was then directed to fishmeal production. Figure 3.2 shows a schematic of the calculations and assumptions made during these estimations and Figure 3.3 shows a screen capture from the Excel database for European production from fisheries and aquaculture. The grey cells are inputs which affect the calculations in the white cells. Some of these are linked to other sheets, such as the edible yields which can also be changed within that sheet. The last column gives the amount of fishmeal that could be made from all of the unutilised by-product that could be made available, if all of that species was processed to the edible yield given, with the associated amount of by-product in the previous column. The prior two columns give the fishmeal that could be made from the unutilised by-product from current processing activities. The individual results for each region can be seen as screen shots in Appendix 1.3. Projections were also made for global aquaculture production of major species based on current growth rates for those species and total world growth in aquaculture. This projection was then used to estimate the quantities of fishmeal that could potentially be realised to 2030.

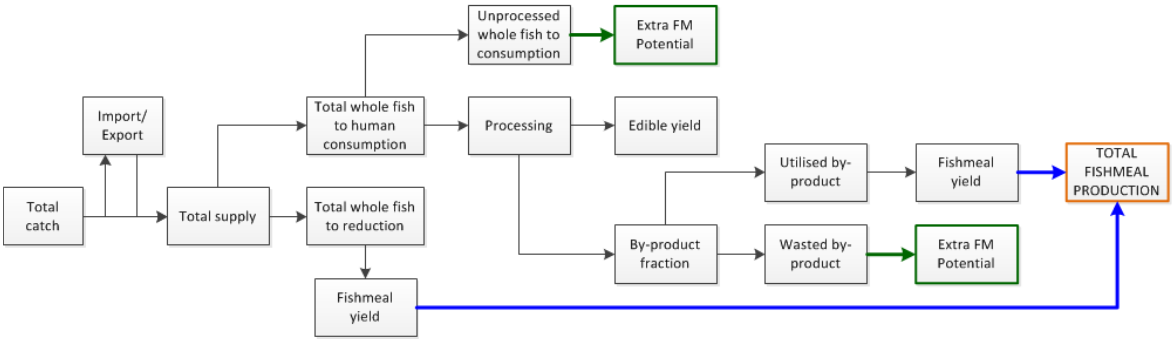
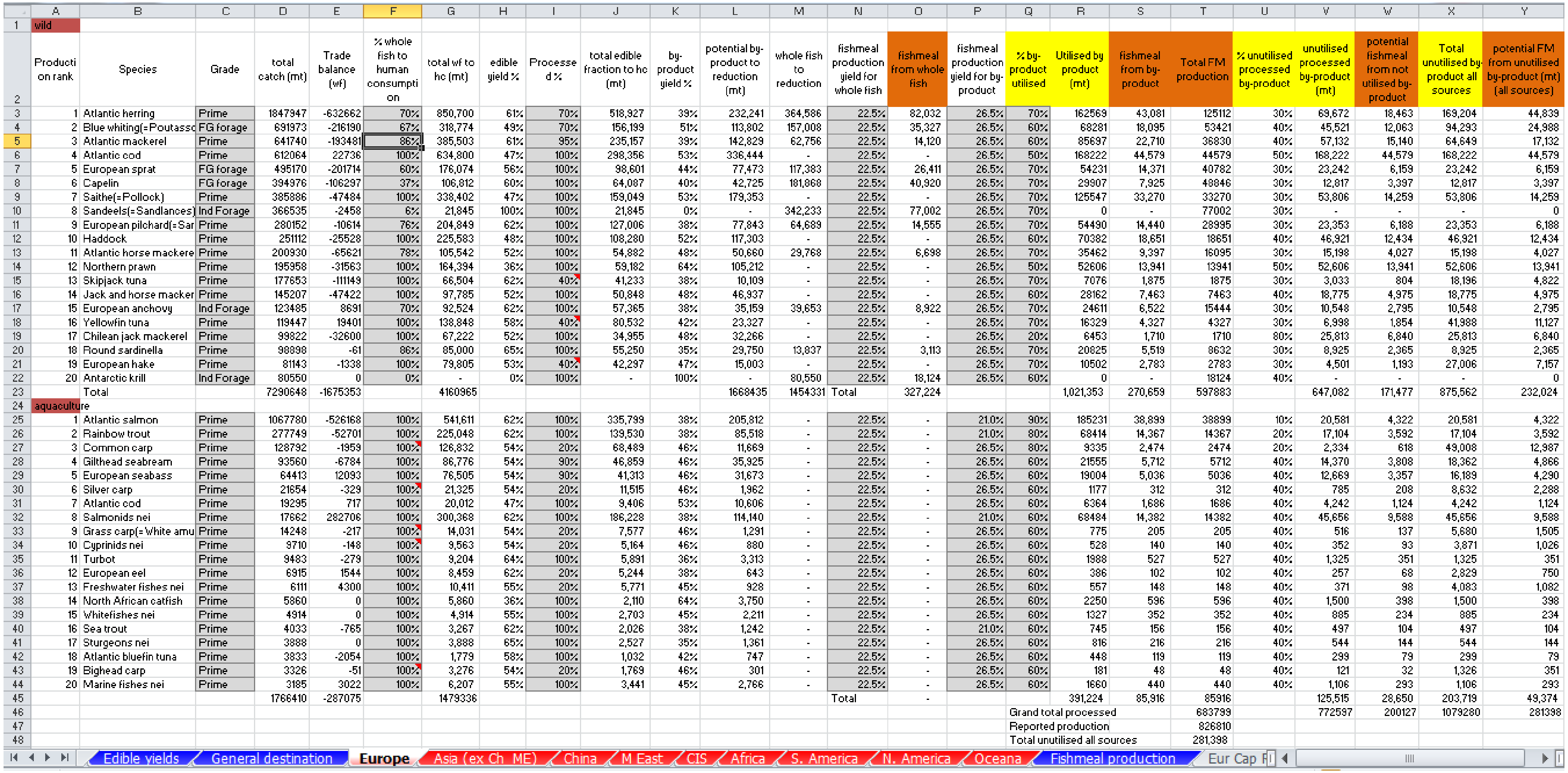


Figure 3.2. Schematic of calculations and assumptions in estimating extra fishmeal potential from fishery and aquaculture by-product resources.

The database is a work-in-progress of which IFFO will take ownership and update as more precise data become available from their members and other sources. However, it offers a starting point in identifying areas of inefficiency which could be improved and in directing fisheries and aquaculture resources towards fuller utilisation which will be



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	wild																								
2	Production rank	Species	Grade	total catch (mt)	Trade balance (wf)	% whole fish to human consumption	total wf to hc (mt)	edible yield %	Processed %	total edible fraction to hc (mt)	by-product yield %	potential by-product to reduction (mt)	whole fish to reduction	fishmeal production yield for whole fish	fishmeal from whole fish	fishmeal production yield for by-product	% by-product utilised	Utilised by product (mt)	fishmeal from by-product	Total FM production	% unutilised processed by-product	unutilised processed by-product (mt)	potential fishmeal from not utilised by-product	Total unutilised by-product all sources	potential FM from unutilised by-product (mt) (all sources)
3	1	Atlantic herring	Prime	1847947	-632662	70%	850,700	61%	70%	518,927	39%	232,241	364,586	22.5%	82,032	26.5%	70%	162569	43,081	125112	30%	69,672	18,463	169,204	44,839
4	2	Blue whiting(=Poutassc	FG forage	691973	-216190	67%	318,774	49%	70%	156,199	51%	113,802	157,008	22.5%	35,327	26.5%	60%	68281	18,095	53421	40%	45,521	12,063	94,293	24,988
5	3	Atlantic mackerel	Prime	641740	-193481	86%	385,503	61%	95%	235,157	39%	142,829	62,756	22.5%	14,120	26.5%	60%	85697	22,710	36830	40%	57,132	15,140	64,649	17,132
6	4	Atlantic cod	Prime	612064	22736	100%	634,800	47%	100%	298,356	53%	336,444	-	22.5%	-	26.5%	50%	168222	44,579	44579	50%	168,222	44,579	168,222	44,579
7	5	European sprat	FG forage	495170	-201714	60%	176,074	56%	100%	98,601	44%	77,473	117,383	22.5%	26,411	26.5%	70%	54231	14,371	40782	30%	23,242	6,159	23,242	6,159
8	6	Capelin	FG forage	394976	-106297	37%	106,812	60%	100%	64,087	40%	42,725	181,868	22.5%	40,920	26.5%	70%	29907	7,925	48846	30%	12,817	3,397	12,817	3,397
9	7	Saithe(=Pollock)	Prime	385886	-47484	100%	338,402	47%	100%	159,049	53%	179,353	-	22.5%	-	26.5%	70%	125547	33,270	33270	30%	53,806	14,259	53,806	14,259
10	8	Sandeels(=Sandlances)	Ind Forage	366535	-2458	6%	21,845	100%	100%	21,845	0%	-	342,233	22.5%	77,002	26.5%	70%	0	-	77002	30%	-	-	-	0
11	9	European pilchard(=Sar	Prime	280152	-10614	76%	204,849	62%	100%	127,006	38%	77,843	64,689	22.5%	14,555	26.5%	70%	54490	14,440	28995	30%	23,353	6,188	23,353	6,188
12	10	Haddock	Prime	251112	-25528	100%	225,583	48%	100%	108,280	52%	117,303	-	22.5%	-	26.5%	60%	70382	18,651	18651	40%	46,921	12,434	46,921	12,434
13	11	Atlantic horse mackere	Prime	200930	-65621	78%	105,542	52%	100%	54,882	48%	50,660	29,768	22.5%	6,698	26.5%	70%	35462	9,397	16095	30%	15,198	4,027	15,198	4,027
14	12	Northern prawn	Prime	195958	-31563	100%	164,394	36%	100%	59,182	64%	105,212	-	22.5%	-	26.5%	50%	52606	13,941	13941	50%	52,606	13,941	52,606	13,941
15	13	Skipjack tuna	Prime	177653	-111149	100%	66,504	62%	40%	41,233	38%	10,109	-	22.5%	-	26.5%	70%	7076	1,875	1875	30%	3,033	804	18,196	4,822
16	14	Jack and horse macker	Prime	145207	-47422	100%	97,785	52%	100%	50,848	48%	46,937	-	22.5%	-	26.5%	60%	28162	7,463	7463	40%	18,775	4,975	18,775	4,975
17	15	European anchovy	Ind Forage	123485	8691	70%	92,524	62%	100%	57,365	38%	35,159	39,653	22.5%	8,922	26.5%	70%	24611	6,522	15444	30%	10,548	2,795	10,548	2,795
18	16	Yellowfin tuna	Prime	119447	19401	100%	138,848	58%	40%	80,532	42%	23,327	-	22.5%	-	26.5%	70%	16329	4,327	4327	30%	6,998	1,854	41,988	11,127
19	17	Chilean jack mackerel	Prime	99822	-32600	100%	67,222	52%	100%	34,955	48%	32,266	-	22.5%	-	26.5%	20%	6453	1,710	1710	80%	25,813	6,840	25,813	6,840
20	18	Round sardinella	Prime	98898	-61	86%	85,000	65%	100%	55,250	35%	29,750	13,837	22.5%	3,113	26.5%	70%	20825	5,519	8632	30%	8,925	2,365	8,925	2,365
21	19	European hake	Prime	81143	-1338	100%	79,805	53%	40%	42,297	47%	15,003	-	22.5%	-	26.5%	70%	10502	2,783	2783	30%	4,501	1,193	27,006	7,157
22	20	Antarctic krill	Ind Forage	80550	0	0%	-	0%	100%	-	100%	-	80,550	22.5%	18,124	26.5%	60%	0	-	18124	40%	-	-	-	0
23		Total		7290648	-1675353		4160965					1668435	1454331	Total	327,224			1,021,353	270,659	597883		647,082	171,477	875,562	232,024
24	aquaculture																								
25	1	Atlantic salmon	Prime	1067780	-526168	100%	541,611	62%	100%	335,799	38%	205,812	-	22.5%	-	21.0%	90%	185231	38,899	38899	10%	20,581	4,322	20,581	4,322
26	2	Rainbow trout	Prime	277749	-52701	100%	225,048	62%	100%	139,530	38%	85,518	-	22.5%	-	21.0%	80%	68414	14,367	14367	20%	17,104	3,592	17,104	3,592
27	3	Common carp	Prime	128792	-1959	100%	126,832	54%	20%	68,489	46%	11,669	-	22.5%	-	26.5%	80%	9335	2,474	2474	20%	2,334	618	49,008	12,987
28	4	Gilthead seabream	Prime	93560	-6784	100%	86,776	54%	90%	46,859	46%	35,925	-	22.5%	-	26.5%	60%	21555	5,712	5712	40%	14,370	3,808	18,362	4,866
29	5	European seabass	Prime	64413	12093	100%	76,505	54%	90%	41,313	46%	31,673	-	22.5%	-	26.5%	60%	19004	5,036	5036	40%	12,669	3,357	16,189	4,290
30	6	Silver carp	Prime	21654	-329	100%	21,325	54%	20%	11,515	46%	1,962	-	22.5%	-	26.5%	60%	1177	312	312	40%	785	208	8,632	2,288
31	7	Atlantic cod	Prime	19295	717	100%	20,012	47%	100%	9,406	53%	10,606	-	22.5%	-	26.5%	60%	6364	1,686	1686	40%	4,242	1,124	4,242	1,124
32	8	Salmonids nei	Prime	17662	282706	100%	300,368	62%	100%	186,228	38%	114,140	-	22.5%	-	21.0%	60%	68484	14,382	14382	40%	45,656	9,588	45,656	9,588
33	9	Grass carp(=White amu	Prime	14248	-217	100%	14,031	54%	20%	7,577	46%	1,291	-	22.5%	-	26.5%	60%	775	205	205	40%	516	137	5,680	1,505
34	10	Cyprinids nei	Prime	9710	-148	100%	9,563	54%	20%	5,164	46%	880	-	22.5%	-	26.5%	60%	528	140	140	40%	352	93	3,871	1,026
35	11	Turbot	Prime	9483	-279	100%	9,204	64%	100%	5,891	36%	3,313	-	22.5%	-	26.5%	60%	1988	527	527	40%	1,325	351	1,325	351
36	12	European eel	Prime	6915	1544	100%	8,459	62%	20%	5,244	38%	643	-	22.5%	-	26.5%	60%	386	102	102	40%	257	68	2,829	750
37	13	Freshwater fishes nei	Prime	6111	4300	100%	10,411	55%	20%	5,771	45%	928	-	22.5%	-	26.5%	60%	557	148	148	40%	371	98	4,083	1,082
38	14	North African catfish	Prime	5860	0	100%	5,860	36%	100%	2,110	64%	3,750	-	22.5%	-	26.5%	60%	2250	596	596	40%	1,500	398	1,500	398
39	15	Whitefishes nei	Prime	4914	0	100%	4,914	55%	100%	2,703	45%	2,211	-	22.5%	-	26.5%	60%	1327	352	352	40%	885	234	885	234
40	16	Sea trout	Prime	4033	-765	100%	3,267	62%	100%	2,026	38%	1,242	-	22.5%	-	21.0%	60%	745	156	156	40%	497	104	497	104
41	17	Sturgeons nei	Prime	3888	0	100%	3,888	65%	100%	2,527	35%	1,361	-	22.5%	-	26.5%	60%	816	216	216	40%	544	144	544	144
42	18	Atlantic bluefin tuna	Prime	3833	-2054	100%	1,779	58%	100%	1,032	42%	747	-	22.5%	-	26.5%	60%	448	119	119	40%	299	79	299	79
43	19	Bighead carp	Prime	3326	-51	100%	3,276	54%	20%	1,769	46%	301	-	22.5%	-	26.5%	60%	181	48	48	40%	121	32	1,326	351
44	20	Marine fishes nei	Prime	3185	3022	100%	6,207	55%	100%	3,441	45%	2,766	-	22.5%	-	26.5%	60%	1660	440	440	40%	1,106	293	1,106	293
45				1766410	-287075		1479336							Total	-			391,224	85,916	85916		125,515	28,650	203,719	49,374
46																	Grand total processed			683799		772597	200127	1079280	281398
47																	Reported production			826810					
48																	Total unutilised all sources			281,398					

Figure 3.3. Screen capture from IFFO/UoS global fishmeal database, showing major steps in estimating fishmeal potential from unutilised by-products for the top twenty capture fishery and aquaculture species from Europe as shown in figure 3.2

discussed in later sections. It shows how much fishmeal is currently estimated to come from whole fish, and by-products from aquaculture and from fisheries. It also compares the estimates from this database to FAO figures for fishmeal production and finally the estimates of fishmeal that could be made from by-products, and the projections for potential fishmeal production into 2030.

3.6 Current production of fishmeal by region

The estimated five year average of total global production of fishmeal from the IFFO/University of Stirling (UoS) database was substantially lower (4939882 tonnes) than that reported by the FAO Fishstat (2013) database (5899156 tonnes). As shown in figure 3.4, this was mainly due to assumed overestimates from China, South/Central America and Europe. However, estimated production from Asia, excluding the Middle East and China, was higher than reported by the FAO. However, despite this, it should be remembered that the IFFO/UoS database took figures from only the top twenty production species in each region. The twentieth ranked capture fishery species in Asia, excluding China, the Middle East and CIS countries (*Stolephorus* anchovies nei) was still higher than the top ranked species in Oceania (skipjack tuna) especially after the high negative trade balance of Oceania skipjack tuna was accounted for. It may be that there was substantially more by-product available in certain regions than that accounted for within the database.

The vast majority of fishmeal from China, as reported by the FAO fishstat database, is from undefined fish waste, i.e. by-products, and this quantity has reportedly risen substantially over the five years for which these data were available, from just over 325,000 tonnes in 2005 to over 1.2 million tonnes in 2009 (FAO Fishstat 2013). This quantity is possible if high levels of processing are achieved, as the five year average production from the top twenty species was over 10 million tonnes and 20 million tonnes for capture fisheries and aquaculture respectively (FAO Fishstat 2013). A 20% yield of fishmeal from this level of production could produce over 6 million tonnes of fishmeal of varying quality.

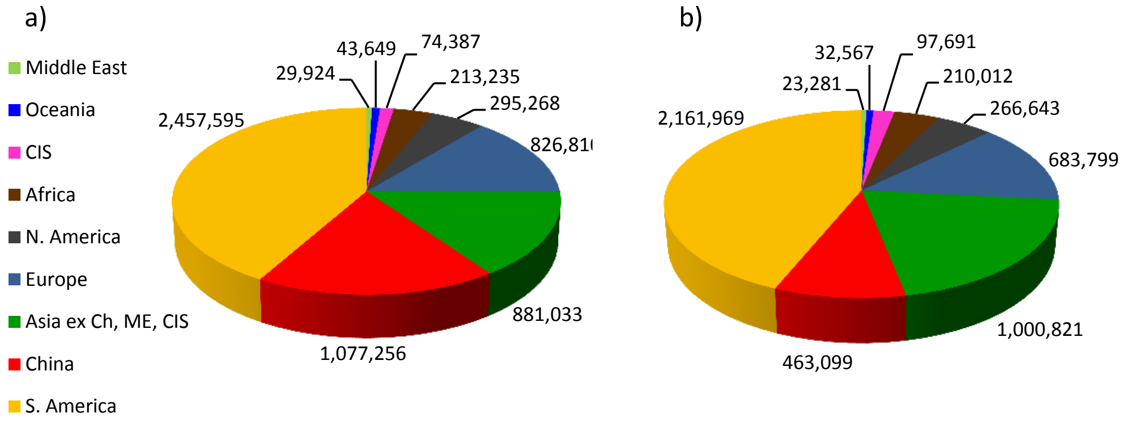


Figure 3.4 Five year average fishmeal production from nine regions a) FAO fishstat database (2013), b) IFFO/UoS database estimates

According to the FAO, the majority of South American fishmeal production is “fish meals nei”, with the highest contribution from Peru at around 1.5 million tonnes, who also contributed no anchoveta meal (5yr averages). However, it is likely that the majority of this is actually anchoveta meal, given the nearly 5.8 million tonne five year average capture of Peruvian anchoveta. The two year gap between commodities and production data with highly fluctuating production may explain some of the differences in FAO and IFFO/UoS figures and this is also the case for fishmeal originating from jack mackerel which also exhibited fluctuating supply.

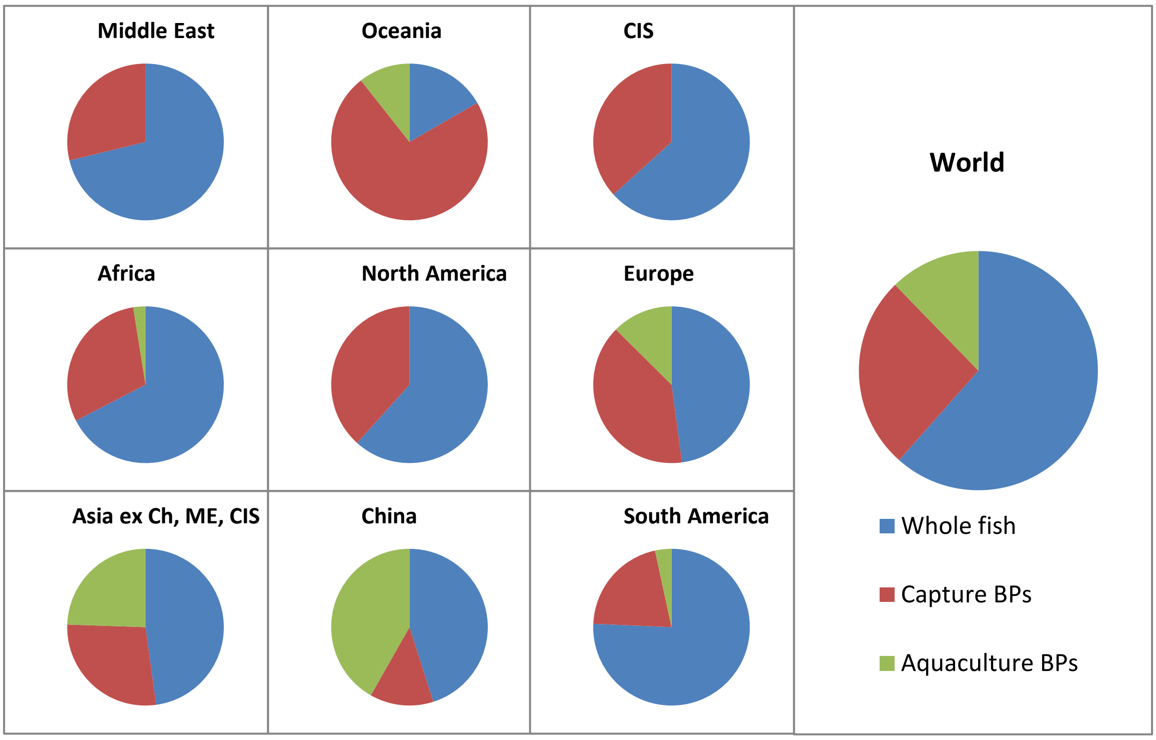


Figure 3.5 Contribution of fishmeal from whole fish, capture fishery and aquaculture by-products (BPs), estimated from the IFFO/UoS database.

The majority of European fishmeal was from “fish meals nei”, at around 700,000 tonnes, according to the FAO Fishstat database (2013). It is not totally clear where this figure originates from as herring, capelin and blue whiting meals are accounted for separately and production is higher than that estimated by the IFFO/UoS database. It may be that much of it comes from mixed fishery by-products, for which the species are difficult to determine, although this would be better declared as “fishmeal obtained from fish waste”, as for China. The declaration of “fishmeals nei” in Europe and South/Central America highlights the lack of consistency in reporting of seafood commodities within the FAO Fishstat database and adds to the difficulty in tracing the raw materials from current production of fishmeal. Figure 3.5 shows the contributions to total fishmeal production in each region from whole fish reduction, fishery and aquaculture by-products as estimated from the IFFO/UoS database.

The total contribution of by-products to global fishmeal production was estimated to be around 38%. This is a little higher than the previous estimate of 33% made by Jackson (2013 pers. comm.). The majority of this comes from South/Central America and Asia, representing around 27% each, with Europe and China as the next biggest contributors. However, China and Asia are the largest manufacturers of fishmeal from aquaculture by-product. According to IFFO/UoS database estimates, much of the Chinese production from aquaculture by-products may actually be shrimp meal from the large *Penaeid* shrimp processing industry there, with rest coming largely from tilapia processing for international markets. In Asia, excluding China, CIS and the Middle East, most of the production of aquaculture by-product meals is coming from the processing of *Pangasius* catfish, which is highly processed for international markets as described in chapter 1. Despite these figures, it is estimated that a very low proportion of Chinese and other Asian seafood is processed as many local consumers prefer to buy whole, live fish. Some of that which is exported may also be whole, frozen. It is not easy to quantify the amount of plate waste that is produced at the household level, which could be directed to fishmeal manufacture because of different attitudes to fish consumption, as mentioned in section 3.2, and hence the edible yields. Instead, the estimated quantities of unutilised by-product were made on edible yields as given by the FAO (1989). Given these figures, the potential for increased fishmeal production is extremely high as shown in figure 3.6

3.7 Potential for extra fishmeal production from by-product processing

It is clear from Figure 3.6a that large quantities of fishmeal could be realised from under-utilised by-products from current seafood processing, estimated at approximately 2.5 million tonnes. More production could come from Asia particularly, both from capture fisheries and aquaculture, and this is despite estimating higher levels of total fishmeal production in Asia than reported by the FAO (Fishstat 2013). A large proportion of this extra production may be from freshwater capture fisheries and aquaculture, however, the database also highlighted large quantities of marine fish that may be being under-utilised, including various mackerel and cephalopod species. The processed by-products from marine fish species alone could represent an estimated extra 375,000 tonnes of potentially good quality fishmeal, high in omega-3 fatty acids, and substantially more could be achieved if a higher level of processing was operated. It is notable that the quantity of unutilised by-product from Chinese seafood processing is substantially lower than that of all the other regions, despite the much higher levels of production. This is because of the assumed low levels of processing of seafood for domestic markets and this is highlighted in figure 3.6b where the extra potential for fishmeal production would be over 40% of the global potential if all seafood was processed to the assumed edible yields given by the FAO (1989).

A similar situation was also assumed for Africa where freshwater fish species such as tilapias and catfish were not considered to be highly processed. However, it was also considered that only around 50% of *sardinellas*, representing approximately 672,000 tonnes, were processed with 83% being directed to human consumption. In total it was estimated that around 280,000 tonnes of extra fishmeal could be made from the by-products of African marine species supplies if all seafood was fully processed. However, a similar situation to Asia may be observed regarding attitudes to fish consumption and how much processing is realistically achievable. In the Lake Victoria region, for example, the introduction of Nile perch (*Lates niloticus*) resulted in the reduction of subsistence fisheries for local communities, so that now many are more reliant on consuming low value fish and processing by-products including heads and frames which might otherwise be directed to fishmeal production (Kabahenda and Hüsken 2009). Therefore, the situation regarding particular consumption practices in various locations is complex and

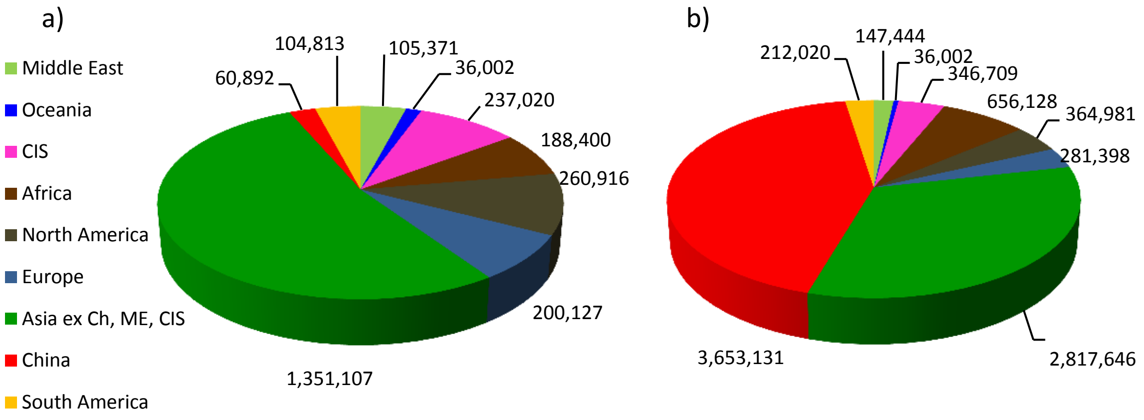


Figure 3.6 Estimated potential for increased fishmeal production if a) all current unutilised processing by-products and b) all current seafood production was processed and the by-products directed to fishmeal.

has considerable bearing on the availability of by-product for fishmeal utilisation from region to region. It is generally accepted that direct human consumption is a more efficient use of the animal than use as feed because of losses during the fishmeal production stage and feed conversion during animal rearing. From a food security perspective it is also important that valuable nutrition is not diverted from poor communities to international markets (Kabahenda and Hüsken 2009). Clearly a lot more work is required in this regard, to identify the trends in regional consumer consumption patterns, in order to establish the best use of various seafood products pre and post processing and the consequences for fishmeal production.

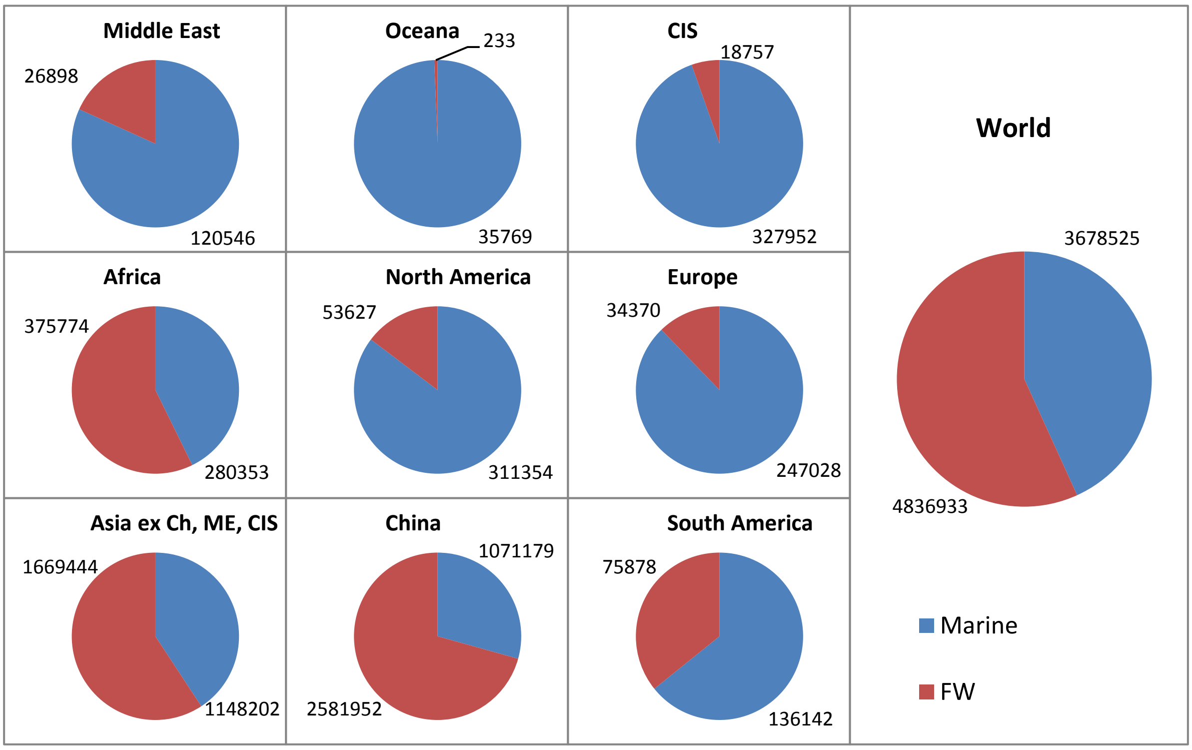


Figure 3.7 potential for extra fishmeal production from marine and freshwater seafood by-product resources

Despite regional consumer patterns and preferences, it was estimated that approximately an extra 8.5 million tonnes of fishmeal could be manufactured from the by-product that could be made available from world seafood production, with 43% of this coming from the by-products of marine seafood resources (figure 3.7). Almost half of global seafood by-product could potentially be sourced from aquaculture by-products, especially China and the rest of Asia except for the Middle East and CIS countries as shown in figure 3.8. This is, of course, an unrealistic number because of the issues raised above but the actual number could be somewhere between the 2.5 million tonnes from current unutilised processing by-products and the higher 8.5 million tonnes figure, depending on the level of processing and the distribution networks that could be achieved. Much of this is dependent on the level of regional growth, urbanisation and demands from local and international markets. The majority of growth in Asian seafood production has arisen through domestic demand and increased seafood consumption per capita (Delgado *et al* 2003), which is responsible for comparatively low volumes of processed fish compared to Western countries. It is likely that this trend may continue with the majority of growth still coming from Asian production, as seafood consumption in the West has stagnated despite increased volumes of imported seafood products (Delgado *et al* 2003). However, some exceptions are evident as characterised by the share of Vietnamese *Pangasius* production which is highly processed for export on international markets.

3.8 Fishmeal quality from aquaculture and capture fishery by-products for use in livestock diets

The various qualities of fishmeal that can be achieved through the reduction of by-products are of key importance. Historically, the vast majority of fishmeal has been sourced from small, pelagic forage fish such as anchoveta (Delgado 2003) which have been high in omega-3 fatty acids and with excellent amino acid profiles. As well as omega-3 FAs and amino acid profiles, fishmeals typically are also a good source of phosphorous and B vitamins. However, the various concentrations and profiles of the various nutrients are different between the different types of fishmeal (FAO 1986). The fishmeals obtainable from fisheries by-products may be temporally and geographically highly variable, from many different species, and both between and within different

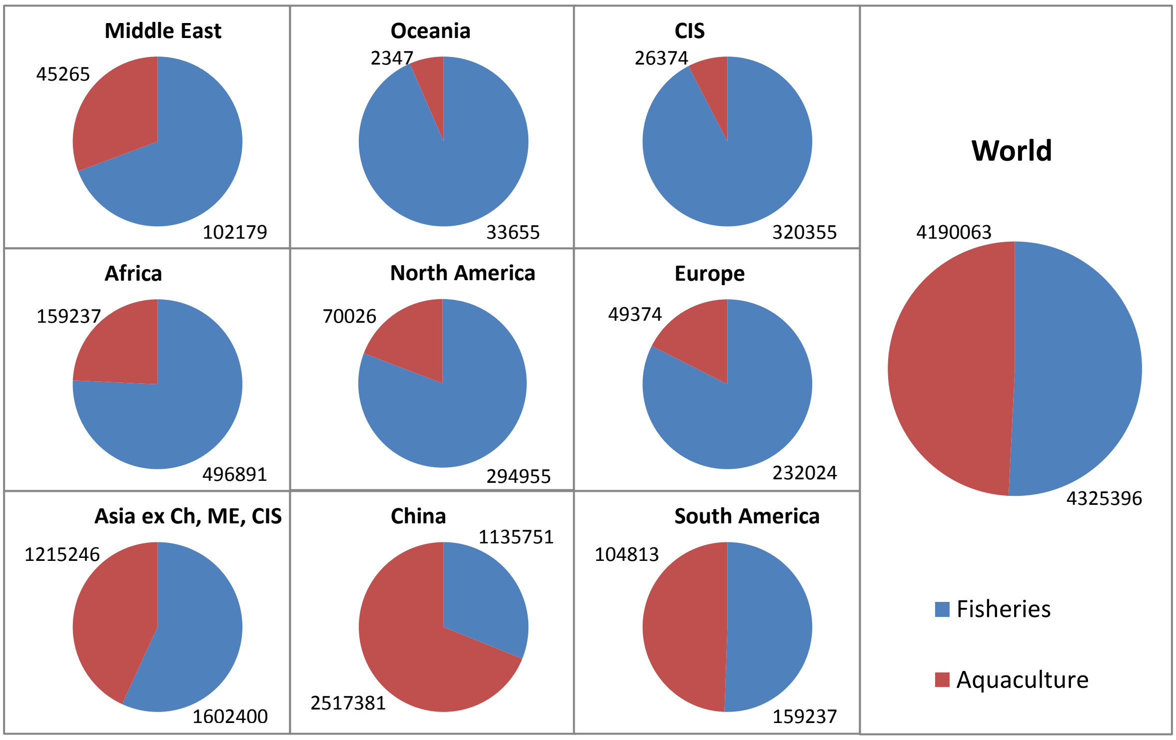


Figure 3.8 Potential for extra fishmeal production from aquaculture and fisheries resources by region

batches. They may also be higher in ash content because of the proportionately higher amount of bone, may have different amino acid profiles, and their FA profiles typically reflect that of their diets. By-products from fed aquaculture species may therefore be much lower in omega-3 FAs and higher in omega-6 FAs from rapeseed and soy inclusions, for example. Table 3.1 shows the differences in proximate analyses between some key fishmeals of significant importance, squid meal, shrimp head meal from *P. monodon* and that of soybean meal for comparison. Most notable are the higher ash contents of by-product meals from *Pangasius* catfish and white fish meals resulting from the high bone fraction of the raw material. Shrimp meal also has a high ash and fibre content from the chitin content within the shell fraction.

The specific amino-acid requirements of livestock depend on the species and their stage of growth. For example, growing pigs have a higher requirement for methionine, cysteine and threonine than suckling pigs and consequently sows (Boisen *et al* 2000). It is desirable to provide the correct ratios in relation to the most limiting amino acids to avoid them being used as energy sources resulting in more nitrogen excretion and thus inefficient use of the protein resource and possibly poorer performance overall. Thus supplying the limiting essential amino acids in correct ratios can lower the overall requirement for crude protein within the diet (Applegate 2008). The amino acid ratio provided by fishmeal as a percentage of the "ideal" protein which provides the optimum ratios of eight of the most limiting essential amino acids for growing pigs is given by Boisen *et al* (2000) and is shown in table 3.2. This is assumed to be for Peruvian fishmeal and the percentages that the other protein sources shown in table 3.1 provide is extrapolated from this fishmeal figure based on the protein content and amino acid profiles given in table 3.1. Boisen *et al* (2000) also gave figures for the percentage of amino acids present in soybean meal as those of the ideal profile for growing pigs but they are not presented here. In general the figures presented in table 3.2 for soybean are within 10% of those given by Boisen *et al* (2000) except for tryptophan which is 12% lower in table 3.2. This is most likely due to minor differences between the profiles given by the FAO (1986) and those calculated from various literature data by Boisen *et al* (2000). However, on this basis, one can have confidence that the figures given for other protein sources in table 3.2 are also within around 10%, but subject to change between various batches. Table 3.2 shows that fishmeal from anchoveta and herring provide the best profile but fishmeal from white fish trimmings also has a good profile with six out of the eight amino acids within 25% of the optimum. Shrimp meal and squid meal are the furthest from having the ideal profile, and shrimp meal has the added problems of having high ash and fibre content (table 3.1). The high content of both ash and fibre in pig feeds was found to be detrimental to nutrient retention with higher faecal and urinary nitrogen excretion and lower lysine availability (Fanimo *et al* 2006). *Pangasius* meal is especially low in threonine and isoleucine but it is possible that these could be supplemented through the inclusion of other protein sources such as soybean, other meals or single amino acid supplements. This is partially supported by the information in chapter 1, where Nguyen (2010) found *Pangasius* meals to perform well in pig diets, despite the *Pangasius* by-product meal having a higher ash and lower crude protein content than that reported by the by-product processor in tables 3.1 and 3.2.

Table3.1 Proximate analyses and amino acid profiles (%DM) of key protein ingredients in aquafeeds. Source *FAO 1986 (Soybean solvent defatted), †Industry data from LCA survey work, amino acid profile from Tuan 2010. ‡FAO 1997, amino acid profile from Hulan *et al* 1979.

	Meal type						
	Anchoveta*	Herring*	White fish*	*Pangasius*†	Squid‡	Shrimp head‡	Soybean*
Crude protein %	65	72	65	60	78	53	46
Crude lipid %	9	9	5	13	5	6	1
Ash %	16	10	20	24	8	26	6
Moisture %	10	8	10	10	7	6	11
Crude Fibre %	0	0	0	0	2	14	6
Amino Acids %							
Lysine	5.07	5.47	4.49	4.90	3.72	1.36	2.88
Methionine	1.95	2.16	1.69	1.68	1.97	0.85	0.63
Cystine	2.60	2.88	2.29	na	0.50	0.34	1.13
Tryptophan	0.78	0.83	0.61	na	1.44	0.44	0.58
Histidine	1.59	1.74	1.31	1.35	0.87	0.76	1.12
Leucine	4.98	5.40	4.21	2.32	4.55	2.26	3.42
Isoleucine	3.06	3.23	2.41	1.11	2.86	2.11	2.20
Arginine	3.81	4.21	4.14	3.28	2.16	2.26	3.24
Phenylanine	2.75	2.82	2.14	1.31	1.52	1.50	2.20
Tyrosine	2.22	2.25	1.69	2.40	1.24	1.15	1.58
Threonine	2.82	3.07	2.50	1.29	3.91‡	1.37	1.89
Valine	3.46	3.90	2.91	2.01	4.25	1.77	2.25
Glycine	3.68	4.30	6.45	3.28	6.41	na	1.89
Serine	2.51	2.75	3.09	3.16	5.66	na	2.52

Detailed information on the specific amino acid profiles and other compositions of different meals derived from various by-products could not be obtained. However, if there is an assumption that the by-products from cultured freshwater fishes may be more akin to that of *Pangasius*, there could be some quality issues regarding the amino acid balance. Careful formulation with other protein sources may be required to provide efficient diets for pigs and other livestock, including a mix of plant protein sources together with seafood by-product meals (Nguyen 2010). Considering that the biggest opportunity for fishmeal production is in China and Asia (not including the Middle East and CIS countries), and that their seafood production is dominated by freshwater species, the quality of global fishmeal is likely to be much more diverse than that available on global markets at present. However, with good traceability and labelling, various fishmeals can be directed to the markets where their nutrient profiles are best suited.

Table 3.2 Amino acid profiles of key protein ingredients as a percentage of the ideal profile for growing pigs. Source ØBoisen *et al* 2008, others extrapolated from *FAO 1986 (Soybean solvent defatted), †Tuan 2010. ‡Hulan *et al* 1979.

	Meal type						
	Anchoveta[Ø]	Herring*	White fish*	*Pangasius*†	Squid‡	Shrimp head‡	Soybean*
Amino acid %							
Methionine	155	155	134	145	97	83	71
Lysine	108	105	96	113	50	36	87
Threonine	87	86	77	43	75	52	82
Isoleucine	107	102	84	42	42	91	109
Valine	92	94	77	58	58	58	85
Tryptophan	96	92	75	na	111	66	101
Histidine	76	75	63	70	26	45	76
Arginine	165	165	179	154	59	120	198

3.9 Projected fishmeal supplies to 2030

Production from capture fisheries, including for reduction into fishmeal, has been in stagnation or decline for at least a decade now and it is unlikely that there will be any growth in production in the future. New sources of marine ingredients such as from krill or boarfish, while proving promising in the short term have not reached levels that could make a considerable contribution to global supplies to date (Fishstat 2013). However, aquaculture continues to grow and could be a source of valuable fishmeal in the future. It is unlikely that aquaculture will grow at the rates witnessed in the 1980s and 1990s but steady growth of around 5% to 6% per annum over the short to medium term does not seem unattainable (figure 3.9).

It is unlikely that much of the projected growth in aquaculture production will come from carnivorous species as they are considered to be higher end luxury products. Also the available coastal sites for expansion are limited, off-shore aquaculture is still often regarded as higher risk in terms of investment (Bostock *et al* 2010) and the supplies of quality fishmeal and oils, high in omega-3 fatty acids, for aquafeeds may be restricted or difficult to attain in the short term. Instead much of the growth has come, and will probably continue to come, from vegetarian and omnivorous species with lower fishmeal requirements such as carps, tilapias and *Pangasius* catfish for example, most likely the majority being for domestic markets as discussed above (figure 3.10). However, the by-products from these species still offer the opportunity to provide fishmeal with good amino acid profiles with high digestibility for livestock feeds.

Though the experience from the industry is short, *Pangasius* meal in Vietnam is evidently a net contributor to global fishmeal supplies, albeit of different quality, and is indicative of the possibilities for other aquaculture industries. At a 4% fishmeal inclusion and FCR of 1.5, the requirements for a production of around 1 million tonnes of *Pangasius* catfish are 60,000 tonnes. This level of production could provide an estimated 650,000 tonnes of by-product, available for reduction into fishmeal from *Pangasius* given fillet yields reported in chapter 1. Interviews with *Pangasius* by-product processors in Vietnam suggested yields of around 20% each for both fishmeal and oil from the *Pangasius* by-product raw material, resulting in as much as 130,000 tonnes of each per annum. However, the raw data from the LCA work conducted at this site revealed only around a 10% yield of

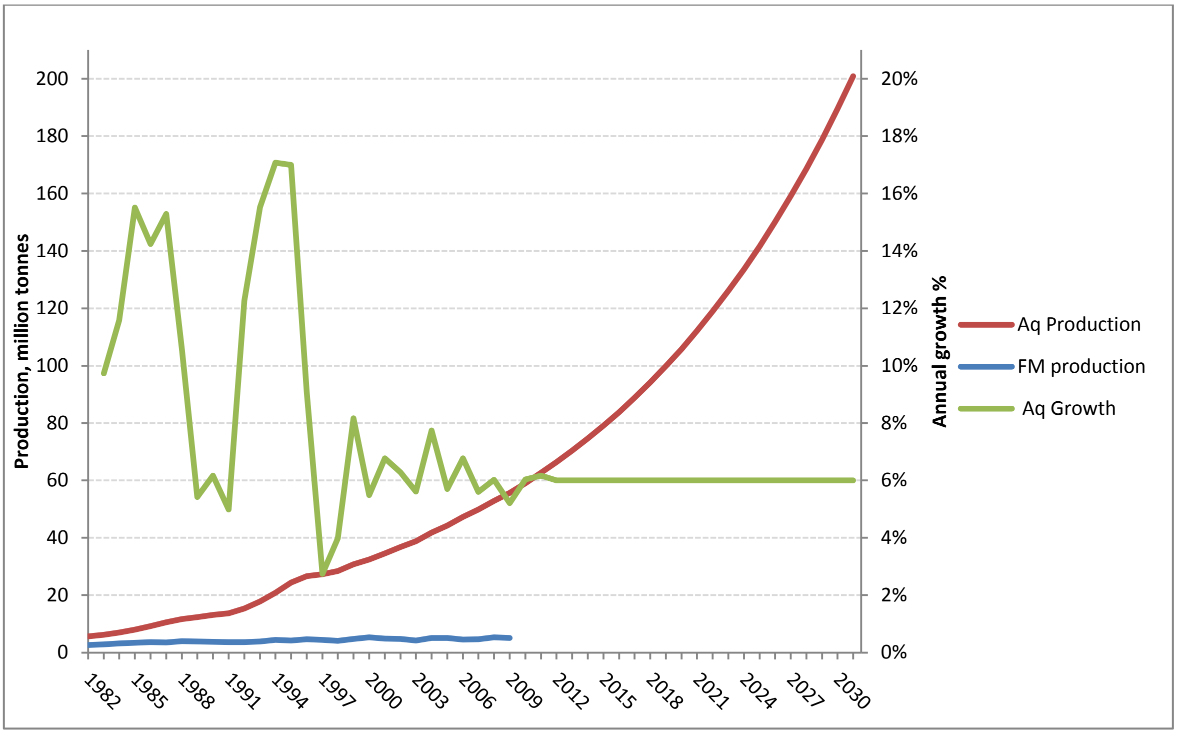


Figure 3.9 historical and projected aquaculture production and growth, 1982 to 2031, fishmeal production 1982 to 2009 (FAO Fishstat 2013).

fishmeal and the FAO Fishstat data (2013) reported Vietnam as producing only 56,300 tonnes in 2009, whereas the data presented in Table 1.1 give a possible yield of only 7.9% for fish oil (Polak-Juszczak 2007). However, this is not in keeping with generally accepted fishmeal yields of over 20%. There could be many reasons for the disparity such as poor data reporting or that not all of the by-product is fully utilised. The efficiencies of fishmeal production from *Pangasius* will be discussed in more detail in chapter 7.

Figure 3.10 shows a projection of fish production for major aquaculture species to 2031. These projections are largely arbitrary and based on lower growth rates than the five year average annual growth rate over the years 2007 to 2011. For example, the five year annual growth rate for *Pangasius* catfish was calculated at 20% per annum which is not probable up to 2031 given fluctuations in production from Vietnam in more recent years. The projected growth for *Pangasius* was therefore set at 7%, more in line with projected global production.

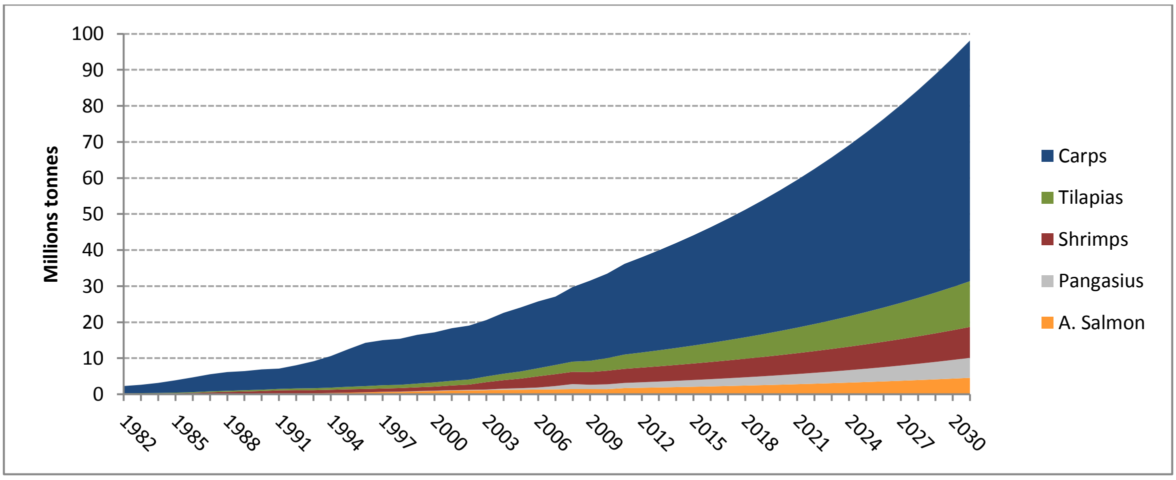


Figure 3.10 Projected growth of major aquaculture species based on 5 year annual growth rates adjusted to projected global growth rates for all species

These projections suggest around 98million tonnes of production from these species by 2031, providing a potential 48million tonnes of by-product mostly from carp production which could provide around 30million tonnes of by-product from 66 million tonnes of production. If all of this by-product could be directed to fishmeal production, with a 23% production yield, it could represent around 11 million tonnes. Given the current low level of processing of carp species it is unlikely that this will ever be achieved but even without the contribution from carps a substantial 4.1 million tonnes of fishmeal could be made from around 18 million tonnes of by-product from the other species shown above in figure 3.10. As these species are much more internationally trade oriented and therefore more highly processed, it is possible that at least some of this production could be achieved. However, the possibility of directing more carp to processed products is still of interest, especially as products such as surimi are becoming globally more popular (Jarfarpour and Gorczyca 2008).

As populations in developing countries become more urbanised and wealth increases, historically fish consumption has also increased per capita and demand for higher value products with it (Delgado *et al* 2003, Chiu *et al* 2013). The trend in urbanisation and fish consumption is likely to continue but how this affects the demand for processed fish products is debatable, as shown by ethnic Asian populations in the USA which still preferred to buy whole fish and consume much of what is often considered as by-products in developed nations (Sechena *et al* 1999). According to Chiu *et al* (2013) almost all carp and tilapia consumed in Shandong, Zhejiang and Hainan provinces in China were purchased as live fish, although there was a small trend towards buying processed tilapia. Hainan is a major area for international trade in seafood and processed tilapia was readily available, and therefore was a popular choice in urbanised areas because of convenience. There may be some small changes to consumer behaviour such as this but entrenched preferences for whole fish may not change substantially in the short to medium term. If change does occur, it may be driven by large companies which seek to maximise their profit through increased product differentiation but how rapid this change will be is open to debate.

3.10 Developing by-product utilisation and directing best utilisation practices

It is clear from this work that the utilisation of by-products from seafood and especially from aquaculture is increasing. From capture fisheries also, there is evidence of increased utilisation as the estimated share of global fishmeal production has gone from a few thousand tonnes at the beginning of the millennium, up to as much as 38% in 2011. In aquaculture, the utilisation strategies may continue to improve as the benefits of providing uniform, fresh product in geographically small areas are shown. It is likely that as the industry grows, develops and consolidates, the service industries will grow in unison in co-located areas, giving an advantage over capture industries which are more fragmented.

Challenges still exist in the capture industry in efficient handling of by-product. As fishing effort increases to achieve the same level of production, the storage of low value by-products (mainly guts and some heads) on fishing vessels becomes less attractive. Despite increased applications of by-products for fishmeal and hydrolysates, survey work for this thesis has shown that their value from aquaculture is still low and may become proportionately less as costs of production of whole fish rise. This is likely to remain the case for fishery by-products also. Although efforts have been made to limit discards, mainly of by-catch, whether this can be achieved for discards of on-board processing by-products is yet to be established. Their highly perishable nature necessitates considerable investment in cold storage which is currently uneconomic (Pérez-Gálvez 2009). Alternatively they could be ensiled as in the aquaculture industry but this still requires space, and the acids involved are also expensive and may constitute a health and safety hazard on board fishing vessels. Even if the problems of storage can be overcome, there will still be issues in the variation of the product over different seasons according to the species make up and their maturity. This variability will continue to make the use of fisheries by-product less attractive than that from aquaculture in many circumstances. However, as much of the fisheries by-product is of marine origin compared to aquaculture by-product, the possibility of providing more valuable omega-3 fatty acid supplies will remain more attractive. Ultimately, the provision of good quality, omega-3 rich by-products from the fisheries industry depends very much on the processing strategies for different species. Species such as tuna which are often sold canned in international markets have clear advantages over those species which are traditionally sold whole or processed to a lower level in local markets.

The attractiveness of supplying omega-3 rich by-product from marine capture fisheries may also be dependent on new developments in the Genetically Modified (GM) feed ingredients industry. Recently, technology is seeking to develop GM strains of oil-seed crops which may be able to supply long chain omega-3 fatty acids (Damude and Kinney

2007). However, the EU continues to ban the use of GM ingredients in food production unless specifically licensed (EC 2003) and as most of the omega-3 fatty acid market is taken up by salmon aquaculture, of which most is in the EEA, the demand for non GM supplies will remain high. If the EU were to open the door to GM utilisation this could also release other technological advances within the industry such as GM strains of salmon which grow faster and perhaps more efficiently than selectively bred strains (Fitzpatrick *et al* 2011). Resistance to this is likely to be very strong, however, amongst consumers and the strong recreational salmon fishermen's lobbies which actively resist salmon aquaculture in its current form (Conley 1998). The possibility of farmed salmon breeding with and thus diluting the genetic integrity of wild populations is of key concern but this may be mitigated if farmed salmon are sterile, through triploidy for example (Benfey 2001).

The situation regarding the pressure on supplying quality fishmeal to where it is most needed, is more complex than global supply and demand. It is also subject to more regional dynamics of supply and demand, and the logistics of global transportation. Fish feed manufacturers typically source their ingredients on best price formulations which are able to provide the performance which their customers demand (Naylor *et al* 2009).

Work carried out as part of the SEAT project, that contributed to the LCA sections of this thesis, identified that some tilapia feed formulations in Asia were using fishmeal inclusions as high as 15%. As herbivorous species, tilapias are not dependent on fishmeal, certainly in the grow-out stages. However, in China and Thailand where there are well developed fish processing industries, fishmeal may be readily available and competitive with other feed ingredients. As fish farmers appreciate the organoleptic properties of fishmeal and regard its inclusion as a good attractant with good performance, it is easy to see why feed companies in these countries may favour high fishmeal inclusion rates.

Table 3.3 shows in inclusion rates of fishmeal in aquafeeds for different species which were included as part of the SEAT LCA surveys. Much of the fishmeal production in Thailand was shown to have originated from tuna by-products. However, only one fishmeal producer was interviewed who claimed that their raw material was sourced

Table 3.3 Fishmeal and fish oil inclusion rates from different sources in Asian aquafeeds, collected as part of the SEAT project. No data were collected on Bangladeshi fishmeal and fish oil inclusions. *Ingredients were from same species, shrimp meal or basa oil. †All *Pangasius* feed were from the same company for different sized fish.

			Fishmeal inclusion, %		Fish oil inclusion, %	
Species	Country	Feed	Local	Imported	Local	Imported
Penaeid shrimp	Thailand	1	23.5	-	1.0	-
		2	29.1*	-	1.1	-
		3	20.0	-	-	-
	China	1	-	35.0	-	2.9
		2	-	25.0	-	-
	Vietnam	1	13.3	20.0	-	-
Tilapia spp.	Thailand	1	7.0	-	-	3.5
		2	10.9	-	1.0	-
		3	6.2	-	0.9	2.5
	China	1	-	15.0	-	-
		2	3.0	-	-	-
		3	2.5	2.5	1.5	1.5
Pangasius spp.†	Vietnam	1	4.0	-	-	-
		2	8.0	-	0.3*	-
		3	10.0	-	2.0*	-

100% from marine by-products. FAO data suggest ever increasing by-product utilisation in China and of the two fishmeal producers interviewed, 78% of the total raw material was from marine by-products with the rest sourced from freshwater species by-products, most likely tilapia. There may be some traceability concerns with this, as shown in table 3.3, there was evidence of a small amount of intra-species feeding in both shrimp and *Pangasius feeds*. Despite growing domestic fishmeal industries, China, Vietnam and Thailand are still importing large quantities of fishmeal. With better networking and logistics it may be possible to redirect fishmeal to where it is most needed, while maintaining performance. A change in consumer attitudes may be required in China and other Asian countries to allow for increased processing of seafood products. If this was to occur, China especially has the ability to become a net producer of fishmeal of varying qualities which could then be distributed to the various value chains where it is most required.

However, fishmeal supplies compete with other available protein sources such as soybean, for which the industry has been expanding and increasingly able to replace fishmeal in aquafeeds. The current relaxation of the EU regulations on monogastric PAPs may also lead to the adoption of this source of protein in the long term, if customer perception allows. Any sustainability concerns in food production have always been out-weighed by public health and safety concerns and while this continues, it is more likely that non-GM vegetable protein sources will be favoured over PAPs, GM ingredients and perhaps also fishery and aquaculture by-products. The now dis-credited study on the bio-accumulation of PCBs in farmed salmon (Hites *et al* 2004) severely damaged the industry in the ensuing months (Maynard *et al* 2008, Krause 2010) and this could also be a cause for concern with the use of fishery and aquaculture by-products.

Despite good opportunities for fishmeal manufacture, this may not always be the best use of the by-product, either from an economic or environmental stand-point. Other opportunities were highlighted in chapter 1, some of which will be assessed in following LCA chapters; 6, 7 and 8. Of particular interest may be hydrolysates from viscera, chitosan and collagen/gelatine extraction which all hold significant economic promise as well as certain direct and indirect environmental benefits.

The database tool presented in this chapter is a starting point in identifying new fishmeal supplies. Currently it has low level, basic information but more work is expected which will add further levels of detail, particularly on the different qualities of fishmeal that might be sourced, as well as substantiating some of the assumptions which have been included so far on processing quantities and by-product utilisation levels. It will also be expanded to include fish oil quantities and more specifically the quantities of EPA and DHA that may be under-utilised. This will enable IFFO members to formulate more strategic sourcing plans into the future.

CHAPTER 4: CAUSES AND DISPOSAL OF MORTALITY IN ASIAN AND EUROPEAN AQUACULTURE SYSTEMS

4.1 Introduction

Seafood production in developed nations has increasingly been unable to keep pace with consumer demand as wild fisheries have stagnated and local aquaculture production has not been able to address the shortfall. This has led to an ever increasing demand for imported seafood, particularly from Asia (Little *et al* 2012). As trade has driven growth in Asian aquaculture, the shrimp and *Pangasius* catfish sectors are increasingly being characterised by widespread consolidation from fewer, small, family run businesses to more, larger, vertically integrated value chains (Lam *et al* 2009, Little *et al* 2012). Some comparisons may be drawn with the salmon industry which went through widespread consolidation during the latter part of the 20th century into the 21st and is now dominated by a few large companies (Marine Harvest 2014). However, Asian production is still much more diverse and it may be many years before the same level of consolidation is seen. With the rapid growth in Asia, problems have arisen with disease, as they did in the salmon industry, sometimes resulting in large mortality events. In the developed world, many of these issues have largely been solved with vaccine development and improved health management plans, in the salmon industry for example. It is now unusual for large mortality events to occur in the European salmon industry, however, low levels of routine mortalities due to a range of factors do occur amounting to between 5 and 10% of individuals per annum over the entire industry (SEPA 2004; Statistics Norway 2009), which can still cause disposal problems. In the developing world, other newer industries such as the Vietnamese *Pangasius* industry, where effective vaccines have not yet been adopted, mortality can be as high as 30% of stocked individuals during the main grow-out stage and even higher at the nursery stage (Lam *et al* 2009), although production strategies are very different to those in Europe. Disease has been a continuous problem in *Penaeid* shrimp culture. Although good management techniques and testing of broodstock and seed can reduce the risk, disease can still cause significant losses. The most recent global aquaculture epizootic, EMS is causing substantial economic losses to the shrimp industries of SE Asia and the Americas (Coutteau and Gousans 2013).

Such large mortality events can cause a disposal problem to the producers in terms of logistics, cost and biosecurity risks (although in the case of EMS, the shrimp are very small and more easily disposed of). This is partly because of the production certification standards that export producers are often expected to adhere to in Asia. As the EU and US have become more reliant on imports from Asia to satisfy their fish consumption demands, a higher degree of food safety, environmental impact mitigation and other sustainability and ethical issues have been expected, as reflected in international certification schemes (GAA 2010, GobalGAP 2012, ASC 2012), described in chapter 2. Countries importing to Europe are also expected to adhere to the EU ABPR, as are Atlantic salmon producers operating in Scotland (European Commission 2002a; 2003; 2009). In EU countries these regulations and standards may limit more traditional approaches to mortality disposal or utilisation, which Asian farmers practice currently, or that European farmers may have used in the past, such as fermentation or feeding to livestock. The EU ABPR, in particularly have been regarded as excessive by some aquaculturists and a ‘knee-jerk’ reaction to the BSE crisis of the 1990s (SEPA 2004).

Scoping for the SEAT project revealed that in Asian production there is a wide range of aquaculture techniques, ranging from large and small scale extensive, horizontally integrated and polyculture to large intensive monoculture systems (Murray *et al* 2011), which are more familiar to Western countries. Scale and culture system are believed to be a major factor in the level and cause of mortality and are often related. Larger, corporate monoculture systems were hypothesised to have much more access to better facilities, quality seed, technology, water quality and disease diagnostics, for example and possibly have more highly trained staff compared to small family run businesses (Belton *et al* 2012, Murray *et al* 2011, Bush *et al* 2010).

Thai shrimp, Vietnamese catfish and white-leg shrimp (*Litopenaeus vannamei*) production systems included in this research were exclusively intensive monocultures and this approach also dominated Chinese shrimp production. However, other countries and species often use a wide range of more extensive systems and polycultures of different fish, shrimp and crustacean species. The project hypothesised that farm scale will have a major effect on the farmers’ abilities to respond to challenges that may affect their production performance and may dictate the market orientation strategies employed. More extensive systems are not necessarily dictated by scale in all countries as there are many large extensive farms, in Vietnamese shrimp production for example (Murray *et al* 2011). However, more extensive systems may be employed in an attempt to mitigate against challenges that the farmers may encounter and it was hypothesised that this strategy was employed mostly by small to medium scale farmers who may not be able to invest in higher levels of infrastructure to prevent against poor water quality and mitigate against disease problems. This hypothesis was based on observations by Bush *et al* (2010) who suggested that there were two competing scenarios in the development of shrimp aquaculture. The first being the more extensive approach where ecological services of the environment such as mangroves are maintained and a second where more intensive and advanced closed water recirculation systems are employed to maintain the integrity of the water supply against outside risk. In the first instance, where extensive systems are located in the intertidal zone, mangroves may serve as a biofilter, provide shade and shelter, and tidal flushing may serve to help maintain water quality. However, stable conditions may be more difficult to maintain and the influx of pathogenic organisms from the outside environment cannot be avoided (Bush *et al* 2010). Conversely, closed systems may be located away from the intertidal zone and rely on recirculating water with minimal water exchange and high aeration, often in lined ponds in order to maintain water quality. This enables a larger level of control and the risk of introducing outside pathogens is reduced (Bush *et al* 2010).

4.2 Data collection

4.2.1 Asian integrated farm survey design and enumeration

As part of the FP7 funded Sustaining Ethical Aquaculture Trade (SEAT) project (http://seatglobal.eu/), data on mortality were collected as part of an integrated survey, covering four major species groups from four countries that represent major imports into the EU. The integrated survey also included Life Cycle Assessment (LCA) data collection which formed the foundation on which LCA models for by-products for shrimp and *Pangasius* were built (Henriksson *et al* 2014a).

The aim of this section was to investigate mortality across the different systems and scales of production in Bangladesh, China, Thailand and Vietnam for four different export orientated commodity-species; giant freshwater prawn (*Machrobrachium spp.*), tilapia (*Oreochromis spp.*), shrimp (*Penaeid spp.*) and striped river catfish (*Pangasius spp.*). These species, from these countries, represent some of the most important imported seafood products to the EU over recent years and have often been highlighted for their sustainability concerns in a number of contexts (Little *et al* 2012, Cao *et al* 2011, Bush *et al* 2010, Murray *et al* 2011). Two of the major export oriented species for each country were included in the SEAT integrated survey as indicated in table 4.1 as the most important species of the original four in their relative importance as export commodities to the EU from each country. The different scales of production are described below. The scope of this section of the thesis includes the survival rate, the major mortality causes as perceived by the producer and the subsequent strategies of utilisation or disposal. Data on Scottish salmon mortality were also collected but separately, as it fell outside of the SEAT project and were not collected as part of the integrated survey.

Research was conducted in major aquaculture production areas considered representative of the four Asian study countries during winter (dry season) 2010 to 2011 and before the EMS epizootic hit the SE Asian shrimp industry (Akazawa 2013). This was based on a multi-phase, multi-stage sample design to define farm clusters which could be randomly selected from, as described by Murray *et al* (2011).

Table 4.1. Number of farms surveyed by country, species and scale for SEAT integrated survey.

		Number of farms surveyed		
Country	Species	Small	Medium	Large
Bangladesh	Penaeid Shrimp	58	83	31
	FW Prawn	80	80	0
	Shrimp/Prawn polyculture	40	40	0
China	Penaeid Shrimp	94	73	30
	Tilapia	106	78	26
Thailand	Penaeid Shrimp	130	60	16
	Tilapia	155	41	3
Vietnam	Penaeid Shrimp	135	55	10
	Pangasius	110	64	38

A series of indicators were developed that could describe scale more effectively than just the geographic size alone (Belton *et al* 2012). This was based on data collected during an initial two month scoping period, conducted before more detailed data collection began, using key informant interviews and piloted surveys, and included factors such as number and size of ponds and stocking density for example. The criteria for scale allocation for Vietnam that were developed during the scoping phase can be seen in table 4.2 and the geographical scope of the integrated survey from which the sample clusters for randomised farm selection was made can be seen in table 4.3. For all species in all countries, fewer large scale farms than small or medium were interviewed, with only three large scale tilapia farms interviewed in Thailand and no large scale prawn farms in Bangladesh (table 4.1).

Table 4.2. Example of farm scale criteria as used in Vietnam for catfish, shrimp and prawn pond, and tilapia cage systems (Murray *et al* 2011).

Criteria	Catfish			Shrimp/Prawn			Tilapia		
	S	M	L	S	M	L	S	M	L
Farm size ha	<2	2-5	>5	<1.5	1.5-4	>4	<300	300-500	>500
Pond/cage size ha/m^2	=<1.5	1.5-3.5	3.50	<1.1	1.1-3.0	>3.0	<301	300-501	>501
No.of pond/cage	1-3	4-8	>8	1-2	3-8	>8	<3	3-6	>6
Water storage	No	Yes	Yes	No	No	Yes	No	No	Yes
Reservoir/ sediment ponds?	No	Yes	Yes	No	Yes	Yes	na	na	na
Supply/draining canal system?	No	Yes	Yes	No	Yes	Yes	na	na	na
Stocking density individuals/m^2	25-35	30-50	30-50	<10	10-20	>20	<100	100-120	100-120
FCR ration	1.65	1.65	1.65	<1.2	1.2-1.5	>1.5	1.55	1.55	1.55
Production yield, tonnes/ha	<300	300-500	>500	<0.5	0.5-2.0	>2.0	<80	80-100	>90
Hired technicians	No	Yes	Yes	No	No	Yes	No	No	Yes
Type of model, individual/contract	I	I	C	I	I	I/C	I	I	I/C
Biosecurity?	Yes	Yes	Yes	No	No	Yes	na	na	na

The sample framework was also designed to include all of the major systems as identified during the scoping phase of the project based on a randomised probability based design, with an ultimate goal to remove bias in the overall site selection. A full description of the sample framework design can be seen in SEAT deliverable 2.8 (Murray *et al* 2011). The characteristics of the different systems which were encountered and included within the surveys are given in table 4.4. They were predominantly characterised by their stocking densities which determined their intensification, however, there were many other diverse characteristics between the systems within species groups and between countries.

Table 4.3 Geographical scope of SEAT integrated survey (Murray *et al* 2011)

Country	Species	Province	District	Location
Bangladesh	Shrimp	Khulna	Satkhira	SW coast
	Prawn		Khulna	
	Shrimp &Prawn		Bagherat	
	Shrimp	Chittagong	Cox's Bazaar	SE Coast
Thailand	Shrimp	Chachoengsao		SE Central Coast
		Chantaburi		
		Surat Thani		SW Coast
	Tilapia	Samut Sakhan		S Central Coast
		Samut Prakhan		
		Pechburi		
Vietnam	Shrimp	Soc Trung		SE Coast
		Bac Lieu		
		Cau Mau		
	Catfish	An Giang		Upper and lower Mekong
		Dong Thap		
		Can Tho		
		Vinh Long		
		Soc Trung		
China	Shrimp	Guangdong	Zhanjiang	SW peninsular
	Tilapia	Guangdong	Maoming	
		Hainan	Wenchang	SW Island

Table 4.4. Description of studied Asian production systems characteristics from survey data.

Species	**System**	**Country**	**Stocking density, number per m^2**	**Other characteristics**
Shrimp (*L. vannemei and P. monodon*) and fresh-water prawn (*Macrobrachium rosenbergii*)*	Intensive monoculture	Thailand, Vietnam, China	>25	Aerated ponds, often lined with plastic. "High-level" systems in China
	Improved extensive	Vietnam, Bangladesh*	<10	
	Semi-intensive polyculture	China	15-30	Low input, integrated with fish, crustaceans and livestock
	Semi-intensive monoculture	Vietnam, China	10-40	
	Rice-shrimp alternate	Vietnam	<10	Low input land used alternately for rice/shrimp
	Mixed mangrove	Vietnam	<10	Extensive with areas of mangrove incorporated into ponds
Tilapia (*Oreochromis niloticus, Oreochromis mossambicus* x *Oreochromis niloticus*)	Intensive monoculture	Thailand	25 – 100	Typically cage systems with some ponds
	Intensive polyculture	China	2 – 53	Typically mixed with carps in large ponds
	Semi-intensive monoculture	Thailand	<10	Typically pond systems
	Semi-intensive polyculture	Thailand, China	<10	Pond systems mixed with carps and other species
Catfish (*Pangasius hypophthalmus*)	Intensive monoculture	Vietnam	20 – 100	Ponds up to 4m deep

*Prawn farms were extensive systems with very low stocking densities, in Bangladesh only.

Data were collected by staff of the partner universities in each country (Kasetsart University, Thailand; Can Tho University, Vietnam; Shanghai Ocean College, China;

Bangladesh Agricultural University, Bangladesh) under the supervision of representatives from different work packages within the SEAT project to maintain consistency and data quality. A structured survey technique was used that included questions from all work packages included in the SEAT project and which could be applied to all species in all countries. The survey took around 1.5 to 2 hours to complete, of which questions on mortality took around 10 to 15 minutes to answer. Farmers were asked an open question to cite and rank the main causes of mortality in their farms for their primary production species. A further question was then asked on the disposal routes which they used for their mortalities and the cost of disposal or any income they received from their sale. They were also asked to give the estimated percentage survival to harvest. For the presence of disease, it was assumed *a priori* that many farmers' diagnostic capacity may be quite limited, therefore farmers were not asked to name diseases which they had encountered. Farmers were also asked questions regarding their disease diagnostic capacity, water management, feed supplies and other factors that may be related to mortality and their production performance in other sections of the integrated survey.

4.2.2 Data collection from Scottish Atlantic salmon farms

In Scotland, Atlantic salmon grow out systems are universally net pen monoculture situated on the west coast mainland, Orkney Islands, Shetland Islands and Outer Hebrides. Data were collected from six farms belonging to a major Atlantic salmon producer as part of wider data collected for the LCA section of this thesis. This data were also collected using a structured survey. Farm sites were selected by the company but representatives were asked to provide data from farms which were demonstrative of their company's production. The data totalled over 4 million stocked individuals from the six farms which had a total harvest weight of over 8 thousand tonnes, representing around 5% of total Scottish production. All farms had vaccination programmes against major notifiable diseases and treated against sea-lice using in-feed medication. Detailed records of the number, biomass and cause of dead fish were provided from the farms' computerised management systems in contrast to the perceived causes and ranks estimated by Asian farmers from their recollection. A question concerning the disposal method was also asked of each farm, to cite the disposal method, distance travelled and any chemicals used.

4.3 Data analysis

Data from the integrated survey of Asian farms were assessed and cleaned using Microsoft ACCESS and Excel, and statistically analysed using Minitab 16, as follows. Raw mortality cause data were first aggregated into nine causes as shown in table 4.5 Ranks were adjusted and split accordingly. For example, floods and drought were aggregated into one category of "extreme weather". While some of these responses could be put into several categories and some categories may not be mutually exclusive in determining the mortality cause, these were deemed the best for determining the best disposal options. For example, animals which have been exposed to disease or parasites which may be a biosecurity risk as opposed to those which are unsold harvest or have been culled may have further utilisation options available. Stress was cited in a few cases but could not be re-categorised as there are many possible stressors and it is not possible to determine what the cause of stress was. “Don’t know” and “Unwilling to answer” were re-categorised as blank responses.

Statistics were performed on arcsin transformed survival percentages against scale and system for each species in each country using a pairwise Analysis of Variance (ANOVA) comparison model. Data on the perceived causes were statistically analysed using binary logistic regression for the citation of each cause only. Data on selected farmers’ production practices were also analysed against their transformed survival data using ANOVA. These were identified for species where systems or scales had significantly different survival from each other, e.g. Vietnamese shrimp systems.

Table 4.5 Mortality cause category aggregation in Asian production systems

Mortality cause category	Responses included
Disease	Disease, parasites, disease carrier (birds, crabs)
Water quality	Water quality, soil quality (in pond), environmental
Extreme weather	Extreme weather, drought, flood
Seed quality	Seed quality
Unsold	Unsold harvest, cull
Feed quality	Feed quality, lack of minerals
Predation/escape	Predation, escape, cannibalism, poaching
Management	Poor management, stocking density, too much feed
Stress	Stress

The data from Scottish salmon farms from the computerised management system were treated separately because of the different format in which they were presented. However, data were also aggregated into categories, including seal and other predator causes being pooled, and different physical damage causes also being pooled.

4.4 Mortality in Asian aquaculture systems

4.4.1 Survival

Variance was very high within the survival data within the different scales and production systems. This may be an indication of the level of record keeping that farmers practice and their ability to recall and assess their various inputs and yields. Table 4.6 shows how many farms kept written records of mortality. Mortality record keeping was generally better in larger farms although Bangladeshi farms had no written records and for China it was also very poor, in shrimp farms especially, across all scales.

Despite poor record keeping, considering the size of the data set, some conclusions can be drawn. Scale was only a significant factor for survival rates (Figure 4.1, table 4.7) of shrimp in Bangladesh, where larger farms suffered higher mortality compared to medium farms ($p = 0.004$) but not smaller ($p = 0.0595$).

Table 4.6 Percentage of farms keeping written records of mortality for each species by country and scale.

Species	Country	Scale	Written records %
Penaeid shrimp	Bangladesh	Small	0
		Medium	0
		Large	0
	China	Small	2.1
		Medium	4.1
		Large	16.7
	Thailand	Small	21.5
		Medium	30.0
		Large	93.8
	Vietnam	Small	23.0
		Medium	41.8
		Large	100.0
Tilapia spp.	China	Small	6.6
		Medium	15.4
		Large	53.8
	Thailand	Small	21.9
		Medium	9.8
		Large	66.7
Pangasius catfish	Vietnam	Small	53.6
		Medium	62.5
		Large	92.1
FW Prawn	Bangladesh	Small	0
		Medium	0

Survival in shrimp systems was highly variable but generally above 50% on average, for all countries except Bangladesh. A description of the different systems can be seen in table 4.4. Higher mortality in Bangladesh may be because it is dominated by extensive systems, but also because it cultured *P. monodon* exclusively. Extensive culture of *P. monodon* also

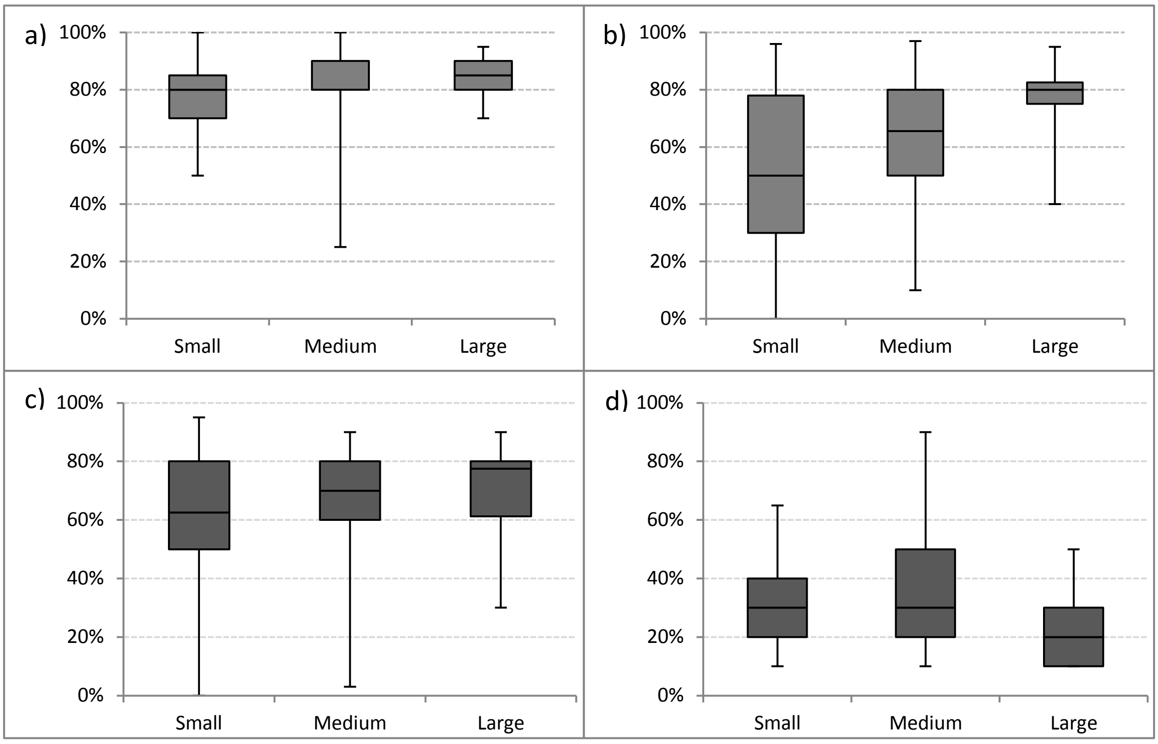


Figure 4.1. Shrimp survival rates (%) in 4 Asian study areas by scale; a) Thailand, b) Vietnam, c) China, d) Bangladesh. Error bars indicate maximum and minimum values.

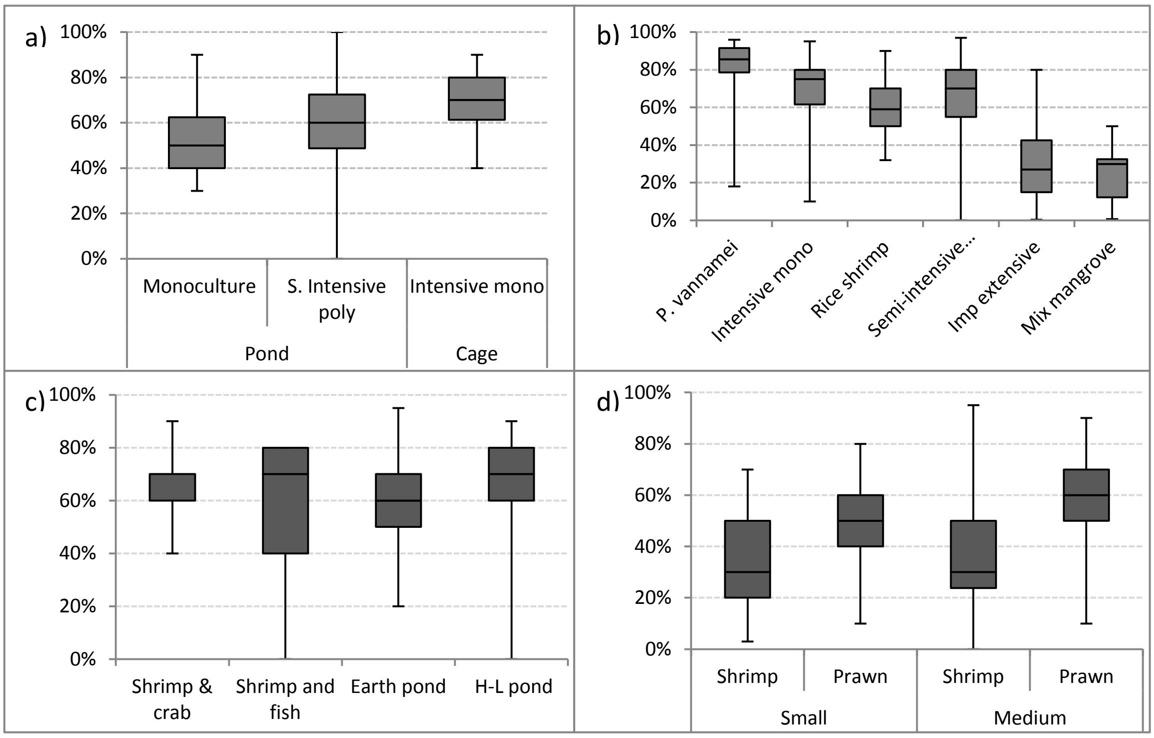


Figure 4.2. Survival in different production systems for selected species in different countries (%); a) Thailand tilapia, b) Vietnam shrimp, c) China shrimp, d) Bangladesh shrimp/prawn polyculture by scale. Chinese shrimp earth pond and H-L (high level) pond systems were both *L. vannamei* monoculture. Error bars indicate maximum and minimum values.

showed significantly lower survival than more intensive systems in Vietnam (Figure 4.2, table 4.7). Here system was highly significant (p = <0.001), with mixed mangrove and improved extensive shrimp systems showing significantly higher mortality than other systems and intensive *L. vannamei* culture showing significantly better survival than *P. monodon* in all systems except intensive monoculture. Although it appears from figure 4.1b that smaller shrimp farms suffer higher mortality than other scales in Vietnam, this is an interaction effect as all large farms were intensive monoculture, whereas mixed mangrove and improved extensive farms were only at the small scale level. All but one *L. vannamei* farm was small scale, explaining the large variance in survival for small scale farms in Vietnam. Vietnam is the only country where the survival rates of *P. monodon* and *L. vannamei* can be directly compared or monocultures in extensive versus intensive systems. The extensive systems in Vietnam showed survival rates similar to those in Bangladesh, with medians around 30%, whereas *L. vannamei* farms in Vietnam were similar to monocultures in Thailand, albeit with larger variance.

All high-level pond culture in China was monoculture of *L. vannamei*, whereas earth pond culture was a mixture of *L. vannamei* monoculture and polycultures of either fish or crabs with *L. vannamei* or both *L. vannamei* and *P. monodon*. For shrimp and prawn polycultures in Bangladesh, there were only improved extensive concurrent systems. In China, “high-level” pond systems had better survival than earth pond systems (Figure 4.2c). In Bangladesh, there was no significant difference between small and medium scales of production, but there was a significant difference in survival between the two species within the systems (figure 4.2d). However, there was no significant difference between shrimp or prawn survival in monocultures compared to shrimp and prawn polycultures (table 4.7).

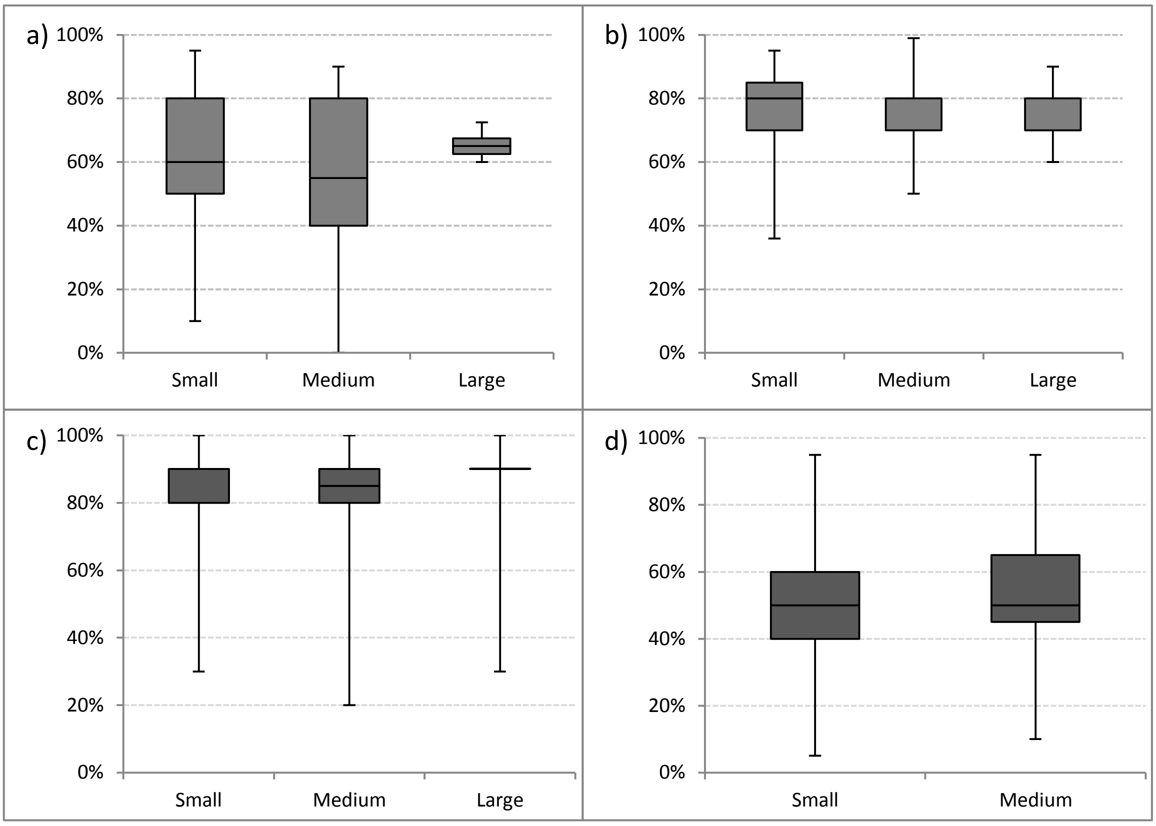


Figure 4.3. Survival rates of secondary species (%) in 4 Asian study areas by scale; a) Thailand tilapia, b) Vietnam catfish, c) China tilapia, d) Bangladesh giant freshwater prawn. Error bars indicate maximum and minimum values. Error bars indicate maximum and minimum values

Bangladesh was the only country where scale was a significant factor and here medium scale prawn farms demonstrated better survival than small farms (p = 0.032), (figure 4.3, table 4.7). However, considering the lack of written records, it is difficult to draw too many conclusions regarding the differences in mortality between the different scales. For other species, system was also significant.

In Thailand, tilapia survival was better in cage based systems than ponds (p = 0.001) but there was no significant difference between monoculture and polyculture in earth pond systems (figure 4.2, table 4.7).

Table 4.7 Statistical analysis of survival to harvest using pairwise ANOVA comparisons between different scales and systems for different species in 4 SEAT study countries.

Species	Country	Parameter	P value
Shrimp (*L. vannamei and P. monodon*)	Thailand	Scale	0.351
	Vietnam	Scale	0.266
		Species[*]	0.013
		System	<0.001
	China	Scale	0.350
		Species[†]	0.373
		System[‡]	0.010
	Bangladesh	Scale	0.006
		System	0.142
		Polyculture	0.083
Tilapia (*Oreochromis niloticus and Oreochromis mossambicus x Oreochromis niloticus*)	Thailand	Scale	0.947
		System	0.902
		Containment[ø]	0.001
		Sub-species	0.766
	China	Scale	0.858
		System[‡]	0.334
		Containment[ø]	0.279
Catfish (*Pangasius hypophthalmus*)	Vietnam	Scale	0.975
Giant river prawn (*Macrobrachium rosenbergii*)	Bangladesh	Scale	0.032
		System[‡]	0.699

*Vietnam shrimp species is *P. monodon* vs. *L. vannamei*. †China Species is the primary species, i.e. includes comparisons of shrimp monoculture vs. polycultures of shrimp + crab etc. øChina containment is pond vs reservoir. Thailand containment is pond vs cage. ‡China system for shrimp is high-level pond vs earth pond and for tilapia is level of intensity and integration with livestock. Bangladesh system is prawn or shrimp only vs. those species included in a shrimp/prawn polyculture.

4.4.2 Farmer perception of mortality cause

For *Penaeid* shrimp, disease was cited as the highest cause of mortality in all countries, although its relative importance to other causes was different between them (Figure 4.4). In all countries, water quality, extreme weather and poor seed quality were ranked as next most important causes of mortality after disease, apart from in Bangladesh where predation was fourth most important. In Vietnam and Bangladesh, disease was significantly more important than all other causes ($p = <0.0001$), whereas in Thailand and China, disease was significantly more important than all other causes except water quality and extreme weather ($p = <0.0001$). In all countries seed quality was cited fewer times by larger farms compared to the others, but mostly by more extensive systems in Vietnam. Disease was cited less by *L. vannamei* farms in Vietnam, which cited feed and water quality more than the other systems. However, the low response makes the results somewhat unreliable, with only five *L. vannamei* farms giving an answer to the question. Statistical analysis could not be performed on ranked data using Friedman's test because of the number of blank responses for many categories. Instead, binary logistic regression tests were performed on citation of each cause against the independent variable. However, pairwise comparisons were not possible using this method. Disease and water quality were significantly different between Vietnamese shrimp systems ($p = 0.008$ and 0.004 respectively). In China water quality and extreme weather were significantly different between systems ($p = 0.009$ and <0.001 respectively) whereas seed quality was significantly different between scales in Bangladesh ($p = <0.001$). No other parameters were significantly different between systems or scales in any country for *Penaeid* shrimp where survival was also significant according to table 4.7.

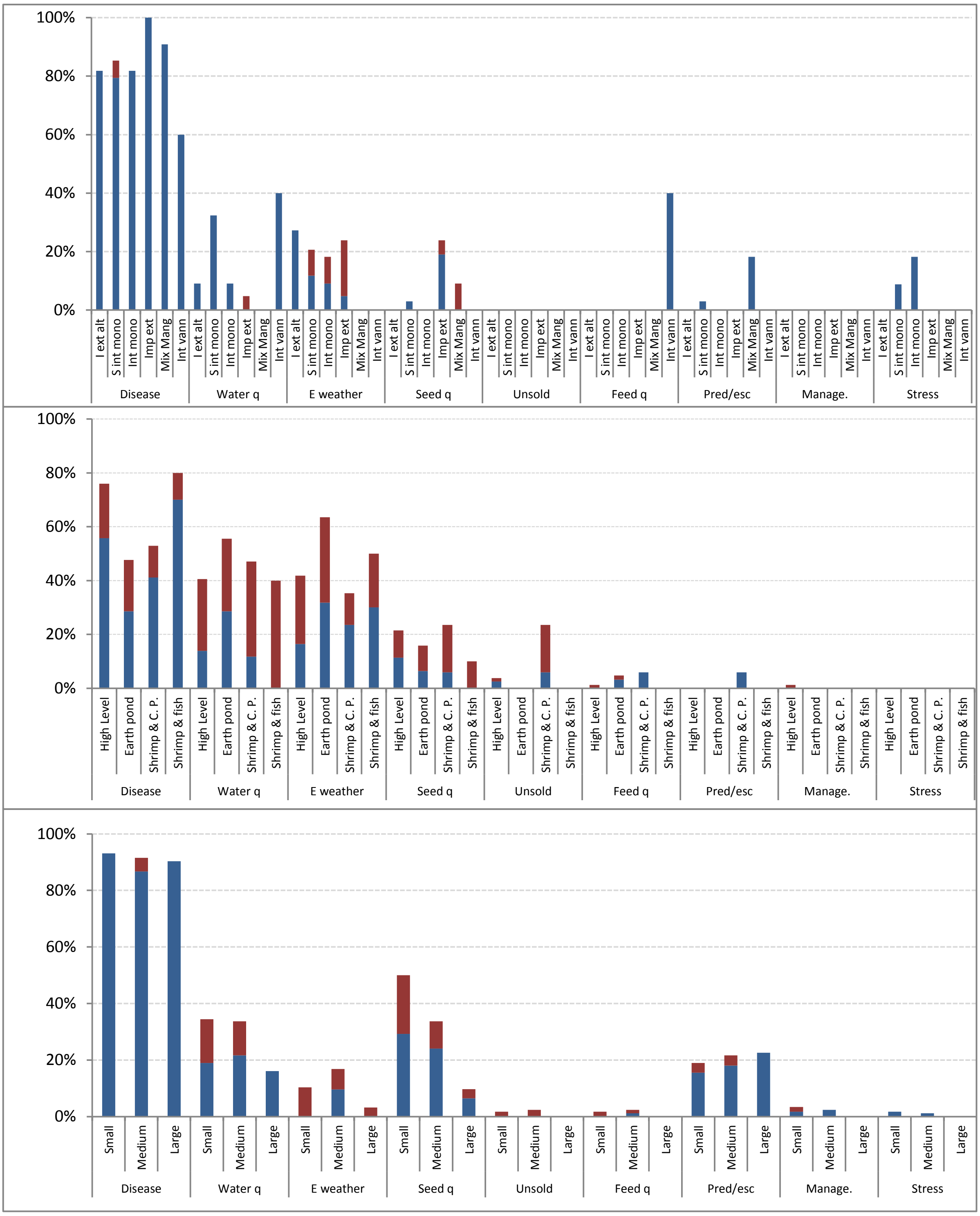


Figure 4.4 Ranked causes of mortality in selected Asian shrimp aquaculture systems/scales, where system or scale was a significant factor for survival, percentage of farmers in a) Vietnam, b) China, c) Bangladesh. Blue equals ranked 1 or 2, red equals ranked 3 or lower. I ext alt = Improved extensive alternate, S Int mono = semi intensive monoculture, Imp ext = Improved extensive, Mix mang = mixed mangrove, Int vann = intensive vannamei monoculture, Shrimp & C P = Shrimp and crab polyculture, q = quality, E = extreme, Pred/esc = predation/escape, Manage= poor management.

Although disease is clearly the most important cause of mortality in shrimp farms, this can be linked to other parameters, including water quality, extreme weather and seed quality (Ferreira *et al* 2011, Bush *et al* 2010, Racotta *et al* 2003); the next most important causes of mortality. Asian shrimp producers have battled against a number of particularly costly disease problems for decades, including white spot syndrome (WSV), yellow head virus (YHV) and Infectious Hypodermal and Haematopoietic Necrosis (IHHN) amongst others. Most recently EMS has caused widespread mortality across SE Asian production systems. In many cases, disease and water quality are linked, where deteriorating water quality may trigger the manifestation of a disease event, although the pathogen had been present beforehand without any harmful effects. Recently it has been suggested that pH may be the main determining factor in the manifestation of EMS (Akazawa 2013). Farmers have suspected links between water quality and other diseases too (Ferreira *et al* 2011, Bush *et al* 2010) and have often used chemical applications to control the pH and to avoid the build-up of ammonia. This has sometimes included biocides to reduce phytoplankton levels (Funge-Smith 1996).

Crustaceans lack a developed immune memory and therefore effective long-term vaccination programmes are not possible to the same degree as in vertebrates (Arala-Chaves and Sequiera 2000). Instead farmers rely on a diverse range of management practices to try to prevent against disease outbreaks where possible and manage their risk in terms of economic investment and return (Bush *et al* 2010). In Thailand a major move from the production of black tiger prawn *(P. monodon)* to white-leg shrimp *(L. vannemei)* occurred during the early part of the century and has almost 100% uptake. This was for several reasons, but includes a wider range of tolerances to temperature and water quality, and they are easier to rear at higher stocking densities, with higher survival rates than *P. monodon* (FAO 2004). In China *L. vannemei* is the dominant species with some *P. monodon*, whereas in Vietnam, *L. vannemei* represents only around 40% of production (VIFE 2009) and in Bangladesh, *P. monodon* dominates. Vietnamese data suggests that *P. monodon* may be more susceptible to mortality than *L. vannamei* and is supported by the statistics, although no extensive *L. vannamei* farms were surveyed and it was the more extensive *P. monodon* farms which suffered the higher mortality rates. Ideally, some surveys of more extensive systems that cultured *L. vannamei* could confirm this. *P. monodon* is a much higher value species than *L. vannamei* due to its larger size and demand, and therefore the risk associated with *P. monodon* can be justified, if mortality levels can be managed.

It was hypothesised that farmers have often used more extensive systems to try to mitigate against the prevalence of disease, especially in Bangladesh, and in Vietnam where a number of unique production systems exist such as the mixed mangrove approach. However, the hypothesis that mortality can be mitigated by using more extensive systems is rejected in this study as in Vietnam the more extensive systems suffered much higher mortality than intensive systems and in Bangladesh, which is dominated by extensive systems, compared to other countries. Disease was still regarded as the main cause of mortality in Vietnam and Bangladesh employing both improved extensive and mixed mangrove techniques, cited by over 90% of farmers.

The use of more extensive systems is a choice that is concerned with levels of investment and the perceived risk attached to it. It is extremely difficult to exclude all pathogenic organisms, even in closed systems and in open systems, pathogens may be carried between water courses by copepods and insect larvae, for example. Therefore the huge investment in closed systems may not be perceived as worthwhile to smaller scale farmers if it does not provide total confidence that there will be enough benefit. The investment required for extensive systems is comparatively much lower than closed systems and farmers may extend their farms into the surrounding uninfected areas as the initial areas become degraded by poor sediment and water quality (Bush *et al* 2010). However, this may lead to increasing levels of pathogens in wild crustacea and other disease carrying organisms in the wider area as water is exchanged. The higher prevalence of disease in these systems has often led to increasing use of antibiotics as microbial tolerance to their effects increases. This may then exclude those farms from more lucrative international markets which prohibit these substances. Therefore, in many cases, the surrounding environment becomes ever more degraded and extensive farmers fight a losing battle as they attempt to mitigate against losses caused by more disease and deteriorating water quality, which is ultimately unsustainable. Larger scale farmers can risk the higher investment costs of closed systems to achieve better rewards through higher production and access to these markets because they are better able to absorb the higher risk of initial failure (Bush *et al* 2010).

In most cases, there is clearly little link between scale of farms and the level of mortality which is suffered. Only in Bangladesh was scale a factor for both shrimp and freshwater prawn farms. In large Vietnamese shrimp farms, it was common that managers would be employed to look after one pond each and in effect the system may have been more akin to many co-located small farms with a range of management skills. However, it is usual that other step-wise costs could be reduced in large farms making better infrastructure and access to better quality seed more possible. This was true up to a point. For example in Thailand and China, large farms tended to employ pond lining more than small, however, in China, almost all large scale farms were high-level pond systems compared to only a few small scale. All high-level farms employed lining materials, apart from one, including the small scale farms, but it was the system which was significant rather than the scale. Use of lined ponds increased with increasing scale in Thailand, with 91.5% of small scale farmers having no lining material compared to only 43.8% of large scale. Sediment layers become increasingly anoxic and their build up in ponds can be a reservoir for pathogens and toxic substances contributing to poor water quality (Bush *et al* 2010). The use of lined ponds reduces erosion and enables the better management of sediments within the pond allowing the sediment to be easily pumped out, to improve water quality where there is little or no water exchange (Funge-Smith 1996). However, it was found that pond lining was not a significant factor in determining mortality in shrimp systems in either Thailand (p= 0.303) or in China (p = 0.258).

In Vietnam, it was evident that it was the production system that most affected the level of mortality rather than the scale, as it had the most diverse range of systems compared to other countries. The highest levels of mortality were reported by extensive and mixed mangrove farmers. It could be that water quality was poorer in these farms which could trigger disease events. They typically practiced more water exchange, but few farms of any system type in Vietnam had any form of pond lining. In Thailand, intensive monoculture of *L. vannamei* dominates across all scales but it was shown that the scale was not a significant factor in determining mortality. Here, producers have been employing more sophisticated techniques against the prevention of disease. These include fully lined ponds and a move towards more closed systems with increased water reuse (Bush *et al* 2010).

In the past, in many areas, the close location of farms which use the same water supply and discharge effluent into the same canal without any planning was common and could result in increased disease transfer as discussed above. Over 20% of Thai shrimp farms, including all scales, reported full recirculation of their water supply and less than 25% reported no recirculation at all, but most still had some partial water exchange. In Vietnam, intensive farms did not exchange as much water compared to the extensive and mixed mangrove systems, with no *L. vannamei* and 21% of intensive *P. monodon* farms practicing water exchange, compared to 83% of mixed mangrove and 73% of improved extensive farms that partially exchanged water. This may have been a factor in the higher mortality rates in these systems and was confirmed by ANOVA of water exchange practice vs. arcsin transformed survival % ($p = 0.0346$). Farms which practiced topping up water only, rather than exchange or partial replacement, tended to have better survival. However, the cause and effect is not proven, as farms may have been replacing water in an attempt to improve poor water quality, rather than the exchange of water being responsible for the mortality directly. Clearly though, there are some water quality issues which have affected survival rates which are more of an issue in more extensive systems. There could be many reasons for this for which data are not available. All water was sourced from local rivers and streams but there were no data collected on surrounding industries and land use, therefore it is not possible to ascertain what influence this may have had. No significant difference could be found between different water exchange practices and survival for shrimp in any other country.

Seed quality has long been associated with subsequent performance in shrimp grow-out systems. There are several factors which can influence seed quality, including the rearing conditions of the post larvae and the health status of the broodstock from which they come, and this may influence their ability to counter the presence of pathogens as well as other stresses in their environment (Racotta *et al* 2003). During the latter part of the last century, shrimp production stagnated due to increased mortality from disease, despite increasing culture area and this led to increasing use of specific pathogen-free (SPF) seed. The production of SPF seed involves the breeding of broodstock strains of known origin in bio-secure facilities, solely for the provision of disease free seed (Lotz 1997). However, adoption of SPF seed is not 100% and according to the collected data for this project, some farmers still rely on the provision of wild sourced seed that has unknown disease status.

There was little difference in seed source between systems or scales in most instances across the farms which were surveyed. All farmers in Thailand used commercial broodstock and from domesticated stock where known. In China only a small proportion used wild seed from traders, with the majority using commercial, domesticated sources. There were some hatcheries which used “exotic” (most likely SPF) broodstock, but there was no difference between the various grow-out systems in which source was used. In Bangladesh, there was also some seed sourced from wild broodstock but there was no difference between the different scales as to where seed was sourced. The main difference was in Vietnam where intensive farms and particularly *L. vannamei*, sourced their broodstock differently from other systems. *L. vannamei* seed was exclusively from domesticated commercial broodstock, whereas all others, except for a small proportion of those in intensive and semi intensive *P. monodon* farms, were from unknown or wild origin. However, there was no significant difference in survival between the different seed sources.

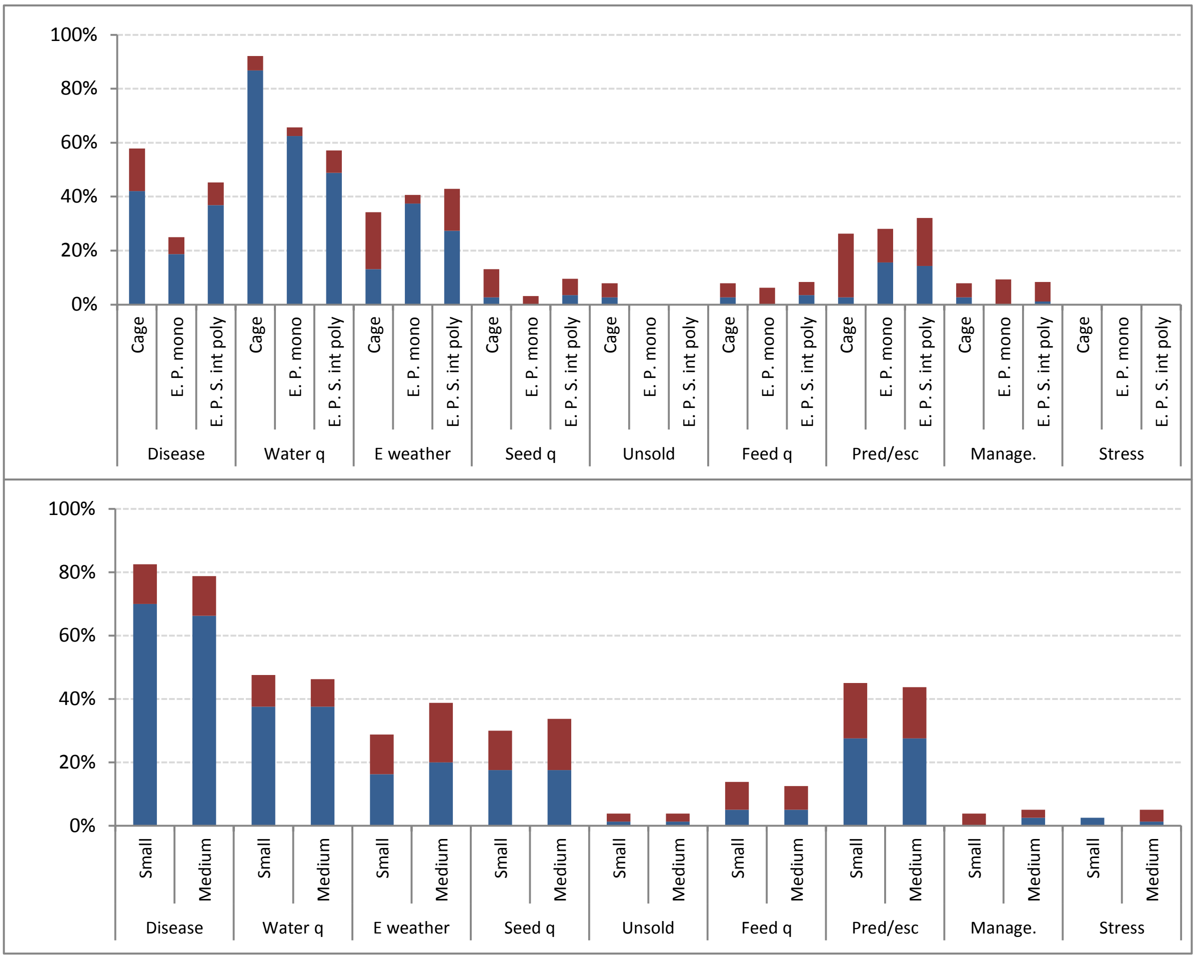


Figure 4.5 Ranked causes of mortality in selected Asian aquaculture systems/scales, where system or scale was a significant factor for survival, percentage of farmers in a) Thailand tilapia, b) Bangladesh FW prawn. Blue equals ranked 1 or 2, red equals ranked 3 or lower. E. P. mono = Earth pond monoculture, E. P. S. Int poly = Earth pond semi intensive polyculture, q = quality, E = extreme, Pred/esc = predation/escape, Manage = poor management.

In Thai tilapia, where the system was a significant factor in survival, disease was not considered solely the most important cause of mortality with Thai farmers citing water quality at least as important (figure 4.5a). Water quality was cited significantly more times than any other cause except disease ($p = 0.0645$), which was in turn cited significantly more times than all the others except extreme weather and predation/escape. Binary logistic regression of mortality causes showed water quality and disease to be significantly different between the systems ($p = <0.0001$ and 0.003 respectively), but no other mortality cause.

In Bangladesh, disease was cited as the most common cause of mortality ($p = <0.0001$) in fresh water prawn production (figure 4.5b). Analysis with binary logistic regression showed only citations of seed quality was significant between production scales ($p = <0.0001$). Predation/escape was also cited more frequently in Bangladesh for both prawn and shrimp than in other countries.

In other systems and scales, where survival was not a significant factor, disease, water quality and extreme weather were still cited as the most common cause of mortality (figure 4.6). In Chinese tilapia systems, disease was significantly more important than all other causes except extreme weather, which was significantly more important than all other causes except water quality. These two causes were cited significantly more times by both scale and system. Vietnamese catfish farmers still regarded disease and water quality as the most important causes of mortality ($p = <0.0001$), although feed quality was considered relatively more important than for other species and significantly higher than other causes, not already mentioned, except for extreme weather ($p = < 0.020$). For Thai shrimp, disease was significantly more important than all other causes except for

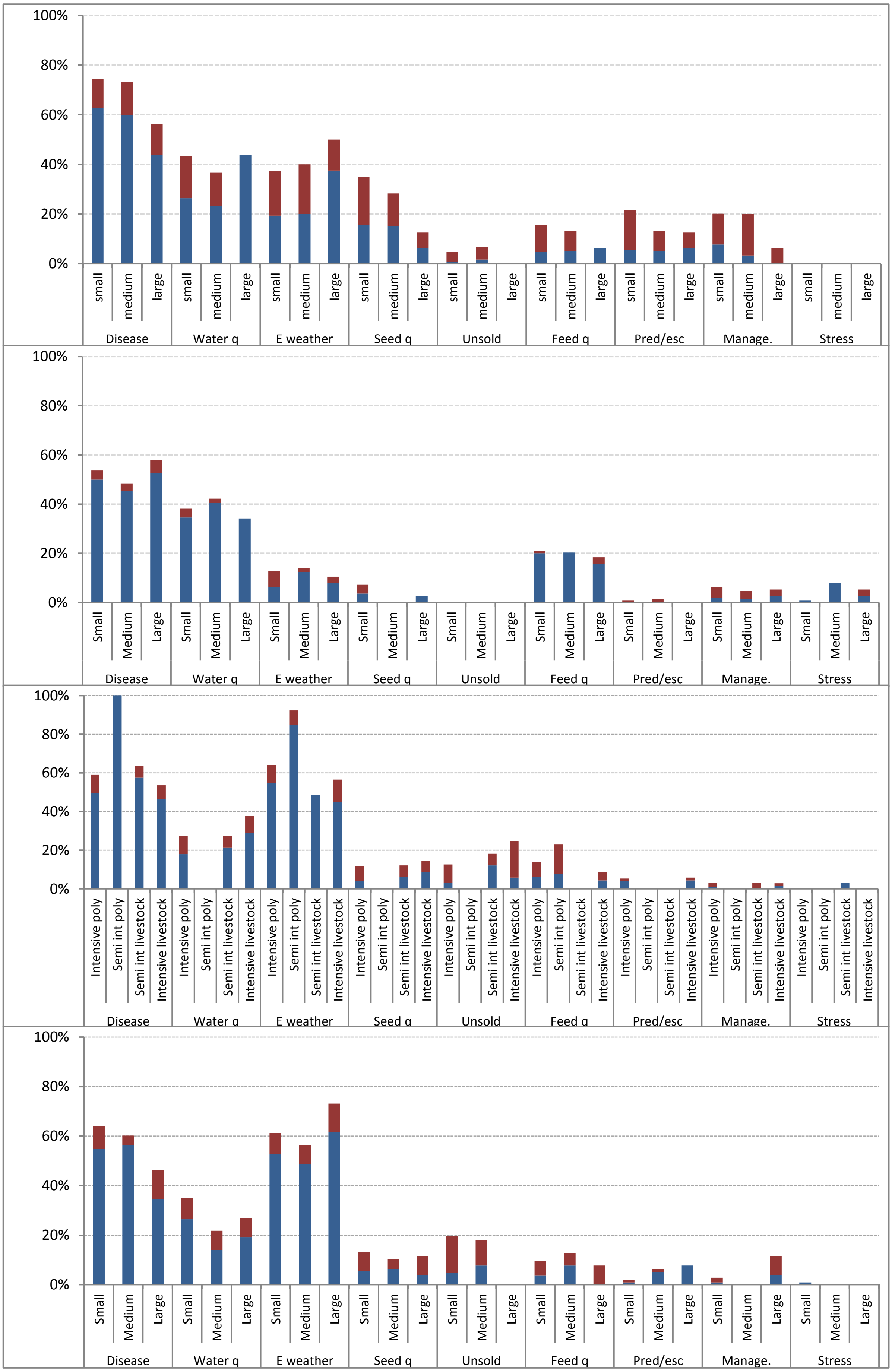


Figure 4.6 Mortality cause as perceived by farmers (%) in systems/scales which were not significant for survival, a) Thai shrimp, b) Vietnamese catfish, c) Chinese tilapia system, d) Chinese tilapia scale. Blue equals ranked 1 or 2, red equals ranked 3 or lower. q = quality, E = extreme, Pred/esc = predation/escape, Manage = poor management.

extreme weather and water quality, which were in turn more important than all other causes except for seed quality.

In the case of tilapia in Thailand, the cage systems suffered less mortality than in the pond systems. Cage systems are often in large rivers where there is constant removal of waste and better oxygen supply from the current. Thai farmers cited disease, water quality and extreme weather as the main causes of mortality. As for shrimp, environmental factors can also trigger the onset of disease in tilapia and other fish species such as high water temperature and build-up of ammonia (Amal and Zamri-Saad, 2011). Despite lower mortality in cage systems, water quality and disease are still considered major issues (Belton *et al* 2010). Recent climate change is thought to be partly responsible for poorer water quality in cage systems with increased flooding leading to soil erosion, together with increased temperatures adding to further water quality problems (Chitmanat 2009). High stocking densities in all systems has often been linked to increased parasitic infections such as from *Argulus* which may then become a source of secondary infections. Important tilapia pathogens such as *Streptococcus spp* may also infect other species in wild populations and act as reservoirs for disease especially in cage systems. Cages are also more susceptible to industrial and agricultural pollution in rivers (Belton *et al* 2010). However, in this study, cage systems were better performers than pond systems in terms of survival with water quality, disease and extreme weather still the most important cause in ponds. This is contrary to Belton *et al* (2010) perhaps due to seasonal or geographical factors which are unknown. In pond systems pathogens may enter through infected fry or through the water course (Amal and Zamri-Saad, 2011).

4.4.3 Disposal of on farm mortalities in Asia

The aim of this section was firstly to assess whether biosecurity and human health and safety were considerations for mortality disposal, and then to assess if farmers could add value to their mortality in an environmentally conscientious manner. There were different approaches to mortality disposal between different species and different countries, which may have reflected the level of development of by-product industries in these locations. The categorical nature of the dependent and independent variables indicated that a chi-squared test would be most appropriate for statistical analysis. However, due to the unbalanced nature of the independent variable, i.e. many more responses for disease compared to other categories as mortality cause in most cases, meant that the output was unreliable. Table 4.8 shows the top six disposal routes for mortalities from each of the top six mortality causes overall, for *Penaeid* shrimp in each country. In Thailand and Vietnam, it was claimed that shrimp mortality mostly occurred in the very early stages of stocking and therefore there was little biomass that could be utilised. In Thailand, it was claimed that many of the mortalities were left in the pond, which would be treated with some form of disinfectant. No data on the size of the individual mortalities were collected. In both Thailand and China, it was common for, presumably larger, shrimp mortalities to be sold to middlemen. However, what happened to them next is unclear and it would be speculative to suggest that they may have eventually been sold to by-product processors, as they may equally have been sold for

Table 4.8 Top six utilisation methods of shrimp mortalities in Asian countries by mortality cause

			Mortality cause					
Species	Country	Mortality fate	Disease	Water quality	Extreme weather	Seed quality	Feed quality	Predation/ escape
Penaeid shrimp	Thailand N = 784	Left in pond treated	76	44	59	38	13	10
		Sold middle man	110	34	36	20	10	2
		Burnt/ buried	44	26	19	23	10	7
		Left on side pond	13	4	8	11	5	4
		Limed	6	8	6	6	1	3
		Fertiliser	8	6	2	-	-	-
	Vietnam N = 131	Left on side pond	74	13	14	7	-	3
		Sold middle man	5	1	2	-	-	-
		Sold local market	1	-	1	-	-	-
		Consumed	2	-	-	-	-	-
		Limed	-	1	-	-	1	-
		Burnt/ buried	-	-	-	-	1	-
	China N = 528	Burnt/ buried	31	28	30	19	2	3
		Sold middle man	36	23	22	11	5	-
		Left on side pond	9	5	5	5	1	-
		Consumed	6	4	5	4	1	-
		Discharged to sea	3	2	1	2	-	-
		Disposed of in field	4	-	-	1	-	-
	Bangladesh N = 245	Left on side pond	67	26	-	21	2	4
		Burnt/ buried	80	5	3	-	1	1
		Sold local market	6	5	-	8	-	-
		Sold middle man	1	2	-	1		
		Consumed	-	-	-	3	-	-
		By-product processor	-	-	-	-	-	1

consumption in local markets, as some were directly in China. However, if this were the case, one might expect there to be a similar level of selling to middle men in Vietnam and Bangladesh, which was not the case. Both China and Thailand have well established industries for both shrimp meal and chitosan manufacture, whereas these industries are largely undeveloped in comparison, in Vietnam and Bangladesh. In these countries, it was much more common to leave mortalities on the side of the pond, or to burn or bury them. The former could be considered as a reservoir for spreading disease, via vermin for example. Burning or burying mortalities is generally the more favoured route in the international standards, such as ASC (WWF 2011), as it offers a simple solution to disposal in most cases and is generally bio-secure, especially if they are limed. Farmers in Thailand showed the most ability to sell their shrimp mortalities directly to by-product processors, although the nature of these industries is not known, it is likely that they will be directed to shrimp meal and/or chitosan industries as the most commonly identified by-product industry. Farmers claimed that they were able to sell their mortalities for between 20 baht and 75 baht per kilogramme (around US$0.60 to US$2.30), either directly to by-product processors or to middle men. This is compared to their average sale price for their finished product of around 100 baht to 120 baht per kilogramme (US$3.00 to US$3.60). Therefore there was substantial benefit to be able to sell their mortalities in these by-product markets. However, it is not known where the middlemen were selling to.

Table 4.9 shows utilisation and disposal routes of other species according to their mortality cause. Thailand was unusual in that many of the tilapia mortalities were used to make fertiliser for use on the farm but many were also burnt or buried, or left on the side

Table 4.9 Top six (where cited) utilisation/disposal of mortalities of other species in Asian countries by mortality cause.

			Mortality cause					
Species	Country	Mortality fate	Disease	Water quality	Extreme weather	Seed quality	Feed quality	Predation/ escape
Tilapia spp.	Thailand	Fertiliser	40	39	22	5	7	6
		Burnt/ buried	31	22	18	7	-	3
		Left on side	13	18	15	3	2	4
		By-product processor	11	13	12	2	2	2
		Sold middle man	9	21	5	2	-	-
		Fed other species	2	7	3	-	-	-
Tilapia spp.	China	Burnt/ buried	66	34	66	19	13	5
		Limed	6	2	5	-	-	-
		Left on side	8	-	1	-	1	-
		Sold Middle man	4	-	3	2	-	-
		Fed livestock	4	-	1	-	1	-
		Disposed of in field	3	-	1	-	-	-
Pangasius spp.	Vietnam	Limed	38	42	13	3	23	1
		Sold middle man	59	12	4	2	6	-
		Burnt/ buried	24	17	9	2	3	-
		By-product processor	4	8	-	-	9	-
		Left on side pond	5	3	1	1	-	1
		Sold local market	-	-	-	-	1	-
FW prawn	Bangladesh	Left on side pond	69	30	15	14	11	11
		Consumed	7	19	1	7	4	1
		Burnt/ buried	22	4	2	-	1	-
		Sold local market	1	6	3	4	-	-
		Sold middle man	4	1	-	1	-	1
		Fed cultured species	4	-	-	2	-	-

of the pond. Thai farmers were also able to sell some of their mortality waste to by-product processors, perhaps for reduction to fishmeal or for collagen extraction.

In China it was more common to dispose of mortalities through burning or burying, sometimes with liming, or directly feeding them to livestock. This was also the case for *Pangasius* in Vietnam where most mortalities were limed, or disposed of by burning or burying on-site. A substantial amount were sold to middle men however, and it is most likely that these were directed towards fishmeal manufacture, although this cannot be certain. *Pangasius* mortalities were sold to middle men for between 1000VND and 2500VND (around US$0.05 and US$0.13) per kilogramme compared to the market price of around 15000VND to 20000VND (US$0.75 to US$1.00) per kg for harvested fish and around 6500VND (US$0.30) for post processing by-products directed to fishmeal manufacture. In Bangladesh, the vast majority of prawn mortalities were disposed of by being left on the side, or burnt or buried. However, a substantial number were consumed by the household or staff of the farm but proportionately fewer from animals suspected to have died from disease than water quality, for example. In general, there seemed to be little distinction between the disposal route according to the mortality cause.

Figure 4.7 shows the disposal routes by scale for selected species and countries. There is little difference in the ability for different scale farmers to be able to access the services of middle men in either Thailand or Vietnam for shrimp or catfish mortalities respectively. For Thai tilapia there were only three large farms, for which only one claimed that they sold their mortality waste to by-product processors whereas there were 13 small farms out of 155 which cited this route. Larger farms may be considered to use more on-site disposal methods such as burning, burying or leaving in the pond with treatment. Therefore it does not seem that scale is important in deciding the fate of mortality waste, however, no statistical test could be performed because of the unbalanced nature of the data and it is highly dependent on the level of response from the different farms.

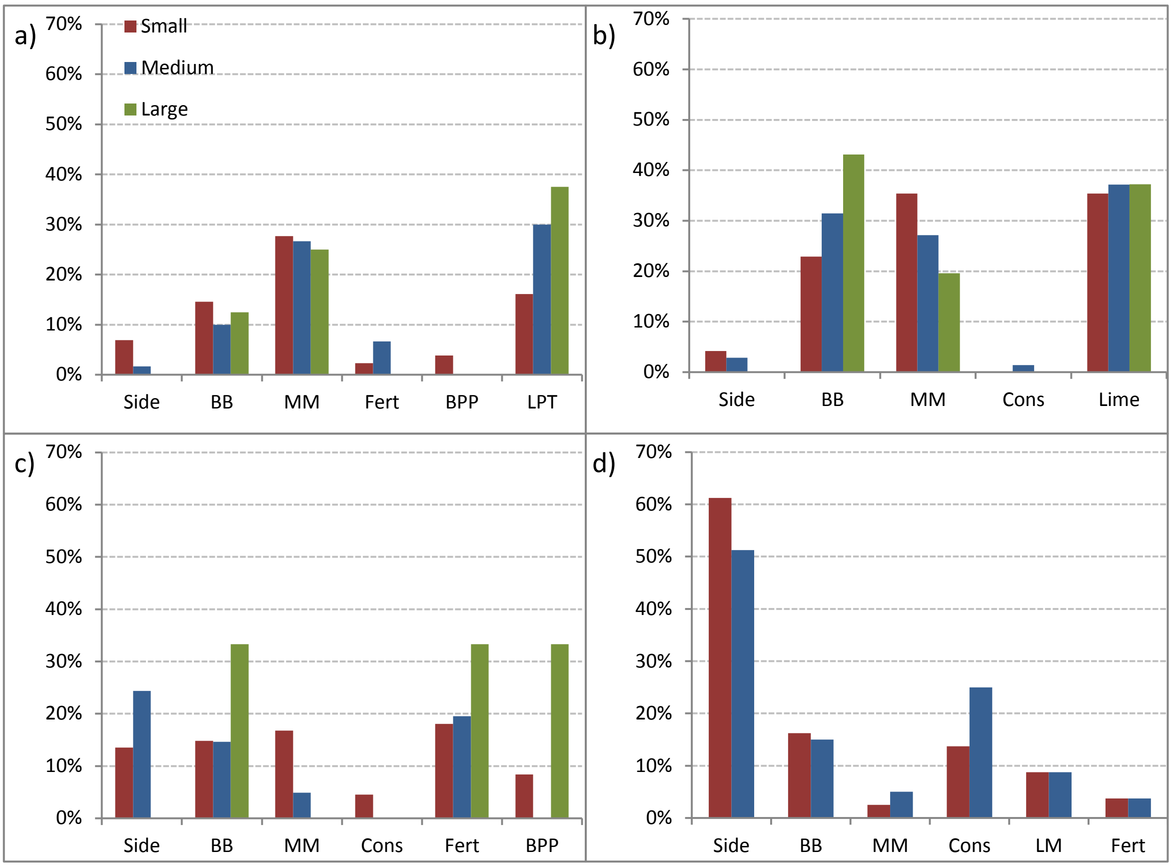


Figure 4.7 Mortality utilisation/disposal in selected Asian species by scale, % of farms (N values, small, medium, large) in a) Thailand shrimp (N = 130, 60, 13), b) Vietnam catfish (N = 110, 64, 38), c) Thailand tilapia (N = 155, 41, 3), d) Bangladesh FW prawn (N = 80, 80, 0). BB = burnt/buried, MM = sold to middle man, Fert = fertiliser, LPT = left in pond and treated, Cons = consumed by staff or household, LM = sold to local market, BPP = sold to by-product processor.

Overall, across all species and countries, it was most common to dispose of mortalities by burning or burying (21.6% of farms) and this may be because it is most supported by certification schemes such as ASC but also the convenience of doing so and for hygiene reasons. However, this route does not offer any value addition and burning can be a health hazard for workers. Although EU regulations do not allow for utilising mortality waste in human food chains, shrimp mortality could be directed towards chitosan extraction with the protein waste used in pet foods or for other non-livestock animals. Use as a fertiliser, as for Thai tilapia, may also be considered an attraction for vermin if not treated correctly but prior fermentation or composing on site could reduce this. There has also been some interest in vermicomposting in Asia with red-worm (*Eisenia foetida*) and certainly composting can be an effective disposal route which can deactivate many pathogens as described in chapter 1 (Smail *et al* 2009). Vermicomposting is attractive in that the worms have excellent economic value as nutritious supplementary feeds in aquaculture. Red worms, especially, have been shown to have excellent nutritional profiles and are highly valued as feeds for *Penaeid* shrimp. Some studies have shown that the addition of red worm as a supplementary feed can reduce mortality in shrimp culture and also contribute to better water quality (Liu *et al* 2006). This could provide a low cost solution to disposal of mortalities and other farm waste such as pond sludge with little expertise required, offering a potential financial benefit through reduced feed costs and possibly better survival rates.

The evidence that important pathogens are continuously present in production systems and that it is environmental triggers which cause disease outbreaks has important consequences for mortality disposal. Although it is likely that pathogens are ubiquitous in the environment and transferred through water channels, poor mortality disposal practices could further spread the pathogens to other production and water systems. They could also lead to poorer water quality parameters in some cases. Therefore a precautionary approach should be taken to their disposal, even if there is no evidence of disease presence. The EU regulations and global standards are clear on approaches to mortality disposal. In the case of the EU regulations (EC 1069/2009) mortalities are category 2 by-products and must not re-enter the human food chain, this includes products which are imported into the EU from 3rd countries. This could have implications for producers who are selling to middlemen, where further traceability cannot be verified and feed producers are sourcing ingredients from various by-product processors. The regulations and standards universally forbid intra-species feeding (EC 1069/2009, ASC 2010, GAA 2010, GlobaGAP 2012) but it is possible that this is still occurring in some parts of Asia but at low levels, having interviewed several feed producers who are aware of these regulations. Burning or burying the mortalities may be regarded as the safest means of disposal and is universally accepted as long as this is far enough from the culture area to prevent the spreading of pathogens and contributing to poor water quality.

In the case of shrimp, much of the mortality was reported to occur in the very early stages after stocking. Therefore they are difficult to remove and this is reflected by many Thai farmers leaving them in the ponds and treating. They may then be pumped out with the water at a later stage. How effective this is in deactivating pathogens cannot easily be verified and may lead to the further transfer of pathogens between systems. Leaving mortalities on the side of the pond could be regarded as the least sound method of disposal, as practiced in Vietnam and Bangladesh, as they may subsequently become a reservoir for other pathogens, attract vermin, subsequently become a human health hazard and spread disease to neighbouring systems via carrier vectors (Smail *et al* 2009; Glanville and colleagues 2006, 2009; GlobalGAP 2012b). Rain may also carry the pathogens into water courses and carcass decomposition is also a source of greenhouse gases such as methane and possibly dinitrogen oxide. Dinitrogen monoxide and methane releases may occur during the bacterial breakdown of proteins and other organic materials where oxygen is more limiting such as in water saturated ground and deep effluents but is dependent on a number of factors. The release of non-GHG gases such as nitrous oxides and ammonia are more common in well oxygenated conditions (IPCC 2006). There are considerably more environmentally sound methods of disposal, which can meet the regulations and standards, and still offer some value addition to the mortalities. Composting is a low cost and highly effective method of mortality disposal which can generate temperatures high enough to deactivate many pathogens (Smail *et al* 2009) and is considerably less polluting to air and water than either burial or incineration (Glanville and colleagues 2006; 2009).

4.5 Mortality in Scottish Atlantic salmon production

Due to the computerised farm management system, it was possible to collect data on mortality per month over the approximately 22 month grow out period. This was in numbers of individuals and biomass, in kilogrammes, by cause, from five farms. For the sixth farm, data were given by cause but as a total over the production cycle only. Figure 4.8 shows the total monthly mortality in numbers and biomass for the five farms where data were available and table 4.10 shows the mortality as % of individuals stocked and % of harvested biomass for the six individual farms.

Mortality varied from site to site, with the lowest being 4.01% and the highest 24.87% of stocked individuals, 1.01% to 13.29% of harvested biomass. Total mortality from the six sites amounted to 471,500 fish, some 463.2 tonnes. The majority of mortality, both in numbers and biomass, is from unspecified causes throughout the course of the whole production cycle. The results agree broadly with those reported by Soares *et al* (2011), who studied salmon mortality across over eighty farms in Scotland from one company, although that study found far more mortality attributable to disease. According to staff from the company that supplied the data, a certain amount of fish can be expected to die from no apparent attributable cause and this is common for all farmed salmon production. However, there is massive variation between the sites for mortality from unspecified production causes, dominated by one site, and it is likely that there is some underlying reason behind this mortality or it would be expected to be even across all sites (table 4.10).

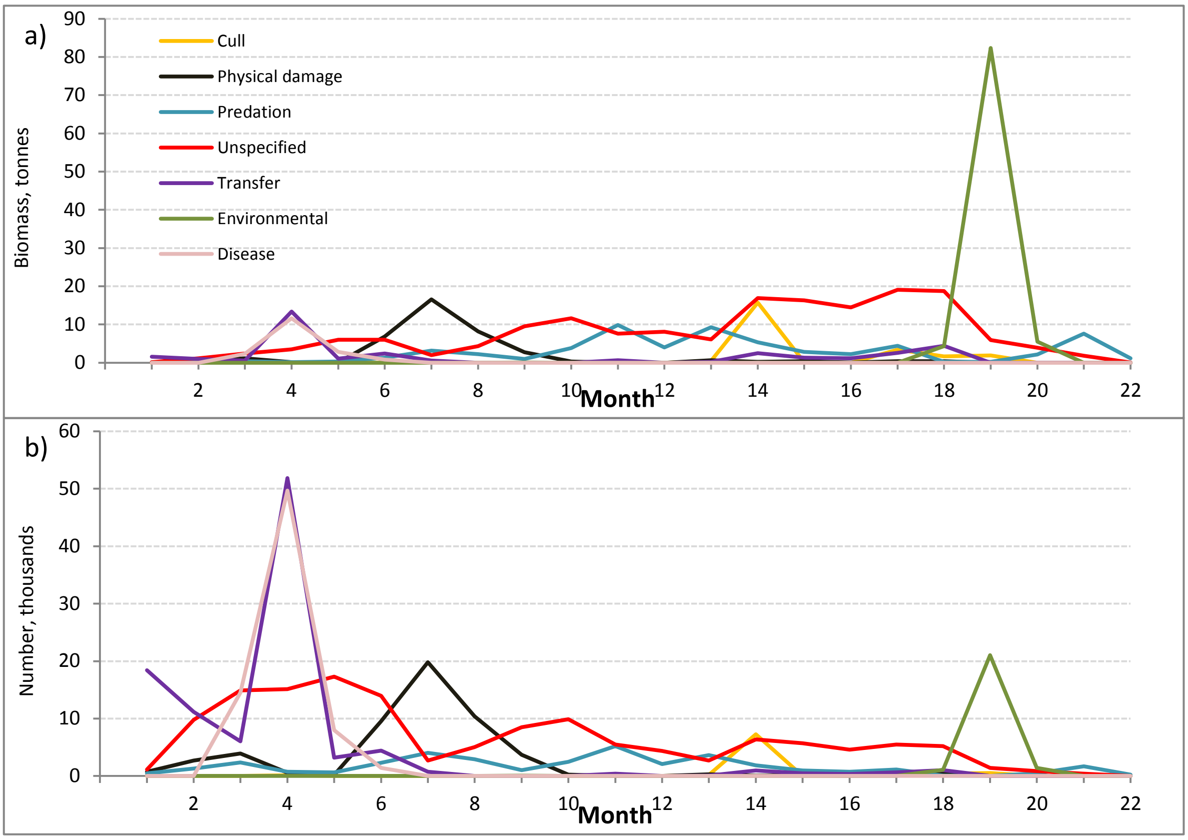


Figure 4.8 Total mortality, months post transfer across 5 Atlantic salmon farms in Scotland attributed to cause, by a) biomass, and b) number of individuals

The next largest cause of mortality in terms of number of individuals, was that resulting post transfer at 2.65% of total numbers stocked between the six sites. These may be fish which have failed to smolt or may simply not have survived the transfer process, which may take place over several days or weeks, according to industry representatives interviewed for this thesis. It is common for fish to be pumped from the fresh water site and then transported, possibly several hundred miles, by oxygenated tanks on lorries and in well-boats before being pumped into the marine holding pens. Understandably this is a stressful procedure, not only from the handling but the transition between environments, from which fish may not recover and it is common to have substantially increased mortality over the following days, post-transfer (Nomura *et al* 2009). However, the majority of these mortalities occurred at one site which suffered over 50,000 dead fish in one month. These fish were transferred in July and it is possible that there may have been some other contributory reason for their death such as elevated temperature, lower oxygen concentrations or other stressors. The data presented in figure 4.8 are months post transfer, not by calendar month and fish were transferred at different times of the year. It is most common for smolts to be transferred, either in around March/April or October/November, depending respectively on whether they have been raised on ambient light or whether they have had their smoltification manipulated by photoperiod control (Imsland *et al* 2014).

Unlike Asian systems, disease featured as the third most common cause of mortality in Scottish Atlantic salmon farms. This may be attributable to several causes, as diseases were not specified, but of most concern over the last decade, has been mortality and damage due to sea-lice. Despite development of in-feed treatments such as emamectin

Table 4.10 Salmon farm mortality by individual site attributed to cause in % numbers of smolts stocked and % biomass of final harvest weight.

Mortality cause		Farm site 1	2	3	4	5	6
Cull	Number	2.01	0.03	-	0.04	0.01	0.10
	Biomass	3.23	0.01	-	0.09	0.02	0.11
Physical damage	Number	5.49	0.72	0.01	1.96	0.50	0.45
	Biomass	2.21	0.06	0.02	0.62	0.19	0.09
Predation	Number	0.87	3.57	0.20	0.02	2.33	0.31
	Biomass	0.60	1.61	0.05	0.01	4.42	0.14
Unspecified	Number	12.68	5.09	2.76	3.56	1.41	4.23
	Biomass	7.20	3.21	0.90	1.76	2.12	2.42
Transfer	Number	3.82	1.39	0.96	1.10	6.66	1.40
	Biomass	0.56	0.11	0.04	0.55	1.64	0.20
Environmental	Number	-	1.19	0.09	0.01	-	3.74
	Biomass	-	0.37	0.01	0.00	-	4.69
Disease	Number	-	2.82	-	0.24	3.63	5.60
	Biomass	-	0.17	-	0.03	1.00	0.36
Total	Number	24.87	14.82	4.01	6.93	14.55	15.83
	Biomass	13.29	6.55	1.01	3.07	9.37	8.01

benzoate and preventative measures such as fallowing and single year classes, sea-lice can still cause major losses in Scottish salmon farms (Soares *et al* 2011). Notifiable diseases such as IPN or ISA have been of little concern since the widespread uptake of vaccination programmes against these diseases. Such an out-break results in the immediate closure of the production site for several months (Murray *et al* 2002). This had not occurred at any of the sites which supplied mortality data. Most of the disease, in terms of numbers, was from only two sites, which suffered over 60,000 dead fish between them, but mainly in the first few months post transfer. At one site the disease loss coincided with major post-transfer loss, which may be connected.

Losses to predation may also occur throughout the production cycle. These may be divided into losses from seals, mink or birds. Around 75% of these losses were due to seals with the rest being undefined. Seals not only cause direct fish mortality and losses, they can also cause damage to the holding nets resulting in large escape events (Scottish Parliament 2013). Effective management against seal predation is therefore of upmost concern to producers. A variety of measures have been used to control seals, these include shooting them, use of anti-predator nets and acoustic deterrents. It is also common to tension the holding nets as much as possible to make it more difficult for seals to attack the holding pens (Scottish Parliament 2013, ASC 2012). Despite these measures, seals still cause significant mortality, although no losses due to escape were reported by any of the farm sites. Unlike Asian farms the losses due to predation mainly cause damage to the fish as the predators cannot gain full access to the pens. The fish subsequently dies, with much of the carcass still present and requiring disposal. The ASC does not advocate the use of lethal measures in controlling seals, but may allow it where it can be proven that all other measures to deter seals, such as acoustic devices and blinds, has been taken (ASC 2012).

The second largest cause of mortality between the six sites in terms of biomass at 1.12% of total harvested biomass was due to environmental causes. This was largely down to one mass mortality event which occurred at one site. According to the producer, this was due to an algal bloom event in the late summer of 2012. Algal blooms can be caused by several phytoplankton species and have historically caused large losses to salmon farms in Scotland and elsewhere. Typically they can cause gill irritations as the result of toxins released by the algae, leading to diverse problems such as anoxia and osmo-regulatory problems (Treasurer *et al* 2003). Therefore, losses through algal blooms can cause the dead fish to be tainted by these toxins and disposal via non-livestock animals should be avoided.

4.5.1 Disposal of Scottish Atlantic salmon mortalities

Only two farms of the six declared their disposal route for their mortalities and this was a combination of on-site incineration and sending to landfill by lorry. The landfill site was 103 miles from both sites and therefore it is assumed that the same on-shore station was used for the sites. Clearly this is a huge expense to the company and is potentially a health hazard to workers and nearby inhabitants. The standard rate of landfill tax in 2012, at the time of data collection was £64 per tonne and is set to rise to £80 per tonne in 2014 (http://www.hmrc.gov.uk/rates/landfill-tax.htm, accessed 10/9/13). If all of the fish were sent to landfill in 2012, this would cost the company just under £30,000 for the six sites, not including transportation, which could also be considerable. Although it was clear that some mortalities were incinerated on site, at some locations, the quantity and associated energy inputs and costs were not given.

Although other options for mortality disposal are available through the EU regulations, they are logistically difficult to implement considering various transport and biosecurity issues. It is not feasible to compost or anaerobically digest mortalities on site given the requirement for pre-treatment under EC142 and collection between sites is unacceptable to producers. Feeding to many animals is unlikely to be acceptable because of biosecurity, toxin and acceptability issues of the receiver.

Another option would be local community composting or anaerobic digestion in villages and towns close to the farm sites, as long as biosecurity measures could be implemented.

Many of these initiatives exist in continental Europe. Germany, for example, produced 4.1% of its electricity and 0.9% of its heat energy from biogas in 2012, representing 17.4% of its renewable energy production (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, (BMU) Germany, 2013). Initiatives for self-sufficient community based energy generation schemes have been in operation in Germany since the Renewable Energy Sources Act of 2004 and in 2006 the first “Bioenergy Village” development was completed. The village of Jühnde has 800 inhabitants of which 70% are members of a cooperative which is supplied by a combination of biogas generated electricity from agricultural activities and a biomass boiler through a heating network to 145 households (IEA 2011). The anaerobic digestion plant runs off of a mixture of agricultural silages and slurry and although there are some technical issues over continuous supply throughout the year, the plant generates twice the energy needs of the village (IEA 2011) and offers an interesting case study which could perhaps be adopted for remote agricultural communities. This could perhaps be a route for fish farm mortalities in Europe and could prove less costly than current measures despite initial investments. As a high nitrogen feedstock, it would need to form part of a larger project taking in high carbon feedstocks from the surrounding agriculture and municipal waste. Therefore, much more work would be required on the economic feasibilities of such a venture.

CHAPTER 5: LIFE CYCLE ASSESSMENT AND ITS APPLICATION TO AQUACULTURE BY-PRODUCTS

5.1 Life Cycle Assessment of by-products from aquaculture production

Life Cycle Assessment (LCA) was used to investigate the environmental performance of several of the by-product utilisation strategies that were identified in chapter 1 for Atlantic salmon, *Pangasius* catfish and *Penaeid* shrimp in Scotland, Vietnam and Thailand respectively. It builds on other work that was carried out as part of the SEAT project as shown in Henriksson *et al* (2014a) to which the author of this thesis contributed. This included contributions to data collection from feed mills and processors in Thailand and Vietnam, and to data analysis at all points within Thai and Vietnamese value chains. All data for the salmon value chain analysis and that connected to by-product utilisation for all species presented were collected by the author.

5.1.1 Life Cycle Assessment in aquaculture

LCA is an International Standard Organisation (ISO) standardised, tool developed for assessing and comparing the environmental performance of industrial systems, from raw materials extraction to disposal of final waste products ("cradle to grave") in a broad range of contexts. In particular, it is useful in identifying the disproportionate impacts ("hotspots") which certain processes might contribute to the overall production (Hospido and Tyedmers 2005). This may be useful for improving the efficiency of certain individual contributing processes or sourcing raw materials for those processes. LCA has only been applied to food production systems relatively recently and this is especially the case for capture fisheries and aquaculture (Henriksson *et al* 2012). Several LCA investigations have been conducted into the impact on the environment of fisheries, aquaculture and their associated service and processing industries, (e.g. Aubin *et al* 2006; Ellingsen and Aanondsen 2006; Hospido *et al* 2006; Hospido *et al* 2005; Grönroos *et al* 2006; Mungkung *et al* 2006; Papatryphon *et al* 2004; Aubin *et al* 2009; Pelletier *et al* 2009; Pelletier *et al* 2007;Roque d'Orbcastel *et al* 2009; Ayer and Tyedmers 2009; Thrane *et al* 2009; Ziegler *et al* 2003; Ziegler and Valentinsson 2006; Pelletier and Tyedmers 2010; Phong *et al* 2011; Cao *et al* 2011; Parker and Tyedmers 2012; Iribarren *et al* 2012; Vázquez-Rowe *et al* 2014). Many LCAs set the boundary at the farm-gate and few have attempted to analyse the various impacts associated with the use of post-filleting by-products from fishery, and especially aquaculture, production. In the majority of cases this is because they wish to compare systems for which the output and downstream processes are the same, and therefore irrelevant to the study. However, in some cases practitioners compare different species with different edible yields, for which the processing and post-processing nodes of the value chains can be critical in the overall performance of that species.

5.2 Life Cycle Assessment methodology

5.2.1 LCA procedure

According to ISO 14040/14044 (ISO 2006a, 2006b) any LCA should be split into the following sections:

1) Goal and scope definition of the LCA
2) Life Cycle Inventory (LCI)
3) Life Cycle Impact Assessment (LCIA)
4) Life cycle interpretation
5) Reporting and critical review of the LCA
6) Limitations of the LCA
7) Relationship between the LCA phases
8) Conditions for use of the value choices and optional elements

The goal and scope, issues around methodology, data collection for the LCI and the LCIA approach will be covered in this section. The interpretation and other sections will form part of the results of each of the LCA chapters 6, 7 and 8, and the discussion.

5.2.1.1 Goal and Scope

The goal and scope of the LCA defines the intended application of the study, the reasons for carrying it out and the intended audience. It should describe the systems which are to be assessed within the study in enough detail to identify differences between them and points within the assessment which are of critical interest. Crucially it must define the Functional Unit (FU) for the assessment, which is common between the systems under study and is used as a reference for the flows of materials, emissions and impacts. Essentially, the FU describes the function of the systems under study. Functional units for aquaculture and by-products will be discussed in more detail in section 5.2.1.4. The FU is also partly described by the system boundary of the study, i.e. which unit processes are included and which are not. This must be clearly justified and processes should only be omitted where there is no significant change in the conclusion of the study. In the case of most aquaculture studies mentioned above, the system boundary is the farm-gate and the FU is a live weight of whole fish.

The goal and scope phase must also include other critical methodological choices, assumptions and other choices which are made. Many of these can have a large effect on the outcomes and conclusions of an LCA and none more so than allocation procedures for multi-functional processes. This is especially relevant for many food production systems and is inherent when assessing the impact of by-products. Multi-functionality, allocation procedures and their influence on the results of LCA studies will be discussed in detail in section 5.2.1.3.

These methodological choices may be influenced by what data are available and what are feasible to collect, and the data requirements must also be described within the goal and scope phase. In most cases, it is desirable to collect primary data from the systems under study. However, access to industry data and the size of the data requirement for some processes may limit the amount of primary data collection that is possible within the time scale of an LCA study. In such cases data may be collected from literature or from widely available LCA databases. In the case of aquaculture LCAs, it is common to use literature sources for the processes involved in providing ingredients for feed manufacture, for example, whereas the emissions data from the combustion of fuel in transport systems often come from databases such as Eco-invent 2.2 (Hischier *et al* 2010). This is because the time and effort needed for LCIs of individual aquafeed ingredients and the emissions from combustion of fossil fuels is huge and beyond the means of many LCA studies. There are already a wide range of data presented on agricultural production in other LCA literature and environmental impact assessments, whereas the Eco-invent database has many processes related to the burning of fossil fuels in various transport systems and agricultural machinery which can be adjusted to local situations. However, some of these processes may not be representative of the system under study for various reasons such as the age or location from which the data were collected. However, the sample size may be large compared to primary data that can be collected. Therefore, uncertainty should be attached to the data, the methodology for which is described below.

Other methodological choices which must be made are the LCIA method which is responsible for categorising emissions to single references for each impact category, e.g. Global Warming Potential (GWP), measured in carbon dioxide equivalents (CO_2eq) and whether impacts are to be weighted and subsequently normalised to a reference point such as a proportion of total global emissions. These options are available within the CMLCA 5.2 software which was used for the LCA studies in this thesis. For this thesis and the SEAT project, the standard CML baseline method was used which is integrated into the software. No weighting or normalisation was used because they offer little value to the comparisons which are made within this thesis and can be highly subjective. More detail on methodological choices can be seen in the specific sections below.

5.2.1.2 Methodological issues in LCA studies of by-products

Most food production systems are examples of complex assemblies of multi-functional processes, in that each unit process produces more than one product. Within any complex LCA, boundaries are usually drawn around the parts of the system of particular interest to the study according to its goal and scope. Boundary setting results in a requirement to apportion the impacts to products from multi-functional processes within the areas of interest (Finnveden *et al* 2009). In aquaculture contexts, this often means separating environmental impacts between certain feed ingredient inputs such as agricultural by-products from the target product (e.g. rice bran used in fish feeds from the grain which is sent directly to human consumption). It also has implications for separating the impacts between the final product output of interest such as a fish fillet from the by-product which may be directed to other industries, or in the case of this thesis, the by-product industries that originate from the original food production industry.

The broad standards for LCA, defined by the ISO 14040/44, allow for different methodological reasoning that can be used for similar scenarios (ISO 2006a, 2006b). Despite these standards, how these impacts are apportioned is interpreted differently and not always fully explained by practitioners (ANEC 2012, Henriksson 2014b). Many industries and standard setters, e.g. the British Standards Institution (BSI 2012, 2011) are increasingly seeking to benchmark products using LCA so that their environmental performance may be compared to similar products. Therefore, the methodology of boundary setting and attributing impacts to the areas of interest can have implications for comparability. A lack of consistent methodology in LCA and carbon foot-printing studies (which can be regarded as a derivative of LCA) has caused concern within the aquaculture and food industries that publications do not offer a common basis for comparison and therefore may be less accessible for industry purposes (Parker 2012). These issues were highlighted by EU consumer watchdog, the Association for the Co-ordination of Consumer Representation in Standardisation (ANEC) (ANEC 2012). It is common to hear of food products' carbon footprints being expressed and sometimes compared in the popular press, e.g. The Independent (2010). However, many LCAs and carbon footprints present impacts as single figures for comparison with other studies including no uncertainty, when in reality the individual unit processes which contribute to global value chains can be extremely diverse and include their own levels of inherent uncertainty, as well as uncertainty derived from unrepresentativeness, spatial and temporal differences. Uncertainty issues will be dealt with in section 5.2.1.8. Single figure LCAs and carbon footprints can lead to a false impression regarding the accuracy and legitimacy of comparing between products, especially if there are inconsistent methodologies in their determination (de Koning 2010). Consequently, there is a desire within industries for harmonisation of methodologies so that studies can have more significance (Parker 2012).

Efforts are being made to address these concerns such as the United Nations Environmental Programme (UNEP)/Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative (UNEP and SETAC, 2011), PAS2050 (BSI 2011, 2012) and World Business Council for Sustainable Development (WBCSD) / World Resources Institute (WRI) Greenhouse Gas Protocol (WBCSD and WRI 2012), in addition to the ISO standards. However, these still include optional or hierarchical choices in some circumstances and can be interpreted differently.

Despite the aquaculture LCAs cited here not seeking to benchmark, but to compare production systems for the same species within a single study, subsequent papers have sometimes compared their results e.g. Bosma (2011), Parker and Tyedmers (2012). Most relevant to aquaculture studies referred to in this section is their choice of methodology in partitioning impacts between co-product inputs to aquafeeds when comparing between systems within the same study. Although partitioning of co-product impacts has been previously discussed, notably by Ayer *et al* (2007), there are still different and conflicting methodologies that have been used since this publication in subsequent aquaculture LCA papers. Also of relevance to this thesis is the choice of an appropriate functional unit as a reference point for environmental impact for comparing between systems and multiple products produced from them.

Crucially, according to ISO 14040/44 (ISO 2006a, 2006b), wastes are modelled with the reference product, where as a co-product is separated along with its associated environmental impacts and may be modelled in a different LCA. This can lead to very different results for the same by-product when it is redirected from waste to a valued co-product and in previous aquaculture studies it is not always clear if this is the case e.g. Pelletier *et al* (2009), Pelletier and Tyedmers (2007). Practitioners have used different approaches to co-products involved in upstream inputs, particularly as feed ingredients, including fishery trimmings and agricultural by-products, which have had significant consequences for identifying hotspots in one system as well as making it inappropriate to compare between studies.

This section highlights some of the situations regarding by-product issues in aquaculture that pose problems in LCA. These issues define the methodological choices which have been made for the LCA studies within this thesis. They draw and expand on the existing methodology, which may enable comparison between complex systems.

5.2.1.3 Apportioning impacts in multi-functional processes

Issues surrounding the partitioning of impacts from food production systems were discussed by Schau and Fet (2008), for seafood by Ayer *et al* (2007), and capture fishing by Svanes *et al* (2011), for example. Ekvall and Finnveden (2001) reviewed some of the problems in avoiding allocation and remaining consistent in complex multi-functional systems. Discussions around the environmental impacts of specific co-products of interest to aquaculture include, for example, Pelletier and co-authors (2010, 2009, 2007) and Ayer *et al* (2007). Where these issues arise, ISO 14044 stipulates that partitioning methods should be applied according to a hierarchical process (ISO 2006b).

Firstly, ISO suggests that different processes within a production system should be identified, sub-divided and data should be collected for the separate components. Secondly, processes should be separated by system expansion to allow for comparison between alternative options for producing the various co-products (ISO 2006a; 2006b).

System expansion is the preferred choice of consequential LCAs where the adoption of one process has a consequence for other industries and is explained in detail by Weidema (2001). A description of system expansion methodology can also be seen in the ILCD

General Guide for Life Cycle Assessment (EC 2010). Generally, single function processes are found which produce the individual co-products and replace the multi-functional process. In addition, the use of a particular co-product may decrease the use of a corresponding product from another industry which can be credited to the assessment, e.g. the use of fishery by-products results in lower use of fishmeal from dedicated fisheries.

A simple example of system expansion is given in Figure 5.1. In Fig 5.1a, the multi-functional Process A cannot be sub-divided, however both Products A and B can be made separately in Processes B and C. Therefore the impacts from Process C can be subtracted from Process A to give the impacts for making Product A in Process A. For food products, this scenario is impossible in most circumstances because there is no single process that can produce e.g. fish fillets without producing any of the by-products. In these circumstances, there may be other products which perform the same function such as in Figure 5.1b. In this case, Products D and E are generated from Product C. Product F from Process F is not the same as Product E but is able to perform the same function in Process E. This could be akin to fish fillets and by products being produced from whole fish, where the by-products are directed to fishmeal production and perform the same function as fishmeal being produced from a dedicated reduction fishery. The ISO standards state that procedures should be uniformly applied but in practice this may not be possible for a variety of reasons as discussed below.

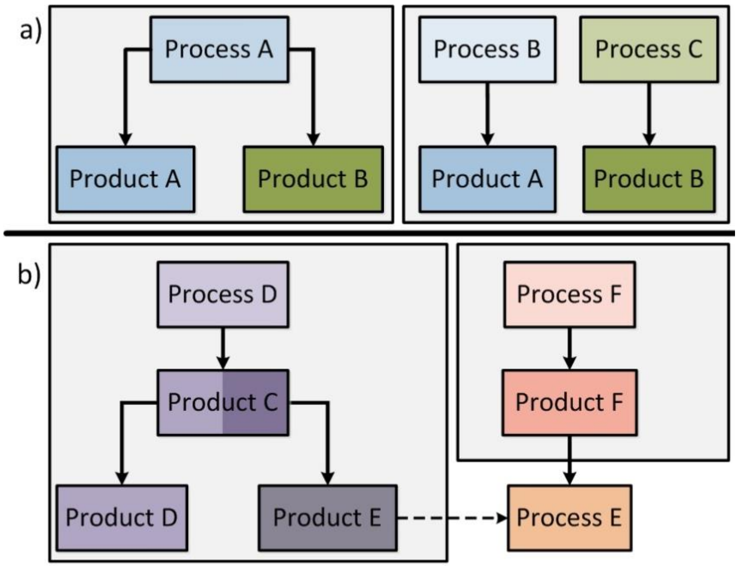


Figure 5.1 Simplified example of system expansion where a) two processes produce the same products as the multi-functional process and b) a single process produces a product that can perform the same function as that produced from a multi-functional process. Adapted from ILCD General Guide for Life Cycle Assessment (EC 2010)

Partitioning impacts using subdivision or system expansion poses significant challenges for complex food production scenarios. For example in Asia, aquaculture, terrestrial livestock and arable co-products, and manure are often used interchangeably in feeds and fertilisers (Phong *et al* 2007; Phong *et al* 2011). Therefore it is extremely difficult to trace the original inputs for the system, and in many cases the inputs of various co-products to fish production cannot be distinguished during modelling, for example between rice bran and rice grain. Consequently, as in this example, it is not possible to sub-divide the multi-functionality of the system as it is impossible to the separate inputs individually to the grain and the rice bran because one cannot be produced without the other.

System expansion has been applied to fisheries by-catch by Thrane (2004) but can become extremely problematic in complex aquaculture systems because of the level of expansion required for the many co-product inputs involved, and difficulty in acquiring necessary data (Ekvall and Finnveden 2001; Heijungs and Guinée 2007; Henriksson *et al* 2012). In many cases, such as by-products of fish processing, there are no single processes which can produce those products, although in some cases there are processes which may produce products which provide the same function, as shown in figure 5.1b. Where there are several alternative processes for a certain product, some of which may also be multi-functional, subjectivity may arise in which one is chosen, thus increasing expansion results in increasing subjectivity (Ekvall and Finnveden 2001; Heijungs and Guinée 2007). This is the case in the example given above, where fishmeal from reduction fisheries can replace that produced from by-products, but in reality, to produce fishmeal, fish oil is also produced and another level of expansion would be required to fulfil its function, which could also be a multi-functional process, *ad infinitum*. Mathiesen *et al* (2009), suggested ways in which subjectivity could be reduced by identifying substitutes based on marginal technologies, but this does not remove the issue of ever increasing expansion. Weidema (2001) claimed that all systems could be modelled using system expansion by attributing the impacts of inputs to the "determining product" in each process. However, this does not overcome the problems of subjectivity and large expansions which may dilute the focus of the LCA. There may also be more than one "determining product" in a multi-functional process, such as the fishmeal / fish oil industry where both products are of significant interest and to which impacts must still be partitioned. It is therefore difficult to justify system expansion as a consistent methodology throughout complex food production systems.

The third methodology (but most common amongst aquaculture studies) in the hierarchy is to partition the impact to each co-product within the multi-functional process by some intrinsic factor, where the impacts are divided between the co-products according to the proportion of mass, energy content, economic value or some other factor to which each co-product contributes as shown in figure 5.2.

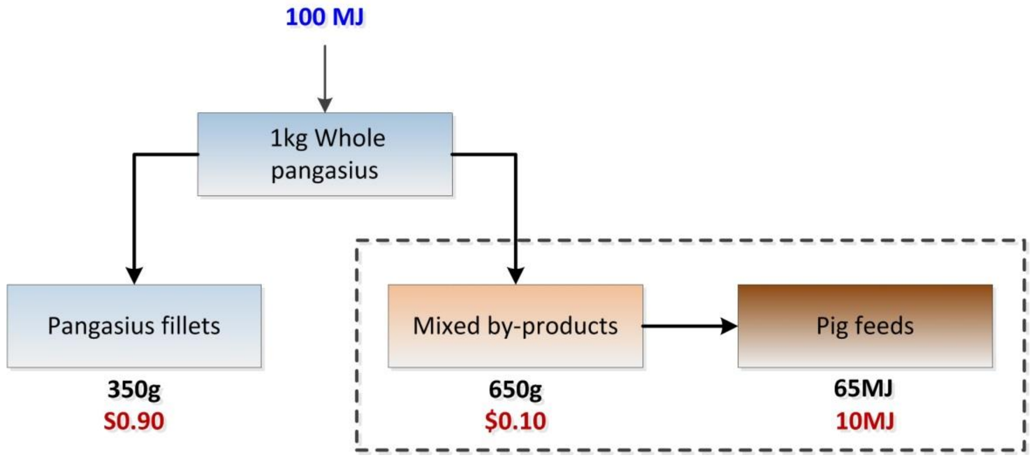


Figure 5.2 Simplified example of allocation by mass (black) and by economic value (red) to *Pangasius* by-products used in fishmeal for pig feeds.

Some practitioners have used mixed methodologies, using system expansion for some co-products but other more simple solutions for others, such as Ayer *et al* (2009) who used system expansion to investigate the use of solid emissions (waste feed and faeces) but gross nutritional energy as an allocation method for the use of livestock by-products in feeds. Parker and Tyedmers (2012) used a mixture of system expansion and gross energy based allocation for investigating products from the krill industry. Although a full system expansion of all co-products may be too complicated, expanding the system for one of many co-products can represent a mix of methodologies and conclusions, and raises questions over the subjectivity of these choices, especially when sensitivity analysis reveals that using the same methodology throughout influences the results. For example, in their sensitivity analysis, Parker and Tyedmers (2012) showed a 42% reduction in global warming potential for assessing the production of fish oil capsules, when using gross energy based allocation throughout, compared to applying system expansion to only one process and allocation to the others.

According to ISO hierarchy, allocation should be based upon underlying causal relationships (ISO 2006b), although what denotes these relationships is not always clear. If it is not possible to allocate based on physical causal relationships, other factors may be used (ISO 2006b). Allocation methodology should be chosen which is appropriate for the co-products involved in the context of directing resources efficiently according to industry dynamics. That is, the allocation choice should endeavour to reflect the environmental consequences of using that resource as much as possible as the next best choice after system expansion methodology. Where this is not apparent, more than one methodology should be applied consistently and compared, to add robustness to the study.

Allocation by mass or nutritional relationships is applied by some because it is perceived to better represent the bio-physical flows of materials and it is regarded as being more temporally consistent than economic allocation, when economic values may be volatile (Ayer *et al* 2007; Pelletier and Tyedmers 2007). Although mass and gross nutritional energy of aquaculture co-products may change in proportion to each other, they are generally regarded as less subject to volatility than the value. Conversely the physical characteristics of fishery by-products may vary considerably with seasonality, due to the sexual maturity of the catch or the constituent species, including by-catch (Davies 2009; Thrane 2004).

Problems may arise with economic allocation as a material previously regarded as waste gradually acquires value through various applications. Although the economic contribution has changed, its actual impact has remained the same (Ayer *et al* 2007). For example, in Vietnam, fat from *Pangasius* catfish production is increasingly used, with improving efficiency, for producing biodiesel and in livestock feeds (Le Nguyen 2007, Nguyen *et al* 2009). However, while the price of the fat increased, the price of *Pangasius* fillets showed a 10% decline (Nguyen 2008). Economic allocation is calculated on the proportion of the price attributed to each co-product, adjusted to mass. Therefore in most cases, for established industries, much of this volatility is absorbed as the values of the co-products often fluctuate in similar proportions to each other (Guinée *et al* 2004). In young industries, this is more of a problem where prices can change very quickly, such as in the *Pangasius* market and associated by-product industries. However, there is more often less of a shift in the proportion of attributed impacts in the transition from waste to utilisation using economic allocation compared to mass or energy content, for example. In any LCA no impacts are attributed to waste products as they are modelled along with the target co-products. The by-product from *Pangasius* is around 2/3 the mass of the whole fish and therefore this proportion of the impacts associated with *Pangasius* production and processing would be carried forward to other industries at the point of utilisation compared to nothing if it is wasted. At the same time, using mass allocation, if a *Pangasius* processor starts to sell its previously wasted by-product for further use, the impacts attributed to the fillet drop by over 65% as both the impacts associated with producing the by-product and their subsequent disposal are no longer attached to the fillet. This is an unrealistic scenario and may serve to encourage waste, as a producer may not wish to utilise a raw material with such high environmental impacts attached to it. Therefore economic allocation may be regarded as more realistic for driving utilisation and problems of volatile prices may be overcome by giving an average over several years.

Guinée *et al* (2004) suggested strategies to overcome problems in attributing economic value in distorted and fluctuating markets. These include averaging prices over several years, using price trends and prices for similar products.

For these reasons allocation has been made on the basis of economic value as a primary choice, as the by-products under study have been regarded as waste until recently and still pose significant disposal problems in some locations. For example, shrimp processing by-products in Vietnam, where there is no established chitosan industry (Trung 2010). Results have also been presented by mass for all products and processes for comparison.

5.2.1.4 Choice of functional unit

The functional unit (FU) of a LCA is defined by ISO 14044 as “the quantified performance of a product system for use as a reference unit” and should describe the function of the system in a measurable way according to its goal and scope (ISO 2006b). In the case of food this could perhaps be some nutritional descriptor, such as a quantity of protein, because two different food items may have different nutritional values and it would be inappropriate to compare their mass alone. The functional unit then defines the “reference flows” for the LCA, i.e. how much of each product is required to provide the functional unit.

In the aquaculture LCAs cited above, different approaches have been adopted when defining systems with multiple products. Also studies may wish to compare various options for using a certain amount of a by-product which may have otherwise been regarded as waste material (i.e. the FU is a starting quantity of by-product, not the function of the final product, resulting from the by-product input), as for Arena *et al* (2003), Lundie and Peters (2005), Kim and Kim (2010). Kim and Kim (2010) for example, showed that feeding municipal food waste to animals produced significantly less emissions than disposal options.

For comparing between different aquaculture or livestock species, it is not appropriate to set the system boundary at the farm gate, as many studies have for systems comparisons of the same species. Setting a live weight FU comparing different livestock species, which produce significantly different edible yields, will give a distorted outcome, as the subsequent use or disposal of the inedible part is not fully investigated (Henriksson *et al* 2012; Roy *et al* 2009). Figure 5.3 shows a simplified hypothetical example of this where 1g of CO_2 is released for every 1g of whole fish produced for both *Pangasius* and Atlantic salmon. The system boundary of the LCA (dotted line) measures only the production of the fish as live weights but because the two species have such different edible yields, they do not perform the same function in providing the same nutritional value and are not comparable. How the edible yields of the species perform in the LCA are then subject to how the impacts are allocated between the edible yields and the by-products. In this example it is assumed that the by-products are utilised and the impacts are allocated to them by mass, for simplicity. Comparisons of live weights of different animals (e.g. Aubin and colleagues 2009, 2006) are also inappropriate because of the differences in by-product utilisation and possible differences in methodology for modelling upstream inputs between the separate studies.

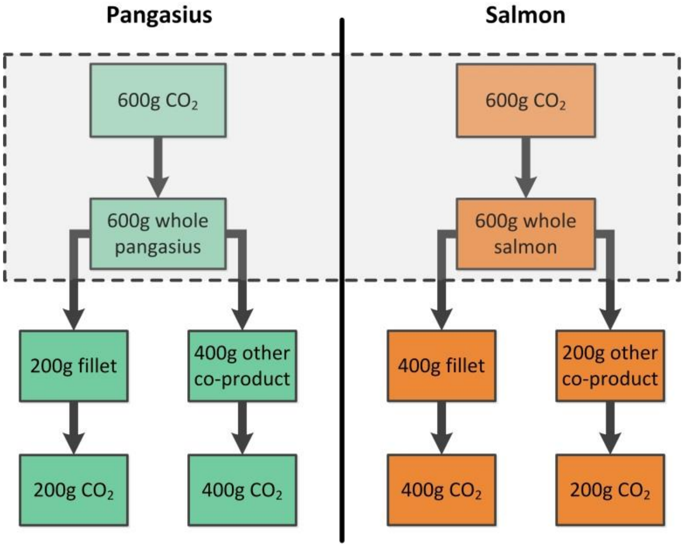


Figure 5.3 Simplified example of how live weights are not appropriate for species comparisons.

The utilisation strategies for the non-edible by-products of salmon and *Pangasius* are quite different as discussed in chapter 1. Despite the high edible yield of salmon at around 62% (Ramíres 2007) and the utilisation of the viscera from primary processing, challenges still remain regarding utilisation of the other by-products in fragmented value chains. Large quantities have often been incinerated or sent to land-fill in the past, with significant environmental and economic cost (SEPA 2004) compared to the extensive utilisation strategies for *Pangasius* by-products in Vietnam. In many cases, allocating the impacts to the fillet by economic value at the processing stage will reflect the utilisation of the other fractions. I.e. the value of the by-product is proportionately higher for *Pangasius* than that of salmon because the by-product applications and markets are more established, although this is not the case in all industries. However, an LCA of equal weight of fillet of the two species, allocated by economic value may be considered as an appropriate choice of FU in many circumstances. For more complex studies such as in this thesis where it is desirable to compare the total amount of products which can be obtained from a species, more novel approaches are needed.

In such cases and where the nature of the products differs greatly the choice of FU is especially important and raises complex issues, for example when assessing integrated systems, where there are several diverse “target” products. These issues were raised by Reap *et al* (2008), where the importance of choosing an appropriate FU that encompasses the functionality of the product or products was highlighted. In many Asian countries and some Western production systems, the nutrient-rich effluent from flow through aquaculture, static pond systems, cage systems or recirculating aquaculture systems (RAS) is commonly used to supply nutrients for production of lower trophic species within the same or co-located systems, including agricultural crops, seaweeds and molluscs. This type of production is commonly known as integrated agriculture-aquaculture (IAA) or integrated multi-trophic aquaculture (IMTA). The IAA/IMTA concept is inherently multi-functional, where lower trophic level species may serve as bio-remediation for fed-species waste, which in turn supply nutrient to supplement the lower trophic levels, producing additional economically valuable products (Phong and colleagues 2007, 2011; Chopin *et al* 2001). There are significant challenges in designing adequate FUs for these diverse and complex systems, especially if comparing between systems or industries, and where it is difficult to subdivide the flows of resources. In such circumstances the LCA could be presented with FUs based on different properties of the products along with the sensitivity analysis (Roy *et al* 2009). For example, Phong et al (2011) chose to present energy and mass alternatively to describe the combined multiple products in expanded (“global”) FUs describing integrated aquaculture in Vietnam. This should be discussed as part of the wider assessment, with supporting data for overall context, transparency and clarity as stipulated by ISO 14040/44 (ISO 2006a; 2006b).

Similar circumstances apply to diverse aquaculture co-product applications at the processing stage, such as industrial uses. A nutritional descriptor is unlikely to be appropriate as it is not the goal of these industries and cannot describe all of the applications resulting from the co-products. Animal production has many examples of this, such as leather from animal skins, cosmetics and biomedical products extracted from various animal parts. In the case of *Penaeid* shrimp in this thesis, the deacetylised products of chitin; chitosan and glucosamine, are used in health supplements, biomedical applications, agricultural and industrial processes (Trung 2010). These components have no nutritional value, cannot be described by energy or other nutritional descriptors and their economic value is highly disproportionate to their mass compared to other products such as the edible yield and shrimp meal. If investigating a global FU for these products, it may be more appropriate to investigate the economic value of the products where their functions are so diverse, e.g. comparing chitosan against shrimp meal production.

Where Kim and Kim (2010) investigated only the use of a by-product and others have only investigated the target product, it is useful to present the subsequent utilisation of the co-products as a proportion of target product. This brings in the principles of more holistic, global FUs suggested above, shows the trade-offs between value addition and economic impact and how these factors can be related to each other for optimum efficiency. Allocating impacts to the co-product at the processor and investigating their utilisation in separate studies, may not always be representative of what can be achieved with the by-product associated with a certain edible yield for different species. Shrimp shells, for example, are of very low economic value compared to that which can be obtained by further processing into chitosan. Similarly, only investigating the target product omits a large part of assessing the overall production efficiency. Incorporating the utilisation of all of the co-product outputs, including the target product is more reflective of the efficiency of the overall system, compared to the point at which the co-products are generated.

Therefore the FU has been chosen in two ways for the LCA studies in chapters 6, 7 and 8. Firstly one of a total mass of products obtained proportionate to one tonne of edible yield, allocated by economic value or mass. Secondly one of US$1000 of total final products allocated by economic value or mass. This gives four separate scenarios and shows a more representative reflection of the industries compared to focussing on single products. The goal and scope of these studies is to show what the environmental impact is in relation to value addition, which is achieved through the utilisation of by-products. In the case of shrimp, two potential strategies for by-product utilisation are compared to identify the most efficient option. Hence, in the first case, the FU is related to a fixed quantity of edible yield, as the primary economic driver of the original production and not the unavoidable by-product. In the second case the FU reflects the impacts associated with a specific economic return, as the values of the final products are disproportionate to the value of the edible yield. This provides an opportunity to investigate the trade-offs between value addition and environmental impact for the various co-product applications for the different species and to be able to compare between species more appropriately than previous studies have attempted. The individual FUs and boundary for each study will be discussed more in their appropriate chapters.

5.2.1.5 Life Cycle Inventory

The Life Cycle Inventory (LCI) includes the individual inputs in terms of raw materials to a system and the subsequent products and emissions for each unit process along a particular value chain within the boundary of the LCA study. It ultimately defines the data collection which is required to construct the LCA model.

Initial data collection for the LCI of the SEAT species formed part of the SEAT integrated survey as described in section 4.2.1. This provided basic data on total harvest, feed inputs, energy use, transport etc. More detailed surveys were conducted on a subset of these farms, processors, service providers and other actors in collaboration with Leiden University and World Fish, who were responsible for providing LCA and LCC (Life Cycle Costing) models respectively on each species to the initial processing stage. A full description of the data collection for in-depth LCA work is given by Henriksson *et al* (2014a) in SEAT deliverable 3.4. Further data were collected personally, by survey in Thailand and Vietnam on by-product processing activities and are given in the individual chapters to which they relate and the questionnaires can be seen in Appendices 2, 3 and 4. The number of facilities surveyed at each node of the value chain in each country is given in table 5.1 and the individual data for each study are described in the relevant chapters. The amount of data that could be collected is highly dependent on the willingness of companies to collaborate and share what is often very sensitive commercial information.

Table 5.1 Number of farms surveyed for each species in each country for in depth LCC/LCA survey work. 5 of the Bangladeshi FW prawn farms were integrated with shrimp and in Vietnam, 5 of the shrimp farms were *L. vannamei* and the rest *P. monodon*

	Species			
Country	Shrimp	Tilapia	*Pangasius*	FW Prawn
Bangladesh	10	-	-	10
China	37	43	-	-
Thailand	20	18	-	-
Vietnam	30	-	20	-

5.2.1.6 Life Cycle Impact Assessment

The LCIA is in several stages. Firstly the impact categories which are being assessed must be chosen. This includes whether an end point or mid-point assessment is to be made. An end point approach attempts to identify the final impact of the emissions upon the environment as a result of climate change, ozone depletion, the effects of toxic substances on human health etc. In practice, however, this is problematic and can be subjective as it can depend on the point of release and how the emissions break down in the environment for which the data are not always sufficiently robust enough to predict these effects (Bare *et al* 2000). More commonly a mid-point approach is taken as by the aquaculture LCAs mentioned above. Mid-point methodology refers to the potential for any emission to have an effect such as GWP. However, an emission can have the potential to cause impact in more than one category and so there is an element of double counting involved. For the purposes of this thesis, a mid-point approach has been adopted according to CML2001 Baseline because it is less subjective than end point approaches and for compatibility with SEAT outputs. The impact categories which have been adopted for the LCA component of this thesis can be seen in table 5.2. These impact categories are the most commonly used in aquaculture LCAs. They were developed during the late 1990s by SETAC with collaboration of academics and industry (SETAC 1999). There has been some debate about how characterisation factors should be supplied, particular for ecotoxicity categories and factors are subject to constant up-dating as new data become available. Discussion around the development of the impact categories can be seen in SETAC (1999), and descriptions of how they can be applied in Guinée *et al* (2002). The LCIA method determines the categorisation of emissions to the different categories, i.e. their equivalent values in terms of their potential to do harm. For example, methane is categorised to GWP as having 25 kgCO_2eq by the CML2001 baseline approach. All LCA analysis was performed using CMLCA 5.2 software (2013) provided by Leiden University, using the Eco-invent 2.2 database. The Eco-invent data base holds LCIs for many processes which are used for the background processes involved in many LCAs. These include the emissions from processes such as fuel combustion in engines and for electricity generation, amongst others, for which there are dozens of individual emissions, the data for which would be too complex to collect for every LCA.

No normalisation or weighting of impacts was performed for these studies because weighting involves value loaded choices over which impacts are more important and normalisation offers little insight into the performance of these systems when compared to each other.

Table 5.2 Impact categories and their characterisation factor used in this thesis

Impact category	LCIA method	Characterisation factor unit
Abiotic depletion	CML2001	Kg Sb eq
Global warming potential (GWP100)	CML2001	Kg CO_2 eq
Ozone layer depletion potential	CML2001	Kg CFC - 11 eq
Freshwater aquatic ecotoxicity potential	CML2001	Kg 1, 4 - dichlorobenzene eq
Marine aquatic ecotoxicity potential	CML2001	Kg 1, 4 - dichlorobenzene eq
Photochemical oxidation potential	CML2001	Kg ethylene eq
Eutrophication potential	CML2001	Kg $PO4^{3-}$ eq
Acidification potential	CML2001	Kg SO_2 eq

5.2.1.7 Uncertainty in LCA; NUSAP approach, horizontal spread and Monte Carlo analysis

LCAs have sometimes been criticised for their lack of scientific robustness in presenting single figures for the various different impact categories with no uncertainty (Heijungs and Frischknecht 2005, Henriksson et al 2014b). In reality, every process within a LCA will be subject to variation based on many factors, including spatial and temporal differences in production yields and constant changes in technology. As discussed above, many of the inputs to a LCA rely on literature sources and these may not always be of high relevance to the system under study. Therefore there is not only inherent uncertainty but also varying degrees of reliability in the data used. Given these areas of uncertainty, several sources of literature may be required for any single unit process and it is necessary to account for the spread of the uncertainty across them (Henriksson et al 2014b).

The Numeral Unit Spread Assessment Pedigree or NUSAP, was first introduced to LCA methodology as early as 1996, as a qualitative assessment tool to attribute a figure to the representativeness of data in the form of an arithmetic or geometric standard deviation. Most LCI data are log-normally distributed, as it is not possible to have a negative input for raw materials within a unit process (which occur in large normal distributions) in reality, which would suggest that they are being returned to the biosphere. However, this is assessed using a decision tree and if necessary distribution is confirmed using goodness-of-fit tests upon the data as in Henriksson *et al* (2014b). The unrepresentativeness can then be horizontally averaged together with the inherent uncertainty and the spread between data sources to provide an overall dispersion as a standard deviation for each input to a unit process, as described by Henriksson *et al* (2014b). This then allows a Monte Carlo analysis to be performed on the LCIA outputs within the CMLCA software. Monte Carlo analysis is performed by repeatedly running the CMLCA model, each time randomly selecting data points that fall within the distribution for each input to every unit process. The more times that the model is run, the more robust the model is, regarding its uncertainty, however, the ideal number of runs is subjective and depends on the complexity of the data. For the purpose of this thesis, 1000 runs were performed for each model, which was deemed sufficient for the purposes of the analysis and feasible in the time frame which is required to run the iterations (Henriksson *et al* 2014a). Uncertainties surrounding the characterisation factors of emissions to different impact categories (which are updated periodically) have not been included in this thesis.

5.2.1.8 Sensitivity analysis

Sensitivity analysis is another level of checking the robustness of the model against its uncertainties and is support by ISO 14040/14044 (2006a, 2006b). It allows for testing the effects of changes in the input data which may have disproportionate effects on the outcome, or those which may have high levels of uncertainty attached to them. For instance there may have been a wide range of electricity requirements reported for chitosan production relative to shrimp shell inputs, which may have also shown to be a hotspot within the manufacturing process. Sensitivity analysis can be used to show how the results change if there is a substantially higher or lower use of electricity, or if electricity is supplied from another source such as nuclear instead of coal. The individual sensitivity analyses will be discussed in the appropriate chapters for each study.

5.3 Life Cycle Assessment of aquaculture by-products

In this thesis three case studies are being presented on the LCAs of by-products resulting from the processing of three major aquaculture species; Thai shrimp, Vietnamese *Pangasius* and Scottish salmon. The by-product applications are different for each species and the methodology described above has been designed in an effort to provide consistency between the three studies. *Pangasius* and salmon are the most similar as the by-products are generally directed to products used in livestock feeds. However, for Thai shrimp the shells can be directed to products used in industrial processes and have no nutritional value. In this case the economic value is used as a proxy for their function to provide comparability between the applications. The value chains and processes behind each by-product and their application are described in the individual chapters for each case study and the overall performance of each species in relation to what all of the products can provide is compared in chapter 9 of this thesis.

CHAPTER 6: LIFE CYCLE ASSESSMENT OF THAI SHRIMP BY-PRODUCT PROCESSING

6.1 Introduction

Although practiced for over a century, the culture of *Penaeid* shrimp (mostly *Litopenaeus vannamei* and *Penaeus monodon*) grew most rapidly during the 1980s and 1990s in SE Asia (FAO 2004, Fishstat 2013). Worldwide estimates for *Penaeid* shrimp culture in 2012 stood at around 2.7 million tonnes (FAO 2012). The edible yield from *Penaeid* shrimp varies between species, but for *L. vannamei*, the by-product from processing is estimated at around 49% by mass, mostly from the head, 71.4%, compared to the shell at 28.6% (Benjakul *et al* 2009). Potentially this leaves up to 1.4 million tonnes of by-product available for utilisation, although this will vary considerably according to local processing practices described in chapter 1. Interviews with shrimp processors in SEAT related work revealed that on average, around 66% of shrimp raw material was sold as finished products of various forms, leaving around 34% by-product (Figure 6.1). Much of this by-product is still being directed towards shrimp meal, although exactly how much is directed to each industry was not collected. Growing industries such as chitosan and hydrolysates may offer better solutions to shrimp by-product use, both environmentally and economically, given the prices and performance that can be achieved from these products outlined in chapter 1. If this is the case, it is likely that there will be a shift in how by-product is directed, primarily driven by economics Guinée et al 2004).

Shrimp hydrolysate is a protein concentrate for which LCI data were collected from experimental production by one company in South America and commercial production by one Thai shrimp processor that also manufactures shrimp meal. It is obtained by the enzyme hydrolysis and concentration of proteins from shrimp heads, leaving a shrimp shell powder from the ground carapace. The remaining shell powder was sold separately but could potentially be directed towards the extraction of chitin for the manufacture of chitosan. There is already an established chitosan industry in SE Asia, particularly in Thailand and China. However, some anecdotal evidence has shown that quality and consistency can be highly variable between different manufacturers and between batches (Taylor, pers comm 2013). Highest grade chitosan is highly deacetylised (>95%), with low molecular weight and is valued for its antimicrobial properties (Lertsutthiwong *et al* 2002); Synowiecki and Al-Khateeb 2003). Evidence from data collection in Thailand also showed that there is a range of technological expertise and company size within the chitosan industry which contributes to the varying product qualities which can be found within Thailand. Production ranged from small scale cottage industries, producing a range of products for local markets to large industries, producing high grade chitosan powders for trade on the international market. Research gathered for this study showed that some smaller producers have little or no access to water treatment facilities and discharge untreated effluent directly into local water bodies. The larger producers, however, had complex recirculation of their effluent, often reusing the acid and alkali, and biological treatment processes before discharge into the environment.

Various trade-offs were apparent between the various routes for shrimp by-products. While shrimp meal production may have lower energy inputs compared to hydrolysis, the performance of hydrolysis in aquaculture and livestock feeds is superior (Whiteman and Gatlin 2005, Hardy *et al* 2005, Córdova-Murueta and García-Carreño 2002). The hydrolysis process also frees up the shell by-product for further utilisation in the chitosan industry compared to the shrimp meal manufacturers surveyed, which used all of the shrimp by-product.

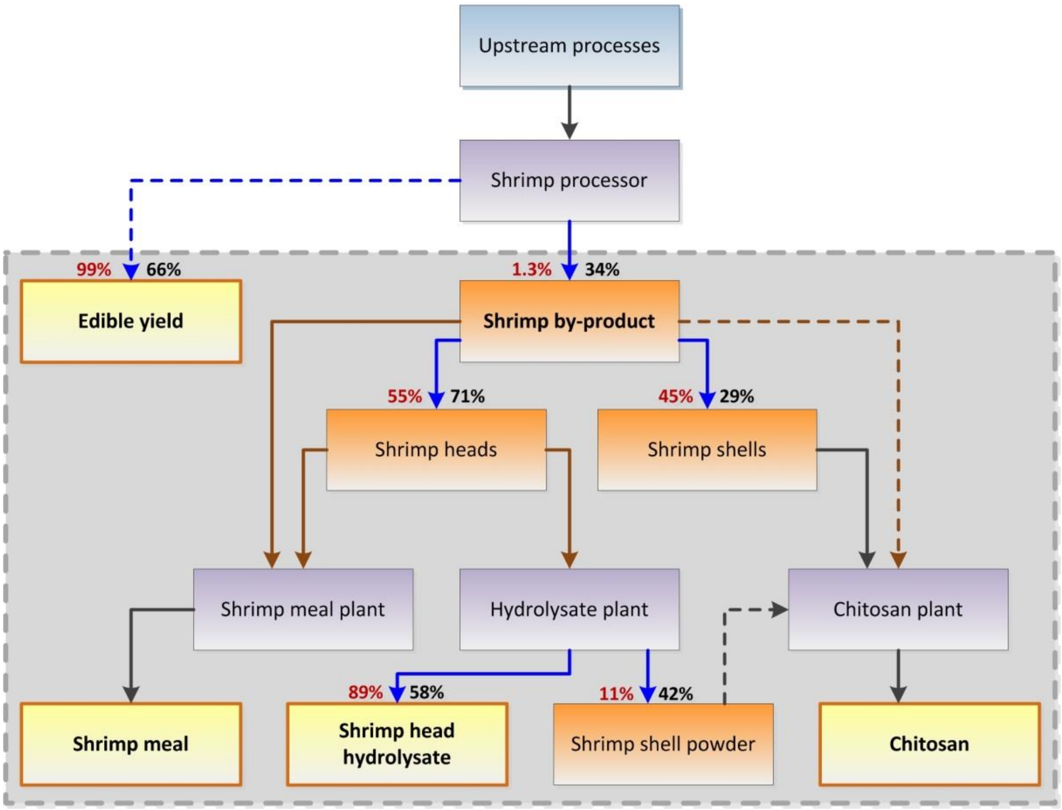


Figure 6.1 Shrimp by-product value chain, showing multi-functional flows (blue arrows), alternative utilisation (brown arrows), economic and mass allocation (red and black percentages) and final products (yellow boxes with brown borders). Yields and economic values from survey work except edible head to shell ratio from Benjajul *et al* (2009)

However, there have also been concerns that chitosan production may be responsible for environmental impact through intensive processes, using strong acids and alkalis, which may be released within resulting effluents, particularly in smaller scale production facilities (Trung 2010; Aye *et al* 2004; Pacheco *et al* 2009). Trade-offs also exist in the value-addition that may be achieved vs. the environmental impact in most cases. While hydrolysate manufacture may be more energy intensive than shrimp meal production, its value is considerably higher, reflected by its performance advantages. Similarly, while chitosan may be an energy intensive process, highest grades are of considerable economic value and their benefits in terms of services provided may be difficult to quantify. An overview of the production value chain can be seen in figure 6.1. The blue arrows show points in the value chain where there are multiple products from one process, whereas the brown arrows show points in the value chain where there can be alternative uses for one particular product. The red and black numbers show economic and mass allocation proportions between the multi-functional processes. Figure 6.1 shows an overview of current practices in Thailand which were being applied by plants interviewed during LCA survey work and forms the basis for comparing utilisation strategies to ascertain the best route for the different by-product fractions.

6.2 Goal and Scope

This study seeks to investigate the most efficient utilisation strategies for the shrimp by-product resulting from processors summarised in figure 6.1, in terms of environmental impact and value addition, and the trade-offs between them, using a combination of Life Cycle Assessment and economic appraisal techniques.

Standard attributional LCA methodology was used to assess two shrimp meal plants, one of which was also a small scale shrimp head hydrolysate producer, four chitosan manufacturers and a prototype shrimp head hydrolysate plant. The scale of the chitosan plants ranged from 2.5 tonnes production in a family run business to a large international producer of 168 tonnes per annum. All of the production facilities were situated in

Bangkok and the facilities studied were assumed to provide a representative sample of chitosan and shrimp meal production in Thailand. Hydrolysate production from shrimp heads is a relatively new innovation with only limited production in Thailand. The data collected from the Thai producer were from a multifunctional process along with shrimp meal production and may not give a representative assessment of its production. Therefore data were also collected from an established multinational hydrolysate producer that is developing shrimp head hydrolysate at a pilot level as part of its range of products. Although the plant for this product was based in S. America, the conditions that would be required were assumed to be similar and representative of how commercial production would be developed in Thailand. Inputs for this plant were standardised to Thai conditions in terms of electricity mix, raw materials, transport etc.

The functional unit for this study was given in two ways as explained in chapter 5. Firstly it was given as the total mass of products obtained in relation to one tonne of edible yield of shrimp. Secondly it was given as $1000 of total products coming from the whole shrimp product, including the edible yield from the shrimp. The separate LCAs for one tonne of product are also presented for each company. The boundary of the study was set at the point of production of chitosan, hydrolysate and shrimp meal and did not investigate the further use of these products in subsequent industries. Although this would have been desirable, particularly for investigating the comparative uses of shrimp meal and hydrolysates in livestock feeds, data on these industries could not be obtained within the time scale of the project. The various qualities of the chitosan were also difficult to quantify, although some of the companies did give the degree of deacetylisation (DD) of their products. The smaller chitosan industries were not able to give this information. The economic value of the chitosan products could be considered as a proxy for their quality and is therefore included within the second functional unit. Allocation to products resulting from multi-functional processes was given first by economic value and then secondarily by mass as described in chapter 5. All data were modelled using CMLCA 5.2 software provided by Leiden University and Ecoinvent 2.2 life cycle assessment database.

6.3 Life Cycle Inventory

Data for the Life Cycle Inventory (LCI) were collected by survey over a fifteen month period during January 2012 to April 2013. The data built on primary and secondary data already collected and compiled in collaboration with Henriksson *et al* (2014a) from shrimp production, feed, processing and service industries in Thailand. The electricity mix for Thailand was developed from the International Energy Agency website (http://www.iea.org/) and other data were adjusted to Ecoinvent 2.2 processes as described below. Initial concentrations of compounds contributing to eutrophication in waste water were calculated from the protein and mineral contents of shrimp shells and heads as given by Mizani and Aminlari (2007), Teerasuntonwat and Raksakulthai (2000), Ruttanpornvareesakul *et al* (2005) and Fox *et al* (1994). The reference period for this data was the entire production during the last entire year of operation, 2011 or 2012, depending on when the data were collected. The blank LCA survey questionnaires which were used in the data collection for the by-product processing part of the value chain can be seen in appendix 2.

6.3.1 Chitosan plants

Data collection was extremely problematic in terms of finding companies which were willing to participate and were then willing to provide full data sets. Of over a hundred chitosan companies contacted, only four responded at all (Satapornvanit pers. comm. 2013) and of those, some were only willing to give incomplete answers to the surveys. Therefore some assumptions needed to be made regarding the total yields of chitosan in two cases, based on the yields and price data that had been collected from other companies and literature data (Lallemont 2008). Plant 2 (CH2), for example, could not give a quantity for the amount of highest grade chitosan that they produced for use in cosmetics. Therefore a 10% total yield was assumed and the figure extrapolated from that. Plant 4 (CH4) gave the quantities of products but not the total amount of raw material which was a mixture of shrimp, crab and squid by-products, and therefore also needed to be extrapolated according to yields from the other companies and literature data. The uncertainty around raw material inputs and yields is reflected in the price data shown in table 6.1 which is highly varied. However, much of this can also be attributed to the product forms. As small companies, CH1 and CH2 both produced finished products of various chitosan solutions for applications as varied as use in agriculture to cosmetics. CH2 produced large quantities of cosmetic chitosan lotions with concentrations of between 3% and 5% for 2000 Thai baht (US$62) per litre. This was responsible for the high price of solid chitosan at CH2. The prices given are per kilogramme of the solid chitosan which is incorporated into these products. In contrast, the larger companies produced solid chitosan raw materials for further sale on international markets.

Although quite unsatisfactory on the surface, the data still provided some insight into the resources and impacts required for chitosan manufacture in Thailand. The LCI for each chitosan plant which took part in the survey is given in table 6.1. Another area where data were somewhat unsatisfactory was on the effluent discharge from the plants. Although some companies said that they used waste water treatment, they were not able to give enough detail to model it sufficiently in terms of concentrations of various impacting compounds within the effluent and other assumptions needed to be made. The data is therefore presented as if there was no treatment. However, for plant CH1 it was declared that 1000L each of used acid and alkali were sold as fertiliser to local farmers and therefore it was judged to have left the system. All of the plants used some water treatment, with at least one settlement pond for collecting suspended solids and some used a small amount of their chitosan production to help flocculate the solids for ease of settlement. CH2 used 12 ponds with gravel, sand and activated carbon filters before utilising some of the water as fertiliser on-site and discharging the rest. The proportion of water discharged was not known. CH4 used a water treatment system with pH adjustment which allowed them to reuse the water around ten times. Only CH3 discharged the effluent after limited treatment in a single settlement pond. It was claimed that there was no need to treat the effluent because chitosan is used commercially for waste water treatment and therefore the water quality of the effluent was good. The typical production process is given in figure 6.2 and described in chapter 1.

Despite companies giving the fuel used in their vehicles, these were used almost exclusively for collecting raw materials for the plant. However, all plants also declared that they sometimes outsourced the delivery of the raw materials for which data were

Table 6.1 Life Cycle Inventory of four chitosan manufacturing plants in Thailand. *Where raw material was given as mixed by-product, it was split between heads and shells as given by Benjakul *et al* (2009), above. †CH4 used a mixture of shrimp, crab and squid shells/pens but it was assumed to be all shrimp shell as no individual quantities were given.

	Plant			
INPUTS	CH1	CH2	CH3	CH4
Shrimp raw material, tonnes				
Mixed by-product	10*	-	-	-
Heads	7.14	-	-	-
Shell	2.86	80	120	1500†
Chemicals, tonnes				
Hydrochloric acid 30%	7.47	0.191	27.4	1.50
Sodium hydroxide 50%	5.92	3.24	24	4.80
Energy				
Electricity, MWh	51.4	17.2	24.0	286
Liquid petroleum gas, MJ	13301	21282	325577	53197
Diesel, L	2400	2000	25500	40000
Water, L	12000	960	5610	562228
OUTPUTS, tonnes				
Chitosan >90% DD, kg	0.84	7.50	-	168.7
Chitosan food grade, kg	0.60	0.30	13.7	-
Chitosan agricultural grade, kg	1.08	0.20	-	-
Total chitosan yield %	25.2	10	11.4	11.2
Price per kg, nearest US$	164	1680	31	62
Other products	Fertiliser, insecticide, soap	-	Ossein	-
Water treatment	Sedimentation, reuse water, adjust pH, use some chitosan as flocculent. Some effluent sold as fertiliser.	Catching points, sedimentation ponds. Uses effluent as fertiliser on site	Sedimentation ponds	Sedimentation, adjust pH, reuse water.

not provided. Therefore, transportation was based on fleet average consumptions per tonne/kilometre travelled for raw material collection, as standardised for upstream processes within the SEAT project by Henriksson *et al* (2014a).

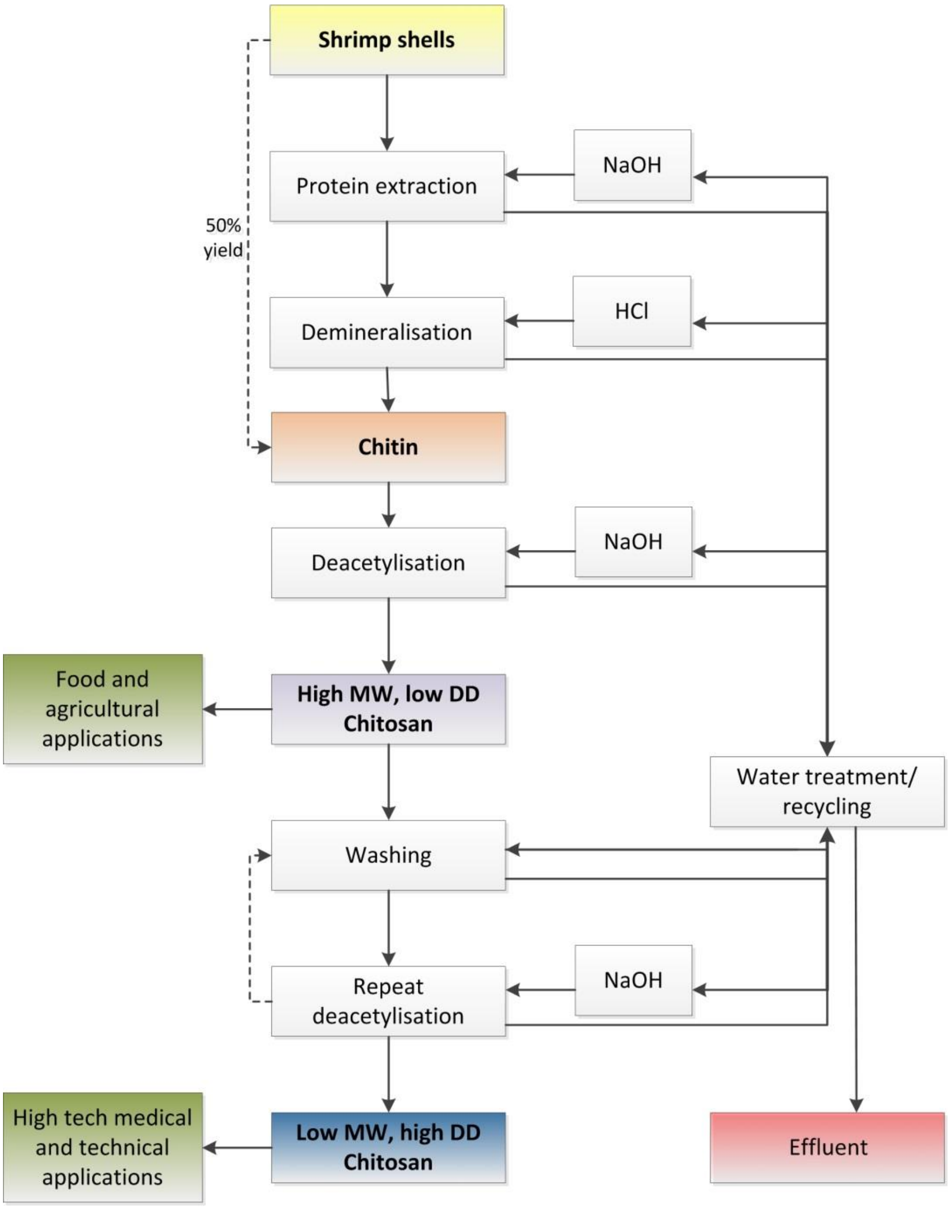


Figure 6.2 Generalised diagram of chitosan production according to LCA survey work in Thailand. Yield of chitosan depends on DD but generally can be expected in the region of 10 to 12% according to Thai industry and Shahidi (2007).

There was little variation in the basic process to produce chitosan between the four plants except that they used different concentrations of acids and alkalis to one another during the process. These needed to be converted to the concentrations given in the

Ecoinvent 2.2 database in kilogrammes, using standard densities, which was 30% w/v for hydrochloric acid and 50% w/v for sodium hydroxide. For example plant 1 (CH1) used 2000L of 80% HCl, whereas CH2 used 5 tonnes of 1% HCl, for 10 tonnes and 80 tonnes of raw material respectively. There were also some differences in the apparent efficiencies of the plants in terms of how much energy they used in terms of electricity and LPG. Plant 3 (CH3), for example used much more LPG proportionately than other plants. This plant also produced ossein, a form of collagen from fish scales, but from two separate production lines and therefore it was possible to sub-divide the contribution to chitosan manufacture. Diesel was mostly used for transport purposes and raw material was mostly sourced from local processors in and around Bangkok except for CH4 which declared transport distances of 350km from southern shrimp processors.

6.3.2 Shrimp meal and hydrolysate plants

Shrimp meal data came from two sources. The first source (SM1) was a very small scale producer, who produced shrimp meal as a side industry to the much larger activities of surimi production. The second source (SM2) was a large scale producer of shrimp meal in a vertically integrated chain of seafood processors and aquafeed producers. As well as processing shrimp, the company also processed tuna and further processed the viscera into a “paste” for use in its feeds. It had also started to commercialise hydrolysed protein concentrates from shrimp heads, which is included in this section. Altogether, it produced over 1500 tonnes of shrimp meal, 600 tonnes of shrimp head hydrolysate and 2000 tonnes of tuna “paste”. The smaller shrimp meal plant, SM1, produced around 100 tonnes of shrimp meal per year.

The main inputs to the shrimp meal manufacturing process at both plants was heating to remove the water content from coal or wood and grinding to reduce the shrimp heads into a meal using electricity. The heat source came from a mixture of wood, coal and electricity between the two plants and can be seen in table 6.2. Processes for the burning of coal and wood were adapted from the Ecoinvent 2.2 database, except wood needed to be converted to units of m^2 for which the density was assumed to be 650kg m^{-2} (taken from http://www.simetric.co.uk/si_wood.htm. Accessed 20/3/2012). According to the database, one tonne of wood and one tonne of coal yielded 5765 MJ and 28901 MJ of heat energy respectively.

Table 6.2 LCI of shrimp meal manufacture from two plants in Thailand. *For SM2, energy resources are 70% of total as given by the plant because of separate production lines. Raw material is allocated according to economic value of shrimp meal and hydrolysate.

	Plant	
INPUTS	**SM1**	**SM2***
Shrimp raw material		
Mixed by-product, tonnes	150	6796
Energy		
Electricity, MWh	2.4	446
Coal, tonnes	-	2862
Wood, tonnes	40	-
Diesel	1200	3948
Water, L	240	3276
OUTPUTS		
Shrimp meal, tonnes	100	1574
Yield total shrimp meal, %	66.7	23.2

Data on shrimp head hydrolysate came from two sources. The first source was the shrimp meal plant described above, SM2, which produced the hydrolysate on a commercial scale. The second source (SHH1) was a pilot scale plant situated in South America, owned by a multi-national aquafeeds ingredient manufacturer that produced a range of hydrolysates and other products from seafood processing waste. It was assumed that the yields from raw materials and energy consumption would be the same as if in Thailand, therefore the standardised electricity mix for Thailand and average transport distances for delivering the raw materials to the plant were used.

The shrimp meal production was sub-divided by SM2 so that 70% of all energy inputs to the plant were to shrimp meal and 12% to hydrolysis with the rest attributed to tuna by-products. The hydrolysate and tuna by-product production were on the same production line. The figures in table 6.2 relate to the 70% of resources attributed to shrimp meal activities only. It is not known exactly how much raw material was directed to shrimp meal and how much to the hydrolysate, although it was declared that the shrimp meal and hydrolysate yields were 11% to 17% and 2% to 4% respectively. However, this makes little sense as from the data given, the yield of shrimp meal alone would be close to 17% and a lower yield would require more raw material than was declared by the producer. Therefore the by-product input was divided proportionately between the two products as they were of equal value, and yield for both shrimp meal and the hydrolysate was consequently the same at 23.1%. The waste-water treatment facility also served the feed production part of the production for this plant. However, according to representatives of SM1, the shrimp meal production process did not produce any waste water, as it is a simple process of drying the shrimp by-product before grinding it into a meal. The water used in the production at SM1 was exclusively for the use of staff for their daily personal use but this was not declared by SM2 and so the water input was allocated as 70% of the total as for the energy inputs. However, no waste water impacts were modelled for shrimp meal production for either plant, with effluent from the plant assumed to be from the feed production and hydrolysation processes only.

6.4.3 Shrimp by-product hydrolysate

The process for shrimp head hydrolysate manufacture as given by the South American pilot operation (SHH1) was as follows. Following transportation to the plant, the shrimp head by-product was put into cold storage, minced and then heated along with an enzyme based ingredient which hydrolysed the by-product. The exact conditions are commercially sensitive, however, at laboratory level, researchers have often used a commercially available enzyme such as Protomex (Nguyen *et al* 2012) or alcalase (Cancre *et al* 1999) at around 40°C. The shells were then separated from the rest of the hydrolysed by-product which was then concentrated by evaporation and spray drying. The separated shells were then put into a flash drier which produced a shrimp shell powder as an end product. Some hydrochloric acid and sodium hydroxide were used throughout the process for pH adjustment and cleaning purposes but only total quantities and concentrations were given, without any detail on their use at any stage. The energy consumption at this plant for these processes was electricity and diesel in contrast to the plant above which produced the hydrolysate along a combined production line, using a mixture of electricity and coal as the main energy inputs. Although the yield of hydrolysate from SM2 in the model was much higher than the estimates from the plant, the yield from SHH1 was also much higher than this estimate. As there was no non-subjective way of dividing the raw material input between the hydrolysate and shrimp meal activities, it was divided by economic allocation, consistent with the rest of the model but with a large uncertainty attached to the yields.

No detail was given on the hydrolysis process at SM2, however, both hydrolysate producers were able to provide some data on the waste water discharge, including chemical and biological oxygen demand (COD and BOD), but no information on nitrogen compounds. For SM2, the impact from waste-water treatment needed to be allocated between the hydrolysate production and tuna by-product activities according to the proportions given by the plant, i.e. 12% to the hydrolysate production. Inputs to the CMLCA software are in kg, whereas effluent concentrations were given in mg/L. It was assumed that 70% of the water usage was used within the shrimp meal production for steam production and the other 18% used for tuna by-product activities. The quantity of effluent was assumed to be equal to the water inputs for each activity with the hydrolysate and tuna by-product processes contributing the same concentrations of BOD and COD to the effluent. The LCI for hydrolysate production can be seen in table 6.3.

6.4 Life Cycle Impact Assessment

6.4.1 Chitosan plants

The production from the different plants was quite varied, both in quality and quantity as can be seen in table 6.1. The yield from CH1 was exceptionally high compared to other

Table 6.3 LCI of shrimp hydrolysate manufacture from two plants, SM2 in Thailand and SHH1 in South America, adjusted to Thai conditions. *For SM2, energy resources are 12% of total as given by the plant because of separate production lines. Raw material is allocated according to economic value of shrimp meal and hydrolysate. †For SHH1 input is shrimp heads only whereas for SM2 it is mixed by-product in the proportions given by Benjakul *et al* 2009

	Plant	
INPUTS	SM2	SHH1
Shrimp raw material, tonnes		
Mixed by-product	2694	-
Heads	-	10000
Chemicals, tonnes		
Hydrochloric acid 30%	-	33.5
Sodium hydroxide 50%	-	11.0
Energy		
Electricity, MWh	76.4	1610
Coal, tonnes	490.7	-
Diesel, L	-	457
Water, L	561.6	8390
OUTPUTS, tonnes		
Shrimp hydrolysate,	624	1360
Shrimp shell powder	-	1000
Total hydrolysate yield %	23.1	13.6
Price of hydrolysate per kg, US$	0.43	3.25
Water treatment	Grease traps, aerated sedimentation ponds, sediment presses. BOD 41.6mg/L, COD 15 mg/L	No details given on process. BOD 100mg/L, COD 250mg/L

plants, but it also produced the largest range of chitosan products of different qualities. The different degrees of deacetylisation of the various products were not given by the company, but it is assumed that both agricultural and food grade will be under 90% and most likely in the range of 75% to 85%, which is the DD which can be expected after one deacetylisation step according to Goycoolea *et al* (2000) and above the minimum 70% DD for food grade chitosan given by Dexter (2005). These products were sold in solutions of 3% and 5% for agricultural and food applications respectively, but it is likely that they were not pure chitosan because of the high yields. They may have had some residues left from the shrimp heads that were used at this plant, as it is most common to use shell only, as demonstrated by all of the other plants. The higher protein content of the head contributes to a much more eutrophic impacting effluent per unit raw material input than just the shells from the other plants. However, considering the high yields of production and that the plant sold around half of its effluent as fertiliser, the eutrophication per unit chitosan production is lower than for the other plants. Plant CH2 also produced a range of products of varying quality and it was stated by them that the highest quality of over 90% DD was used exclusively in cosmetic solutions of around 3.5% concentration. However, they were not able to give a definitive figure of production as discussed above. Only plant CH4 produced a consistently high grade product in large quantities which it sold on international markets. CH3 produced a consistent solid product but at food grade and it is suspected that this was of a lower quality than that produced by CH4. Table 6.4 shows the LCIA for the four plants for production of one tonne of total solid chitosan product, calculated using economic allocation. This was based on the total quantity of solid chitosan as powder combined with that calculated from the concentrations of solutions as given by the plants, and in some cases estimated from economic value of the shrimp by-products leaving the processing plant. The results presented in table 6.4 assume that there was no waste water treatment, with all effluent being discharged into the local water body, except for CH1.

Table 6.4 LCIA of four chitosan production plants per one tonne of solid chitosan using economic allocation, means and standard deviations after 1000 iterations of Monte Carlo analysis, to 3 significant figures. *DCB= dichlorobenzene.

		Plant			
Impact category	**Unit**	**CH1**	**CH2**	**CH3**	**CH4**
Abiotic depletion, rare elements	kg Sb eq	0.0126 ±0.00769	0.00269 ±0.00131	0.0103 ±0.00721	0.00243 ±0.00104
Abiotic depletion, fossil fuels	MJ	265000 ±52900	74800 ±20500	150000 ±21900	59900 ±19600
Global warming, GWP100	kg CO_2 eq	15800 ±2300	5130 ±1350	7820 ±1190	4370 ±1270
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.00214 ±0.000537	0.000589 ±0.000235	0.00167 ±0.000424	0.000494 ±0.000215
Fresh water ecotoxicity	kg 1,4-DCB eq*	2280 ±781	494 ±186	1290 ±594	341 ±184
Marine ecotoxicity	kg 1,4-DCB eq*	946000 ±231000	206000 ±65800	4400000 ±1300000	149000 ±62500
Terrestrial ecotoxicity	kg 1,4-DCB eq*	76.3 ±21.3	18.6 ±5.14	53.4 ±14.8	12 ±4.33
Photochemical oxidation (high NOx)	kg ethylene eq	2.15 ±0.330	1.09 ±0.504	1.82 ±0.440	0.911 ±0.424
Acidification	Kg SO_2 eq	45.4 ±6.09	24.9 ±7.21	37.3 ±6.84	21.7 ±6.62
Eutrophication	Kg PO_4^{3-}eq	114 ±11.1	219 ±17.5	199 ±18.3	197 ±17.2

Despite having the highest yield, plant CH1 had the highest impact in almost all categories. The only category where CH1 had less impact was eutrophication potential and this was due directly to the higher yield, requiring less shrimp raw material, which led to a lower N content from protein being discharged in the effluent and that some of this was then sold. The high global warming potential (GWP) of CH1 is mainly from coal and gas power stations and associated processes, such as mining, required to supply the high electricity usage that this plant has, as seen in table 6.1, and this is mostly responsible for the high acidification, photochemical oxidation and toxicity potentials of plant CH1 too. In the case of other plants, higher fishing effort and higher urea application in upstream processes contribute more proportionately to NOx and carbon monoxide emissions respectively, in order to provide the larger volumes of shrimp raw material required. Both of these emissions are particularly associated with photochemical oxidation potential.

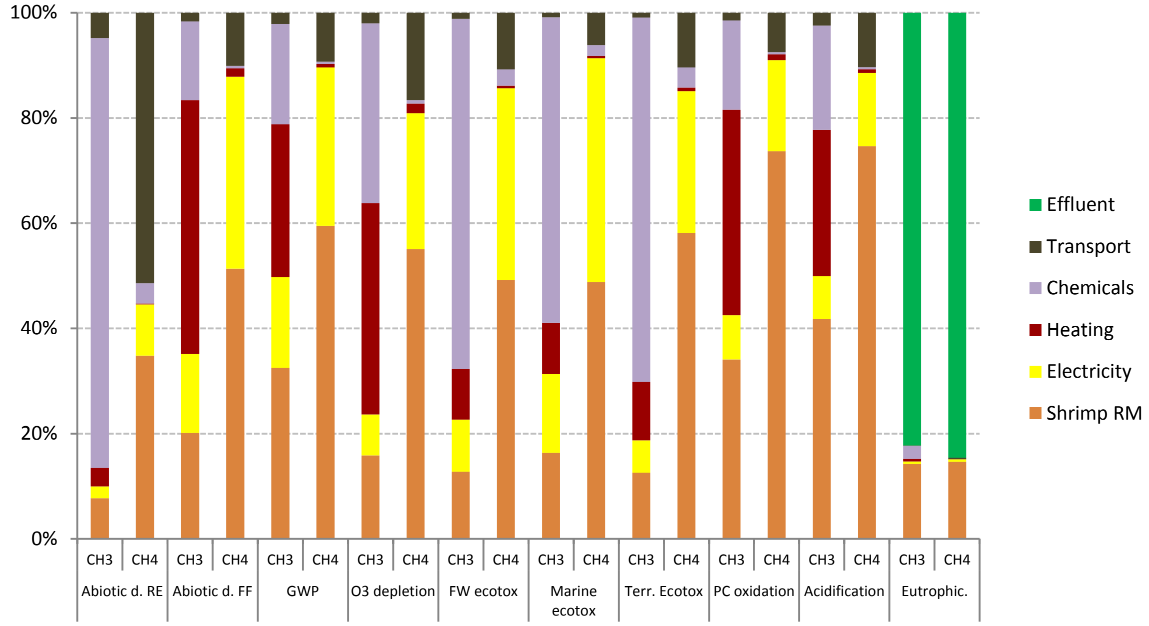


Figure 6.3 contributions to impact categories from individual inputs to selected chitosan manufacturing plants. RE = rare elements, FF = fossil fuels, RM = raw material

CH4 was the best performer of the four plants and this is unsurprising as the largest company, it was more efficient with almost all of its inputs, except for the shrimp raw material. CH2 also performed well comparatively, however it was these two plants for which there was most uncertainty related to their overall yields and this is demonstrated in the standard deviations presented in table 6.4. As this initial analysis was based on economic allocation only, the contribution from the shrimp shell material is relatively small at only 0.5% of upstream impacts coming from the shrimp processor. If using mass allocation, the upstream impacts from the processor would be 9.7% (28.6% of 34%), as shown in figure 6.1. This would mean that the effect of higher yields would be much stronger and CH1 would perform much better on this basis. Despite this, the contribution to acidification and photochemical oxidation from the raw material is as much as 75% each, and a significant proportion to the other impact categories, to the overall LCA. Figure 6.3 shows the contributions to the various impacts from various inputs to the chitosan manufacturing process for plants CH3 and CH4, as the two plants which produced uniform solid chitosan products. These plants had very similar yields and electricity use. The main difference between them was the large amounts of heating (from LPG), acid and alkali at plant CH3 compared to CH4. The high contributions from transport to plant CH4 are also of note.

As no water treatment was included in the assessment, the contribution to eutrophication from the plants' effluent is high, based on the nitrogen content of the protein bound to the shells. Contributions from the organic carbon are not included and their impact is very much dependent on the efficiency of the water treatment facilities. According to the IPCC (2006) the ratios of carbon dioxide and methane that are emitted from waste water are dependent on how anaerobic the treatment plant becomes, which in turn is dependent on many factors, such as the depth of the settlement ponds and the level of aeration. The carbon emissions from shrimp are biogenic and therefore carbon dioxide releases would be neutral, however releases of methane could add significantly to the overall GWP. The total organic carbon content of the shrimp shells was calculated at 14.6% based on Mizani *et al* (2007), Teerasuntonwat *et al* (2000) and Ruttanapornvareeskul *et al* (2005). Figure 6.4 shows the contributions to producing shrimp at the farm and to producing feed at the mill which have a heavy influence on the impacts of producing chitosan. In most cases feed contributes to at least 50% of the impacts to farming and therefore it could be said that it contributes to over 30% of GWP, photochemical oxidation and acidification of producing chitosan at CH4 using economic allocation, and substantially more using physical allocation. The contributions to farming and feed will also have substantial influence on the impacts of other by-product industries. The upstream impacts are beyond the control of the plants but CH4 could reduce its emissions through sourcing by-products from closer processors and could perhaps try to reduce electricity usage. CH3 could best reduce its emissions by reducing its chemical usage through better recycling and water treatment as used in CH4.

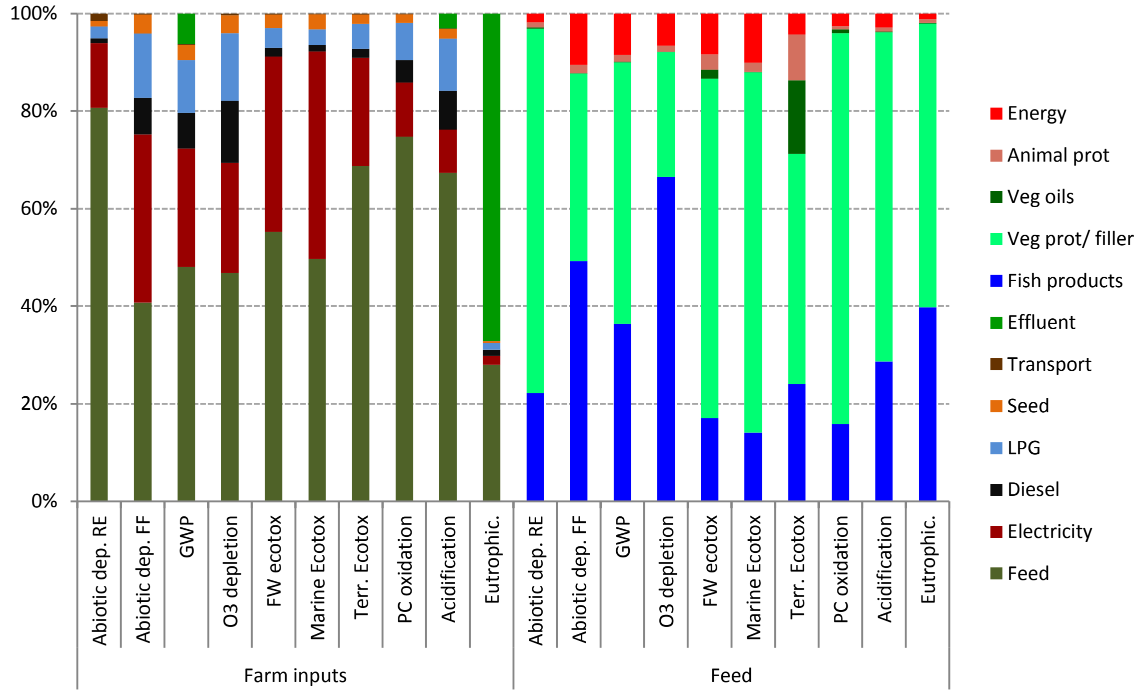


Figure 6.4 contributions to producing shrimp at Thai farms and feed at shrimp feed mills

6.4.2 Shrimp meal plants

The LCIA of producing one tonne of shrimp meal from the two production plants is presented in table 6.5. The impact from SM2 is substantially higher in most categories, although with higher variance, and this can be attributed to the lower energy inputs for heat required in SM1 and the higher production yield. The high variance at SM1 is a consequence of large uncertainties surrounding energy production from the burning of wood for heat. SM1 reportedly used only 0.267 tonnes of wood per tonne of shrimp raw material compared to 0.411 tonnes of more energy containing coal per tonne of raw material in SM2. Also, as coal is a fossil fuel, some of the higher impacts at SM2 can be attributed to the use of coal as a heat source compared to the use of a biomass fuel such as wood. As a “renewable resource”, the carbon emissions from burning wood are counted as biogenic and therefore any carbon that is produced during burning is equal to that which had been sequestered during its growth. This is demonstrated in the contribution analysis presented in figure 6.5. However, the LCA model does not make any provision for the sustainability of the resource in terms of land clearance or destruction of sensitive habitats in this instance, and it is not known where this wood was sourced from. Despite this, substituting the wood for coal in SM1 still produces substantially lower impacts than SM2 because of the higher energy requirements at this plant. Some attempts have been made to include the effects on biodiversity and land change but they still remain underdeveloped and are not included in this thesis, e.g. (Brandão and Mila I Canals 2013, Bentrup *et al* 2002, Weidema and Lindeijer 2001).

There is a much lower yield at SM2 compared to SM1 as can be seen in table 6.2. SM1 produced almost three times the amount of shrimp meal yield as SM2. The low ratio of other inputs to shrimp by-product at SM1, result in the vast majority of almost all impacts coming from the shrimp raw material, the contributions to which can be seen in figure 6.4. The eutrophication potential, ozone depletion and abiotic depletion of rare elements potentials are more proportionate to the yields than other impact categories, as in both plants, the majority of the impact originates from the raw material. In all other impact categories, the majority of the impact at SM2 can be related to the burning of coal for heat.

Table 6.5 LCIA of two shrimp meal production plants per one tonne of shrimp meal using economic allocation; arithmetic means and standard deviations after 1000 iterations of Monte Carlo analysis, to 3 significant figures. *DCB= dichlorobenzene.

		Plant	
Impact category	**Unit**	**SM1**	**SM2**
Abiotic depletion, rare elements	kg Sb eq	0.000234 ±0.0000929	0.000647 ±0.000232
Abiotic depletion, fossil fuels	MJ	7190 ±4280	97900 ±14300
Global warming, GWP100	kg CO_2 eq	593 ±269	7300 ±860
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.0000616 ±0.0000382	0.000214 ±0.0000967
Fresh water ecotoxicity	kg 1,4-DCB eq*	44 ±27.6	1290 ±528
Marine ecotoxicity	kg 1,4-DCB eq*	17800 ±11400	5940000 ±1580000
Terrestrial ecotoxicity	kg 1,4-DCB eq*	2.78 ±1.37	18.1 ±5.83
Photochemical oxidation (high NOx)	kg ethylene eq	0.203 ±0.092	2.23 ±0.38
Acidification	Kg SO_2 eq	3.79 ±1.09	50.1 ±7.58
Eutrophication	Kg PO_4^{3-}eq	6.03 ±1.42	23.9 ±5.55

Eutrophication was largely from shrimp farming and processing activities for both shrimp meal plants, although a contribution also comes from coal mining activities, for direct heat usage and electricity consumption at SM2. According to Focken *et al* (1998) the moisture content of *Penaeid* shrimp is around 74.9% (table 1.1), so it may be considered that either the shrimp meal from SM1 still had substantial water content left within it, or that the raw material that they were using had already been partially dried before processing to shrimp meal. The raw material at SM2 would have come directly off the shrimp processing line at the same facility and the yield of shrimp meal is much more in agreement with the moisture content that had been reported by Focken *et al* (1998) in table 1.1. Therefore it may be considered that the process at SM2 is probably much more representative of that which could be expected, compared to that at SM1.

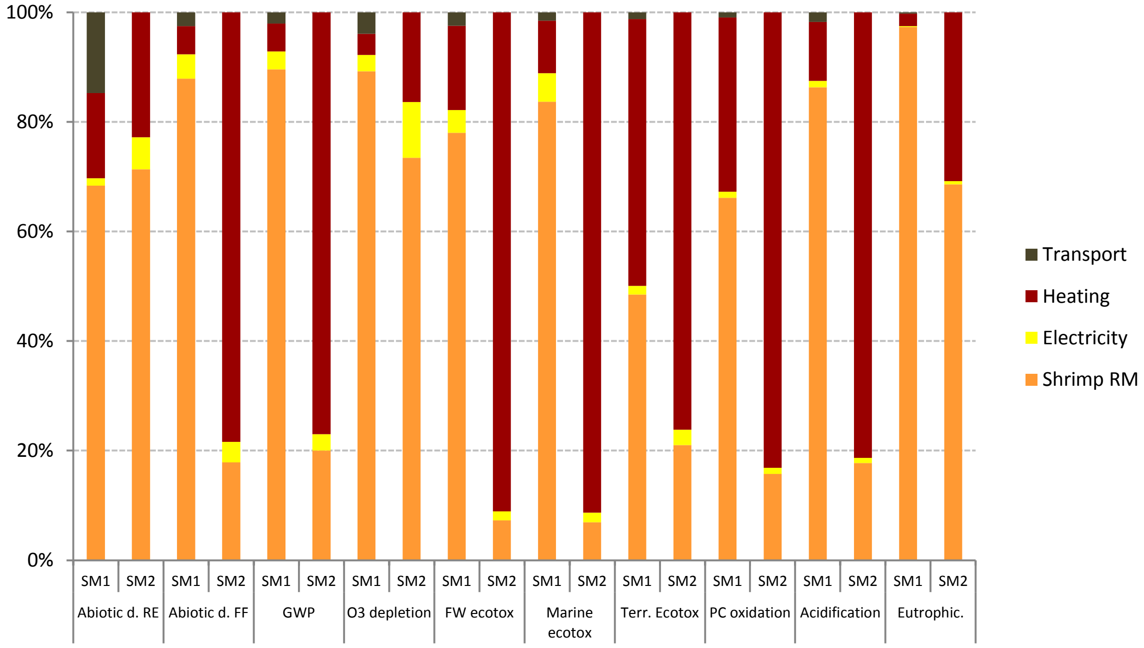


Figure 6.5 contributions to impact categories from individual inputs to shrimp meal manufacturing plants in Thailand. RE = rare elements, FF = fossil fuels, RM = raw material

Many of the impacts associated with the production of one tonne of shrimp meal from SM2 are comparable to those from chitosan plants, such as GWP, acidification and the toxicity potentials. Eutrophication is substantially lower for shrimp meal plants because there is no effluent released directly from them, although some has been allocated to SM2. In terms of eco-efficiency, chitosan vastly out competes shrimp meal production because of the higher value of chitosan compared to shrimp meal. However, shrimp meal and chitosan industries cannot be considered as alternative utilisation strategies as in most cases, the raw material for chitosan is from the shell only, which could be separated from the head waste as much as possible for the production of shrimp meal. The shrimp meal plants interviewed in this study used mixed shrimp by-product, whereas they could achieve better efficiency by directing the shell fraction to chitosan manufacture. This would not only provide raw material for valuable chitosan production, but also increase the quality of the shrimp meal by reducing the chitin content. The trade-offs between different strategies will be investigate in more detail in section 6.4.4

6.4.3 Shrimp hydrolysate

Impacts from shrimp hydrolysate production were similar between the two plants, especially for GWP, fossil fuel use, acidification, photochemical oxidation and terrestrial ecotoxicity. This was despite the two plants having very different energy sources. However, the yield from SM2 was questionable, with the raw material being allocated between the two production streams based on the value of the products and not sub-divided according to the producer’s estimates. The variance was high for both plants. In the case of SM2, because of the uncertainty about yields, and in the case of SHH1 because it was a pilot plant situated in a different geographical area, not truly representative of Thai production. This can be seen especially in the results for marine and freshwater ecotoxicity for SHH1 where the standard deviation would give rise to negative values. Arithmetic means and standard deviations were used in these sections for ease of representation and comparison in tabular form, whereas for section 6.4.4, geometric means and standard deviations were used which do not give rise to negative values.

Table 6.6 LCIA of two shrimp hydrolysate production plants per one tonne of hydrolysate using economic allocation; means and standard deviations after 1000 iterations of Monte Carlo analysis, to 3 significant figures. *DCB= dichlorobenzene.

		Plant	
Impact category	**Unit**	**SM2**	**SHH1**
Abiotic depletion, rare elements	kg Sb eq	0.000609 ±0.000277	0.00140 ±0.000696
Abiotic depletion, fossil fuels	MJ	0.000554 ±0.000196	0.000584 ±0.000192
Global warming, GWP100	kg CO_2 eq	4230 ±1310	4530 ±1300
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.000190 ±0.000124	0.000585 ±0.000279
Fresh water ecotoxicity	kg 1,4-DCB eq*	651 331	314 ±1220
Marine ecotoxicity	kg 1,4-DCB eq*	2960000 ±1060000	1240000 ±1300000
Terrestrial ecotoxicity	kg 1,4-DCB eq*	10.8 ±4.57	10.3 ±4.1
Photochemical oxidation (high NOx)	kg ethylene eq	1.25 ±0.416	0.944 ±0.471
Acidification	Kg SO_2 eq	28.3 ±7.91	25.7 ±6.89
Eutrophication	Kg PO_4^{3-}eq	21.2 ±6.76	29.7 ±10.5

The contributions from the shrimp raw material are noticeable for hydrolysate production in that despite production higher yields at SM2 than SHH1, the contribution from the shrimp by-product is higher at SHH1 in most cases (figure 6.6). This is because of the use of electricity as a main energy source, compared to coal at SM2. Main contributions to GWP at SH2 are from the energy source used on site, mainly from the burning of coal. They are also high at SHH1 but fairly even between the burning of diesel on site and the burning of gas in power plants to provide electricity. In the case of acidification, the main contributions are also from the burning of fuels on site, SO_2 from coal at SH2 and nitrogen oxides (NOx) from the burning of diesel at SHH1. This is also the case for photochemical oxidation, although a large contribution also comes from carbon monoxide for the production of urea, used as fertilisers in upstream processes, especially at SHH1. Contributions to eutrophication are similar between the two production plants. The majority is from phosphorous and ammonia emissions from shrimp farming activities and consequently more could be expected from SHH1 which has a lower yield from shrimp raw material. However, a substantial contribution also comes from NOx emissions, mainly associated with the burning of coal on the production site at SM2.

The impact from the two hydrolysate plants is comparable to the best performing chitosan plants and better than shrimp meal production from SM2, which is assumed to be the more representative of the two shrimp meal production plants. There is some question over the eco-efficiency of the hydrolysate compared to shrimp meal production as there is a vast difference in the price attached to the product between the two plants.

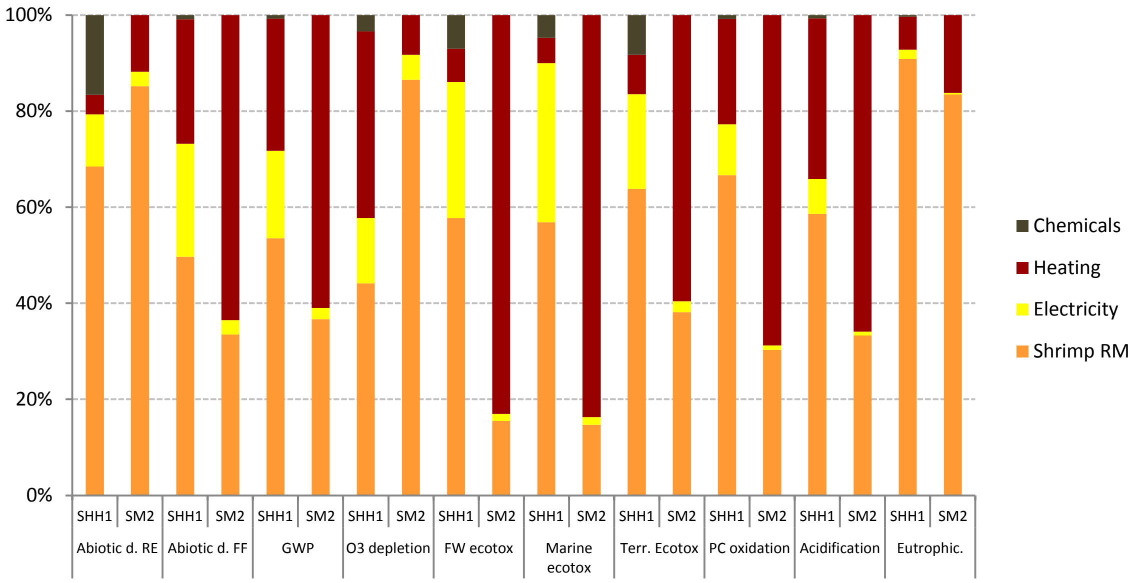


Figure 6.6 contributions to impact categories from individual inputs to shrimp hydrolysate manufacturing plants, SM2 in Thailand and SHH1 in South America, adjusted to Thai conditions and input materials. RE = rare elements, FF = fossil fuels, RM = raw material

According to SM2 the price of hydrolysate and shrimp meal is the same at 14 Thai baht (US$0.23) per kilo compared to US$3.25 per kilo for hydrolysate from SHH1. The price for hydrolysate at SM2 is strange considering the extra expertise required and the purported benefits claimed for the product by SHH1. It may be that the hydrolysate qualities were very different between the plants and little data were available from SM2 in this regard. However, if SM2 was able to separate the shell from the hydrolysate for further sale this would still achieve a better return than the shrimp meal alone. The performance of shrimp hydrolysate in livestock and aquafeeds has not been fully investigated, as it is still largely at pilot level and the market potential is yet to be established. However, if claims surrounding the better performance of hydrolysate are confirmed, a large market could be achieved. This would seem to indicate that directing more shrimp heads from shrimp meal to hydrolysate manufacture would be the best option. This will be discussed in more detail in section 6.4.4.

6.4.4 Comparing best utilisation strategies for shrimp by-products in the Thai shrimp value chain

From the information given by shrimp by-product processors, there are two major alternatives for the use of the raw material. The first option is that all of the by-product is directed to the manufacture of shrimp meal with no remaining by-product for further use. The second option is that the shells are directed to chitosan manufacture and the heads directed to shrimp hydrolysate with a shell powder as a by-product originating from the carapace (in the case of SHH1) which can further be directed to more chitosan manufacture. These will be the two scenarios investigated in this section. It is possible that heads could be directed to shrimp meal with the remaining shells directed to chitosan, but as both the shrimp meal manufacturers used mixed shrimp head and shell raw material, this option will not be investigated. The two options being investigated are presented in figure 6.7.

For this comparison, production of shrimp hydrolysate was based upon that produced at the pilot production plant SHH1, as it used shrimp heads in a single process with the shrimp shell powder as a by-product, which is further used for chitosan manufacture. The chitosan production was based on the production from plant CH4 which was by far the largest plant and also produced chitosan in a single production line. The plant produced solid chitosan only, so there was no ambiguity over the yields compared to CH1 and CH2, whereas CH3 produced lower quality chitosan than CH4. The shrimp meal production was based on that from SM2 as it was deemed the more representative of the two plants, being the larger and having a yield which corresponded more closely to that which would be expected given the moisture content of the raw material.

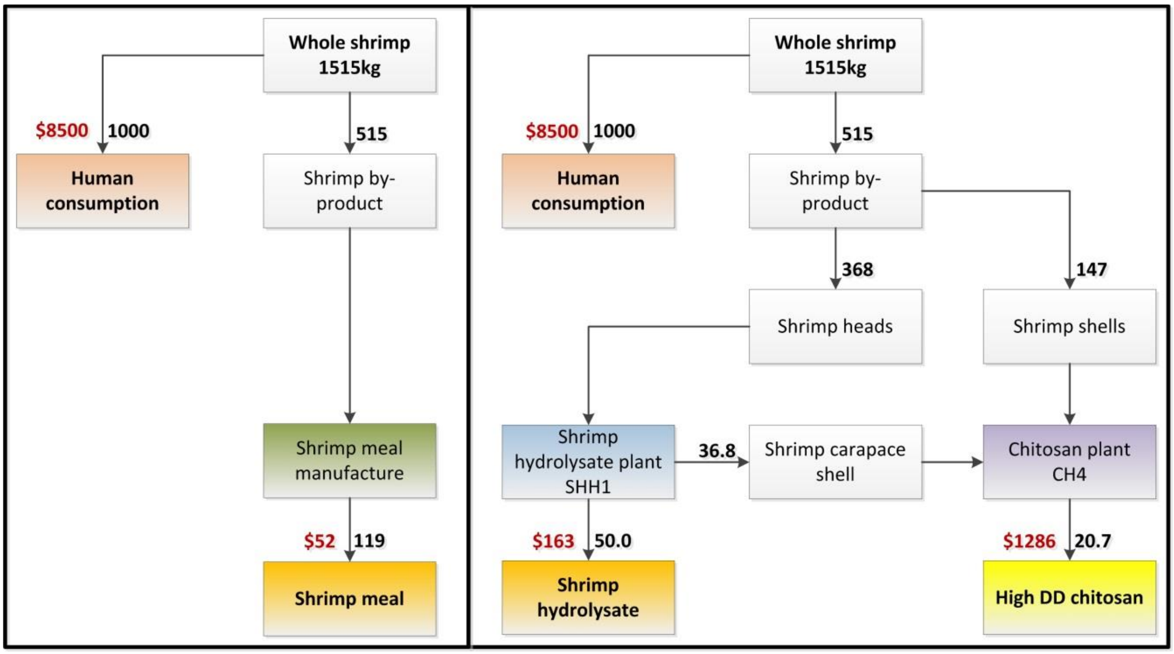


Figure 6.7 Alternative strategies for shrimp by-product utilisation with economic values in US$ (red) and mass of products in kg (black) in relation to one tonne of product directed to human consumption; a) mixed by-product directed to shrimp meal, b) heads directed to hydrolysate with shell by-products directed to chitosan extraction.

The first part of this analysis in section 6.4.4.1 compares the options from the by-product generated from one tonne of product directed to human consumption, from the processor, as described in chapter 5. This was calculated as 515kg, averaged over the processing plants which were interviewed as part of the SEAT data collection. From figure

6.7 it can be seen that although the volume of shrimp meal production in scenario a) is almost double that of the combined products in scenario b), the value of the shrimp meal is far less. The second part of the analysis in section compares the same two scenarios but to produce $1000 of total products. Therefore it will require more production in scenario a) than in scenario b) to achieve this total value.

6.4.4.1 Utilisation alternatives from shrimp by-products associated with one tonne of IQF shrimp directed to human consumption

The LCIA of the production of chitosan and hydrolysate, and shrimp meal in relation to the fraction directed to human consumption can be seen in table 6.7. Using economic allocation and sub-dividing the impacts between the different industries, the impacts from the by-product industries are dwarfed by those of the shrimp production because of the low economic value of the shrimp by-product. Much of the impact on the subsequent by-product industries also originate from the production of the shrimp on farm, especially if mass allocation is used, as shown in previous sections. Its contribution to the different by-product industries can be seen in figures 6.3, 6.5 and 6.6.

Figure 6.8 shows the impacts of the production of the hydrolysate and chitosan versus shrimp meal, from the quantity of shrimp by-product resulting from one tonne of instant quick frozen (IQF) shrimp directed to human consumption, by economic allocation, according to the scenarios demonstrated in figure 6.7. The chitosan and hydrolysate industries are treated separately and the impacts attributed according to the production volumes shown in table 6.7. It can be seen that in most cases that the joint production of

Table 6.7 LCIA using economic allocation showing shrimp meal in scenario a) and sub-divided impacts from chitosan and hydrolysate in scenario b) manufactured from the by-product resulting from 1 tonne of product directed to human consumption. *IQF, Instant Quick Frozen. Means and standard deviations to 3 significant figures.

		Plant			
Impact category	**Unit**	**Shrimp IQF* 1000kg**	**Shrimp meal 119kg**	**Hydrolysate 50kg**	**Chitosan 20.7kg**
Abiotic depletion, rare elements	kg Sb eq	-0.00442 ±0.00183	0.0000852 ±0.0000354	-0.0000708 ±0.0000393	-0.0000521 ±0.0000221
Abiotic depletion, fossil fuels	MJ	-158000 ±94600	12100 ±2680	-2970 ±1390	-1310 ±489
Global warming, GWP100	kg CO$_2$ eq	13400 ±5190	900 ±181	230 ±87.9	95.3 ±32.2
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.00138 ±0.000727	0.0000268 ±0.0000145	0.0000299 ±0.0000155	0.0000108 ±0.00000524
Fresh water ecotoxicity	kg 1,4-DCB eq*	880 ±706	154 ±121	14.3 ±10.4	7.38 ±3.53
Marine ecotoxicity	kg 1,4-DCB eq*	3800000 ±2810000	732000 ±225000	61900 ±40500	32700 ±14000
Terrestrial ecotoxicity	kg 1,4-DCB eq*	35.2 ±14.9	2.31 ±0.900	0.527 ±0.265	0.259 ±0.0989
Photochemical oxidation (high NOx)	kg ethylene eq	3.55 ±2.13	0.275 ±0.0626	0.0476 ±0.0263	0.0196 ±0.00923
Acidification	Kg SO2 eq	84 ±23.5	6.15 ±1.25	1.3 ±0.393	0.473 ±0.156
Eutrophication	Kg PO4^{3-}eq	150 ±33.9	3.02 ±0.914	1.5 ±0.495	4.28 ±1.01

hydrolysate and chitosan results in less impact than shrimp meal production. The large eutrophication potential of chitosan is very apparent but would be substantially less if an adequate waste water process could have been developed. However, a certain amount of eutrophication was allocated to shrimp meal production at SM2 according to the proportions of inputs designed by the producing company, whereas SM1 declared that there was no waste water as the process involved drying the shrimp by-product and milling only. In most cases it is the hydrolysate which contributes more to the overall

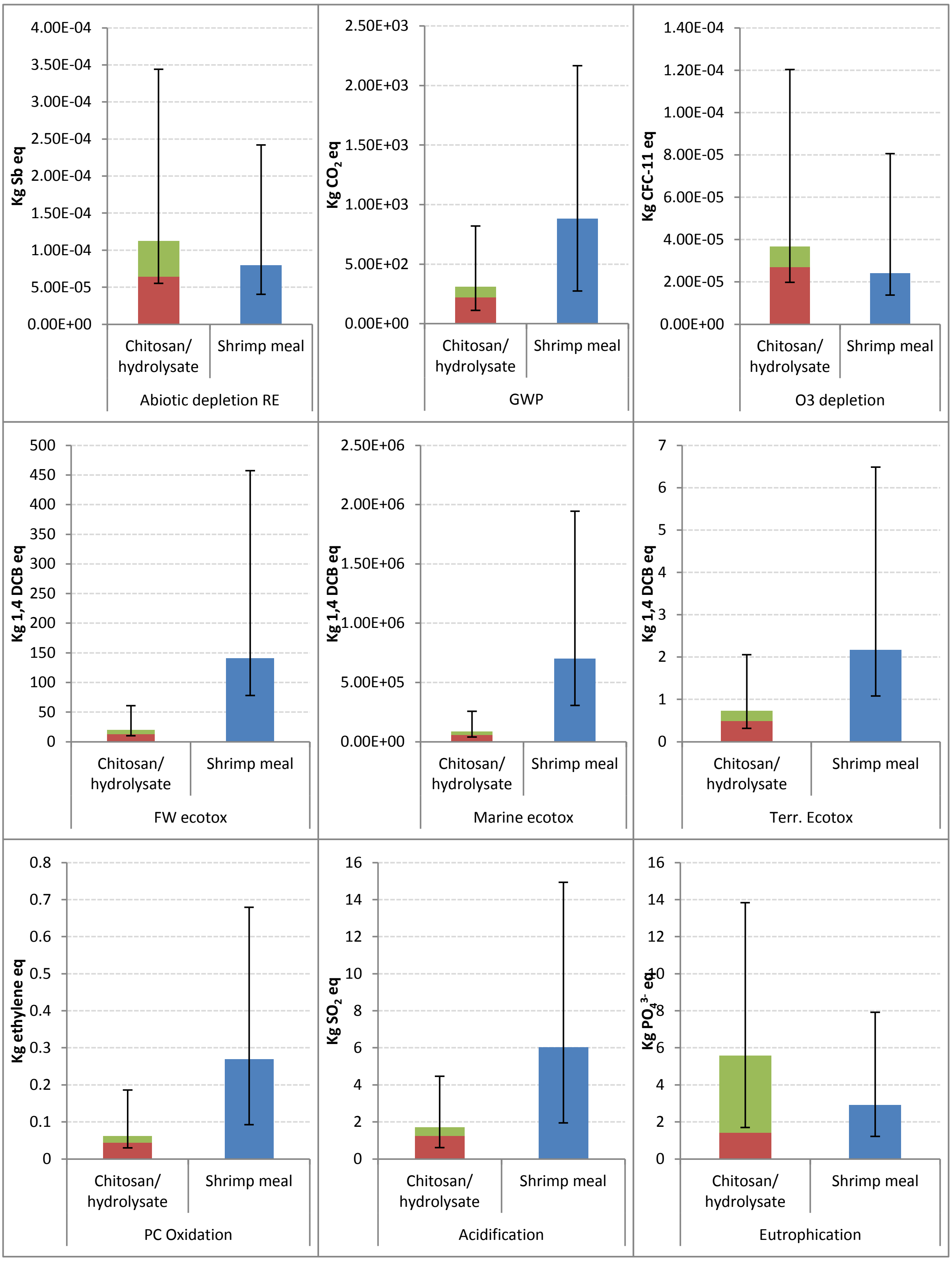


Figure 6.8 LCIA of chitosan (green) hydrolysate (red) and shrimp meal (blue) associated with one tonne of shrimp directed to human consumption using economic allocation. 95% confidence levels around geometric mean of log normal distribution.

impact compared to chitosan in scenario b, which can be attributed to the very large electricity consumption, which is used throughout hydrolysate production, and the high quantities of diesel during spray drying processes. The individual contributions to each impact category are discussed in section 6.4 and will not be discussed further in this section. Figure 6.9 shows the results from the same assessment as figure 6.8, but using mass allocation throughout, including all upstream processes involved in feed production and processing, to produce the shrimp by-product raw materials used for the production of the three separate products.

The results of the LCIA comparing scenarios a) and b), using physical allocation in figure 6.9, show that the impacts associated with producing shrimp meal are higher than the combined production of chitosan and hydrolysate in all impact categories, for the set quantity of by-product produced in conjunction with a tonne of IQF shrimp. These results are linked to the allocation method in that much more of the impact associated with the upstream processes to produce whole shrimp are carried through to the by-product raw material. They are therefore very much influenced by the production yield. The impacts for IQF shrimp using mass allocation, were similar to those using economic allocation but are not shown in figures 6.8 or 6.9. For example GWP using mass allocation was 13200 kgCO_2 eq for IQF shrimp but the total for all three products was 18800 kgCO_2 eq, compared to 13400 kgCO_2 eq for the IQF shrimp and 13700 kgCO_2 eq for all three products using economic allocation. Using mass allocation, the impacts associated with producing whole shrimp are higher because of the many agricultural by-products used in shrimp feeds (figure 6.4), but the share of the impacts divided at the shrimp processing stage are higher for the by-product raw materials. The comparative contribution to the LCIA between hydrolysate and chitosan is also different between mass and economic

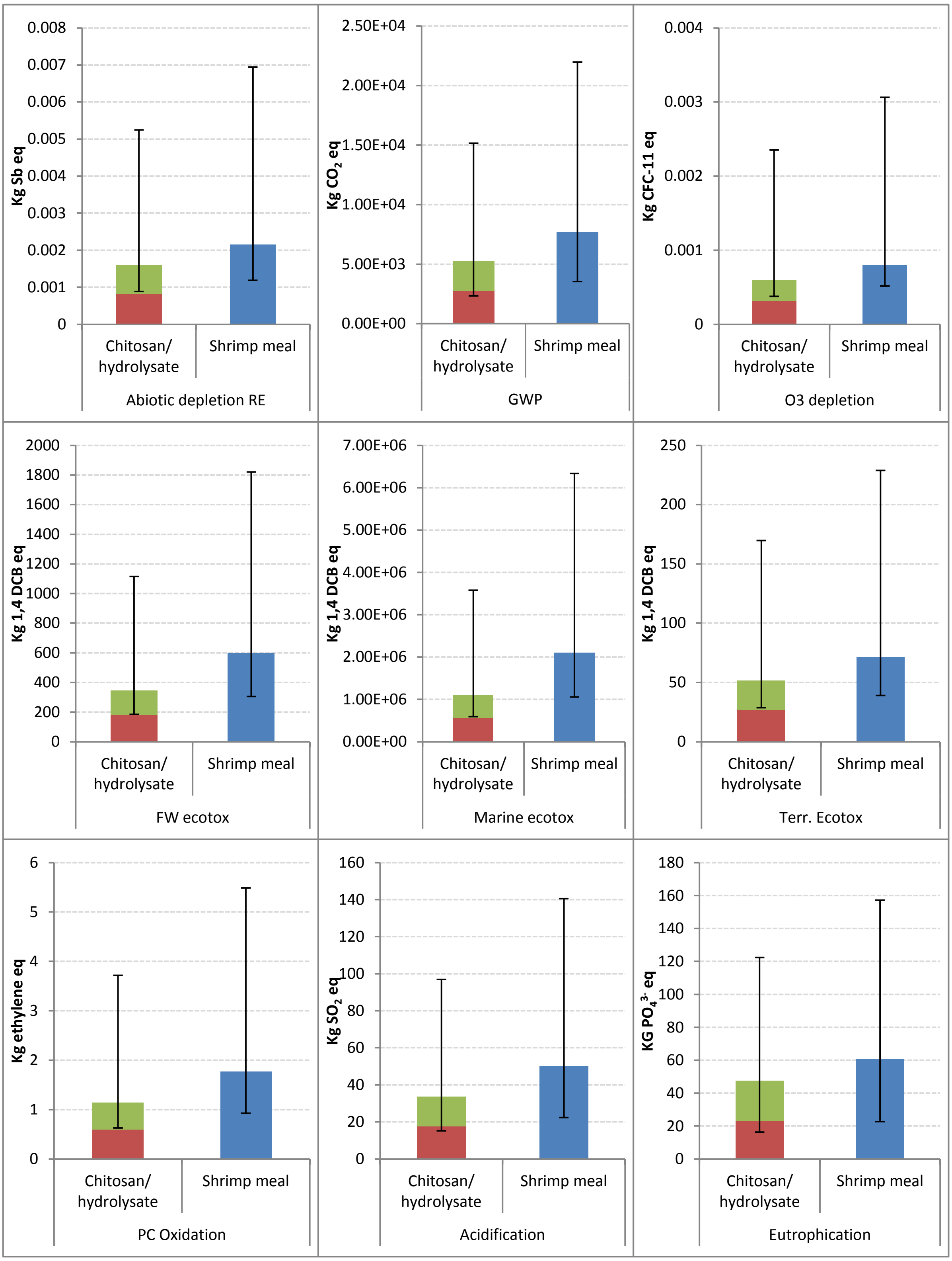


Figure 6.9 LCIA of chitosan (green) hydrolysate (red) and shrimp meal (blue) associated with one tonne of shrimp directed to human consumption using mass allocation. 95% confidence levels around geometric mean of log normal distribution.

allocation. The contribution from hydrolysate is generally around double that of chitosan using economic allocation but more equal using mass allocation. The main difference is that the hydrolysate process also produces 43% low value shell as a by-product from the shrimp carapace which is then also directed into chitosan manufacture. The use of economic allocation is a better reflection of the choices in directing the by-product in this case because the results are not influenced so heavily by the upstream process, over which the by-product processor has no control. However, a producer may wish to consider the results from physical allocation to source shrimp by-products with less impact. In addition, the performance of chitosan and hydrolysate is strengthened over shrimp meal by both allocation methodologies agreeing in all but three impact categories.

6.4.4.2 Utilisation alternatives from shrimp by-products associated with $1000 of value from all products

This section compares the LCIAs of producing the same value of products between the two scenarios presented in figure 6.7. All of the products are produced in the same ratios to the IQF shrimp fraction directed to human consumption as in section 6.4.4.1 but the overall quantities are different because of the different values of the final products. The LCIAs of the production of chitosan and hydrolysate, and shrimp meal in order to produce $1000 of value can be seen in table 6.8. This also includes the value of the IQF shrimp. This methodology may then also be applied to comparing other species where the products are very diverse, using the overall value as a proxy for their functions. This will be discussed in chapter 9.

Figure 6.10 compares the LCIA of scenarios a) and b) and 95% confidence levels around the geometric mean using economic allocation and figure 6.11 shows the same comparison using mass allocation. It can be seen that using economic allocation, the impacts from the IQF shrimp vastly out-weigh those of the other products, because of the low value of the shrimp by-product at the processor gate. However, it can be seen that scenario b) where chitosan and hydrolysate are produced, less IQF shrimp and other products are required to achieve the same value and therefore the impact is lower than in scenario a). Statistical analysis between the two scenarios by ANOVA of the log transformed data showed a significant difference in all impact categories (p <0.003) except for ozone depletion (p = 0.0816). This is also supported using physical allocation in figure 6.11 and therefore it can be concluded, along with the results shown in figures 6.8 and 6.9, that using the by-product from shrimp to produce chitosan and hydrolysate is the more eco-efficient of the two scenarios. The effect of different allocation methodology is apparent in figures 6.10 and 6.11, where the overall contribution to the LCIA is dominated by the contribution from the IQF shrimp when using economic allocation. However, much more analysis is required to test the overall environmental benefits of the products. Shrimp meal is a long established product which has been used in various feeds for decades. Shrimp hydrolysate, especially, is a very new product for which the markets are largely unestablished, whereas chitosan has been available for several decades but its applications have not been fully developed. Therefore, it is unlikely that all shrimp by-products can be directed to the manufacture of chitosan and hydrolysate the short to medium term and a balance has to be struck while markets for these products are established. Initial trials of shrimp hydrolysate in aquafeeds have

Table 6.8 LCIA using economic allocation showing shrimp meal in scenario a) and sub-divided impacts from chitosan and hydrolysate in scenario b) to produce $1000 of final products. *IQF, Instant Quick Frozen. Means and standard deviations to 3 significant figures.

		Plant				
		Scenario a)		**Scenario b)**		
Impact category	**Unit**	**Shrimp IQF* 117kg**	**Shrimp meal 14.0kg**	**Shrimp IQF* 105kg**	**Hydrolysate 5.3kg**	**Chitosan 2.2kg**
Abiotic depletion, rare elements	kg Sb eq	0.000532 ±0.000267	9.81 ±3.71	0.000477 ± 0.000234	0.00000746 ±0.00000549	0.00000549 ±0.00000233
Abiotic depletion, fossil fuels	MJ	18700 ±9760	1360 ±201	16800 ±8760	313 ±146	138 ±51.499
Global warming, GWP100	kg CO_2 eq	1590 ±636	102 ±11.0	1430 ±571	24.2 ±9.26	10.0 ±3.391
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.000164 0.0000969	2.97 ±1.29	0.000147 ±0.0000867	0.00000315 ±0.00000163	0.00000114 ±0.000000552
Fresh water ecotoxicity	kg 1,4-DCB eq*	103 ±62	18.0 ±8.63	92.4 ±55.6	1.51 ±1.10	0.777 ±0.372
Marine ecotoxicity	kg 1,4-DCB eq*	44900 ±27600	82100 ±22700	403000 ±24800	6520 ±4270	4270 ±1470
Terrestrial ecotoxicity	kg 1,4-DCB eq*	4.24 ±1.58	0.255 ±0.0818	3.81 ±1.42	0.0555 ±0.0279	0.0277 ±0.0104
Photochemical oxidation (high NOx)	kg ethylene eq	0.427 ±0.281	0.0311 ±0.00551	0.383 ±0.252	0.00502 ±0.00277	0.0414 ±0.00972
Acidification	Kg SO2 eq	9.87 ±3.18	0.696 ±0.0939	8.86 ±2.85	0.137 ±0.0414	0.0498 ±0.0164
Eutrophication	Kg $PO4^{3-}$eq	17.6 ±4.57	0.339 ±0.0861	15.80 ±4.10	0.158 ±0.0522	0.451 ±0.106

proven promising in reducing the overall reliance on fish ingredients (Aquativ, unpublished data 2013). However much more work is needed on this and an LCA of conventional feeds versus those containing the hydrolysate have yet to be carried out. Chitosan is being applied increasingly in many different sectors ranging from cosmetics to crop protection, to waste-water treatment, anti-microbial food additives and active packaging solutions (Rabea *et al* 2003, Benhamou *et al* 1994, Jeon *et al* 2002, Appendini and Hotchkiss 2002, Beach *et al* 2012). For example, Jeon et al (2002) showed that the shelf life of fish products could be extended by several days by incorporating chitosan coatings. Leceta *et al* (2013) performed the only LCA study on chitosan products to date

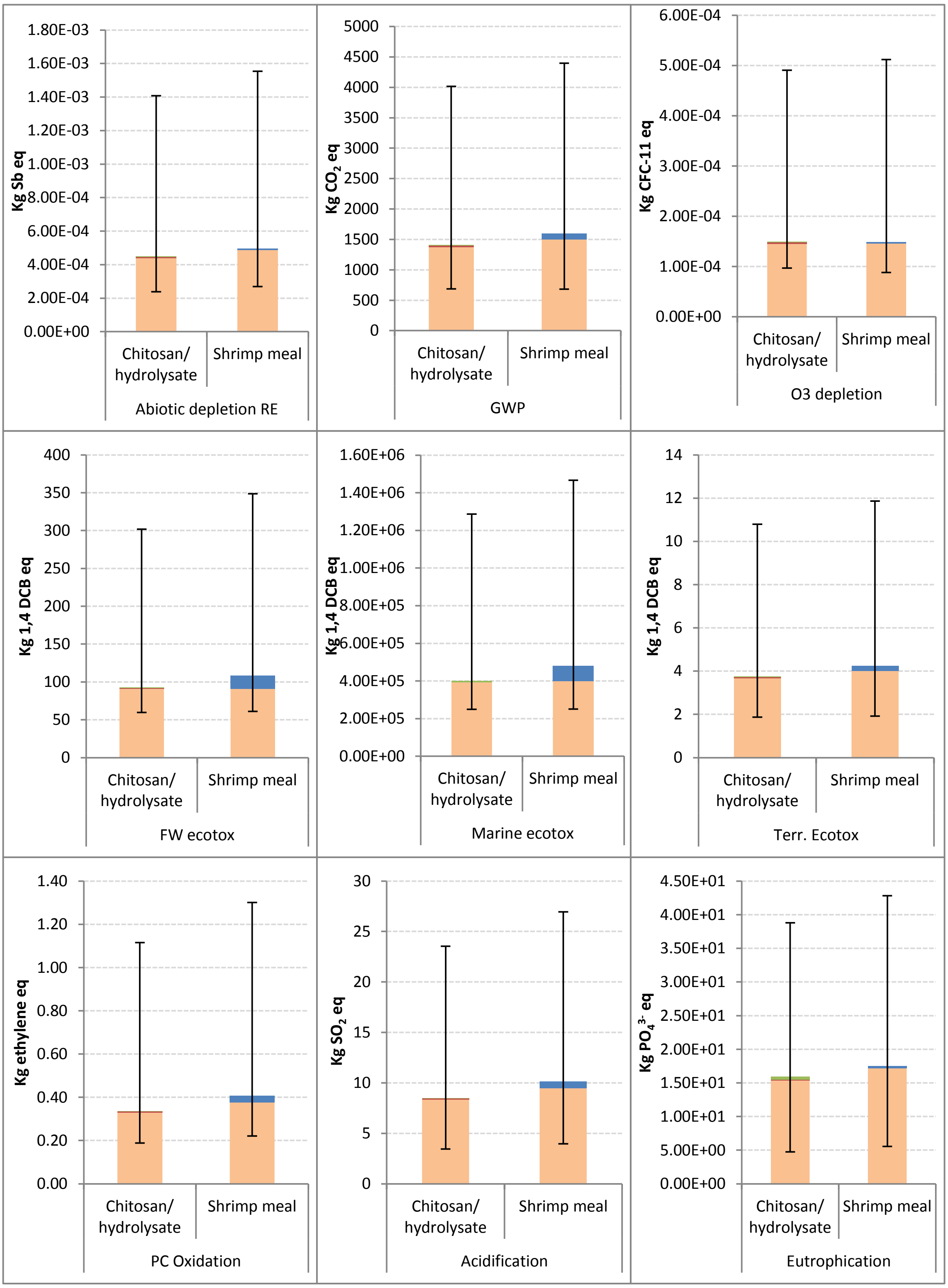


Figure 6.10 LCIA of IQF shrimp (pink) chitosan (green) hydrolysate (red) and shrimp meal (blue) in order to produce US$1000 of total products using economic allocation. 95% confidence levels around geometric mean of log normal distribution. The proportions for each scenario and the characterisation factors can be seen in table 6.8 above.

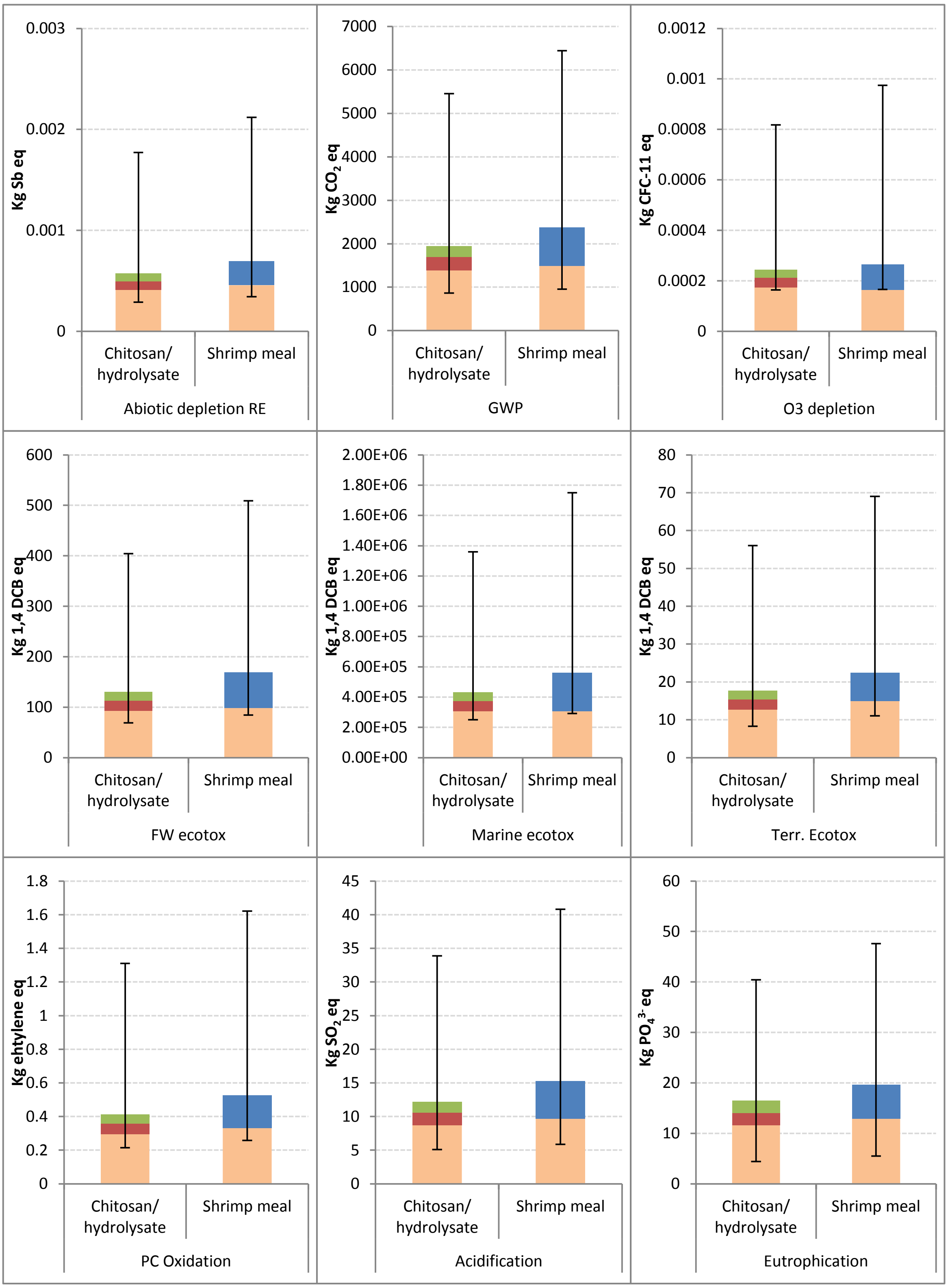


Figure 6.11 LCIA of IQF shrimp (pink) chitosan (green) hydrolysate (red) and shrimp meal (blue) in order to produce US$1000 of total products using mass allocation. 95% confidence levels around geometric mean of log normal distribution. The proportions for each scenario and the characterisation factors can be seen in table 6.8 above.

and showed that the impact of producing chitosan films was less than that of traditional petrochemical based films. However, the effect of lengthening the shelf-life of food products was not included within the study.

The use of chitosan as an anti-microbial seed coating is also of increasingly significant interest. Trials by Benhamou *et al* (1994) and Boonlertnirun *et al* (2008) showed that survival of tomato and rice seedlings respectively, could be significantly improved by using chitosan treatments. There is currently no LCA data readily available to be able to fully test the effects of chitosan treatments on crop performance, however, it would be expected that chitosan treated crops would perform well compared to other non-treated crops. According to Trung (pers comm 2012), only 3000 tonnes of chitosan were produced globally in 2007. This amounts to around 30,000 tonnes of shell, whereas 3.3 million tonnes of shrimp were produced in 2007 (FAO Fishstat 2013) which could yield close to a half million tonnes of shell given the proportions in chapter 1. Therefore, in the short term, shrimp by-product should be directed to where the highest demands are to best reduce waste.

CHAPTER 7: LIFE CYCLE ASSESSMENT OF VIETNAMESE *PANGASIUS* CATFISH BY-PRODUCT PROCESSING

7.1 Introduction

The Vietnamese *Pangasius* farming and service industries have grown rapidly in the last decade and have contributed to greater economic growth in the Mekong delta region (Lam *et al* 2009). Consolidation with more vertically integrated companies has meant that the supply of by-product has also become of significant interest (Lam *et al* 2009, Murray *et al* 2011, Le Nguyen 2007). The vast majority of by-product from *Pangasius* catfish processing is directed to fishmeal and fish oil production for use in animal feeds with some niche production of biofuel from the fat and the extraction of stomachs and swim-bladders for the local market (Le Nguyen 2007, Nguyen *et al* 2009). It was estimated by one by-product processor that there were around ten companies in the region that produced fishmeal and oil from *Pangasius* by-products (Anon pers. comm. 2012). Recently, the production of gelatine from skins has been commercialised by one company (http://www.vinhhoan.com.vn/en/products/1668/1751 accessed 12/5/2013), although frozen *Pangasius* skins have been available for trade on various websites such as Alibaba.com since the beginning of this project in 2009. Due to the emergent nature of gelatine production in Vietnam, no LCI data were collected on this industry, although the producing company and one other that was researching gelatine production were invited to collaborate on this project.

Due to rapid initial growth and subsequent consolidation, the production of *Pangasius* catfish has fluctuated over recent years (VASEP 2010, Vietnamese Ministry of Agriculture & Rural Development 2014). However, production of 1 million tonnes would provide between 600 and 700 thousand tonnes of by-product for utilisation, which can add significant value to the industry (Le Nguyen 2007). This could be in excess of 4 trillion VND (about US$240 million) at the processor gate given the prices for *Pangasius* mixed by-product quoted by the by-product processing company interviewed for this work. The production of fishmeal and fish oil helps provide valuable protein and lipid resources for large livestock industries in the region which would otherwise compete for the same resources (Nguyen 2010). The estimated number of pigs in the Mekong region in 2012 was 372,000 head (General Statistics Office, Vietnam 2014), equating to perhaps 20,000 to 25,000 tonnes. Given an FCR of around 3 (MacLeod *et al* 2013), this production would require in the region of 60,000 to 75,000 tonnes of pig feed. A local pig feed producer, surveyed for this study, reported using between 3% and 5% inclusion of catfish by-product meal within their commercial diets and therefore this could account for between 3000 and 4000 tonnes of fishmeal in the Mekong pig feed sector and substantially more nationwide. However, given the reported yields of 20% fishmeal from catfish by-products, there could be up to 140,000 tonnes available in the region and there are opportunities for expanding the market further afield, to relieve the pressure on other protein resources which livestock feed producers compete for. Despite claims of 20% yields, data provided by the processor only amounted to around 10% yield and this was the figure which was used in the analysis.

7.2 Goal and Scope

This study seeks to investigate the efficiency of the *Pangasius* catfish by-product resulting from processors, in terms of environmental impact and value addition, and to identify hotspots of environmental impact within production. It would have been preferable to compare different utilisation strategies for the *Pangasius* oil, but unfortunately no data could be obtained on this industry. Standard attributional LCA methodology was used to identify hotspots of environmental impact in the *Pangasius* meal and oil production value chain. The study also assesses and compares the environmental impact of a Vietnamese pig feed diet containing *Pangasius* by-product meal versus a traditional pig feed produced in China. No data were collected for the Chinese pig feed and instead values were used from Liu *et al* (2012) and Wang (2010) in the Ecoinvent 2.2 database. The Chinese diet also contained a small amount of fishmeal and it was assumed that the performance of pigs given the two diets would be the same or very similar, although there may be some minor carcass quality and growth performance differences based on Nguyen (2010). It was therefore assumed that the diets were comparable and their function was equivalent. Data for Vietnamese pig feed ingredients were taken from the Ecoinvent 2.2 database and from literature and primary data collected by Henriksson *et al* (2014a).

The functional unit was given as one tonne of pig feed and as products related to the edible yield and economic value of the total products which could be obtained as described in chapter 5. However, the boundary for the second part of the analysis was the by-product processor gate and not the pig feed mill. This allows the performance of the *Pangasius* value chain to be compared to the Thai shrimp and Scottish salmon chains by comparing the results up to the by-product processor gate. Ideally feeds containing either shrimp or *Pangasius* meal would have been compared against each other because of the nutritional differences discussed in chapter 4. However, no data were collected on the inclusion of shrimp meal in pig diets, but comparing equal economic values of total products does allow for a comparison between the overall efficiency of the two species production systems. Allocation to products resulting from multi-functional processes was given first by economic value and then secondarily by mass as described in chapter 5. All data were modelled using CMLCA 5.2 software provided by Leiden University and Ecoinvent 2.2 life cycle assessment database.

7.3 Life Cycle Inventory of pig feeds from *Pangasius* by-products

Data for the *Pangasius* by-product LCI were collected by survey over a six month period during January to June 2012. Similarly to the Thai shrimp data, this data built on primary and secondary data already collected and compiled in collaboration with Henriksson *et al* (2014a) from *Pangasius* catfish production, feed, processing and service industries in Vietnam. The electricity mix for Vietnam was developed from the International Energy Agency website (http://www.iea.org/) and other data were adjusted to Ecoinvent 2.2 processes as described below. The blank surveys used for LCA data collection from the by-product processor and the pig feed manufacturer can be seen in Appendix 3.

7.3.1 *Pangasius* by-product fishmeal and oil processor

One large scale processor of *Pangasius* by-product was surveyed for this study, which had a capacity of 300 tonnes of *Pangasius* by-product raw material per day and claimed to represent around 15% of the *Pangasius* fishmeal production in the Mekong delta. By-product was sourced from Can Tho, Vinh Long and An Giang provinces within the region, with it all being transported by flat-bed lorry without treatment. Although the company reported that it takes less than a day to transport, there would be a loss in quality for some of the longer journeys. The company did not know about ensiling and it is unlikely that they would start to require ensiled material because they could not extract the swim-bladder and stomach for sale as delicacies in local markets. Swim-bladders and stomachs were sorted by-hand, mainly by women, who are paid per kg of product that they sort (Figure 7.1). The best workers could achieve a comparatively high wage to a fish-farm worker of around 4 million VND per month or more (around $US200).

After sorting for stomachs and swim-bladders, the remaining by-product entered the fishmeal and oil production lines. There were two operational lines at the time of the survey. The raw material is first minced and then cooked with steam before being compressed to extract a cake and liquid fractions. The liquid fraction is centrifuged to separate the oil from the aqueous component which is then added to the cake. The cake is then dried and a magnet is used to remove any ferrous metals, before it is ground to give the final product, which is packed into 50kg bags.

Figure 7.1 Female workers at a *Pangasius* catfish by-product processing plant sorting stomachs and swim-bladders for sale in local markets, Mekong delta.

The quality of the *Pangasius* fishmeal is described in chapter 4. The FA acid profile of the *Pangasius* oil was not given by the producing company, however, it reportedly contained more than 98% fat and around 1% water. The majority of the fishmeal and oil are directed to livestock feeds, especially pigs, although the plant reported that as much as 30% of the oil may be directed to biodiesel production. A pilot biodiesel plant was approached about collaboration in the project but they did not wish to participate. The pig feed manufacturer did not use *Pangasius* catfish oil in the diets and therefore no LCI data were collected on further utilisation of the oil product. The LCI input and output data for both the *Pangasius* by-product plant and pig feed mill can be seen in table 7.1

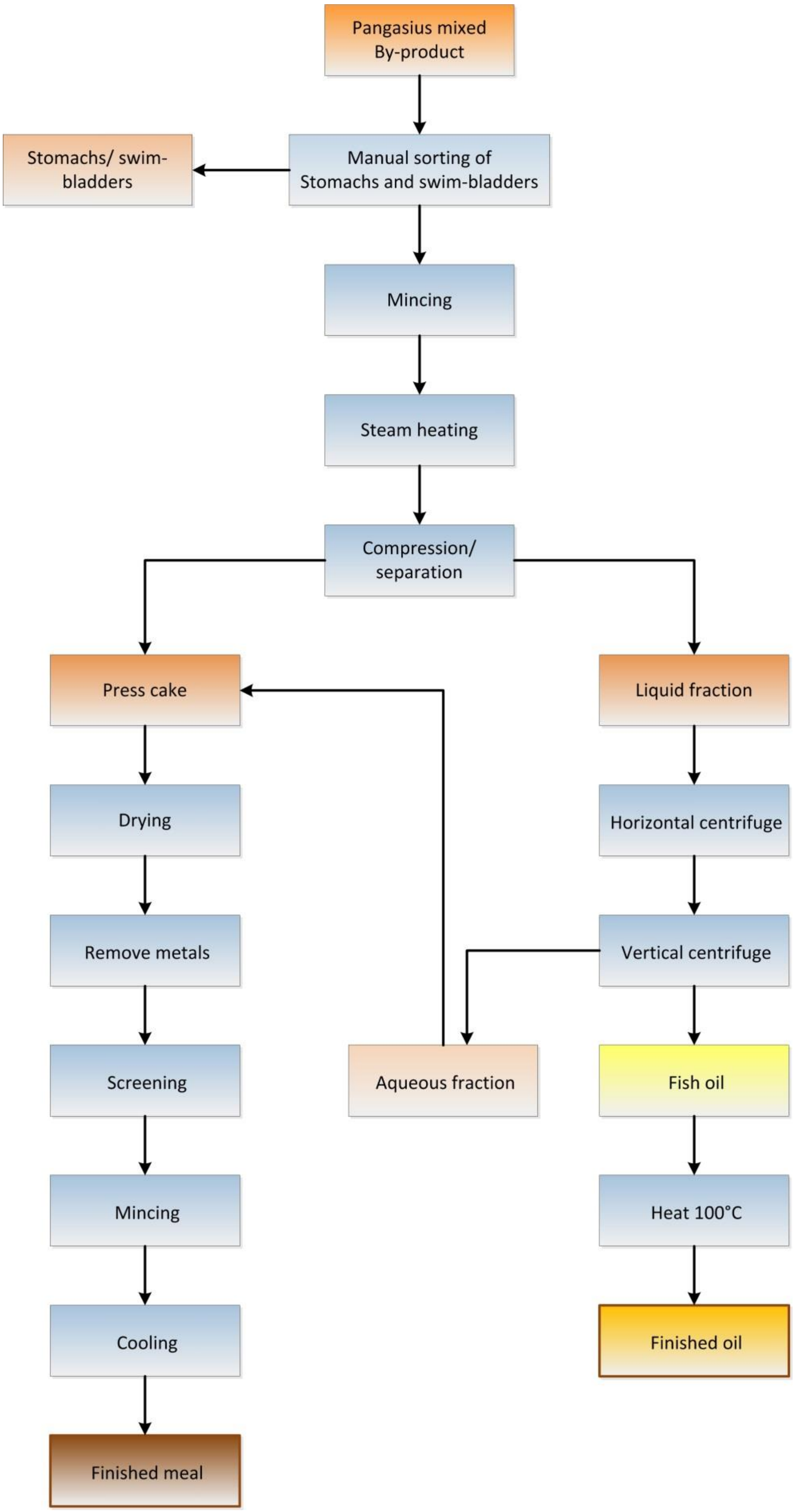


Figure 7.2 *Pangasius* by-product processing to produce fishmeal fish oil, stomach and swim-bladders according to *Pangasius* by-product processor (Can Tho province, Mekong Region).

Table 7.1 LCI for the production of one tonne *Pangasius* catfish meal and one tonne of pig feed from *Pangasius* catfish meal in Vietnam and a comparative European diet.

Input per 1 tonne of production	
	By-product processor
Inputs	
Pangasius raw material, kg	10200
Heat (coal), MJ	79000
Electricity, KWh	714
Yields	
Pangasius meal, kg	1000
Pangasius oil, kg	1880
Pangasius stomachs, kg	42.9
Pangasius swim-bladders, kg	71.4

		Pig feed production	
Feed ingredients, kg	**Source**	**Vietnam**	**China**
Cassava	Indonesia	50	-
Rice bran	Vietnam	150	-
Soybean meal	Argentina	116	90
Corn flour	Argentina	546	-
Canola	Canada	50	40
DDGS*	USA	50	-
Pangasius catfish meal	Vietnam	30	-
Fishmeal	China	-	20
Wheat bran	China	-	70
Maize	China	-	700
Premix	China	-	40
Energy			
Electricity, KWh		4.07	90
Wood, MJ		27800	1156

*DDGS, dried distillers grains with solubles.

7.3.2 Pig feeds including *Pangasius* by-product meal

The data for the manufacture of pig feeds using *Pangasius* by-products were collected from one major producer in the Mekong delta which also produced some duck feed and *Pangasius* catfish feed, for which data were collected as part of the SEAT project. The pig feed production was on a separate line which could be sub-divided from the other production lines at the plant. The pig feed included 3% catfish by-product meal with major ingredients being corn (maize) flour, soya bean meal and rice bran (table 7.1). The Chinese pig feed details were taken from literature mentioned above but plant electricity was adjusted to the Vietnamese mix and ingredients were assumed to be sourced from the same locations as the *Pangasius* fishmeal diet with the same transport distances where equivalent. The Chinese diet used different ingredients, mainly sourced domestically, with 2% fishmeal inclusion. It used a coal fuelled boiler but this was adjusted to wood to be comparable with the Vietnamese diet. The energy used for heat was less than in Vietnam but it had higher electricity consumption than the Vietnamese production. The Vietnamese feed used ingredients which were mostly imported from the Americas. Major power requirements for the *Pangasius* based diet were from steam which was generated using the wood fired boiler and the pelleting machine which ran off of mains electricity.

7.4 Life cycle impact assessment of *Pangasius* by-products

7.4.1 *Pangasius* by-product meal, stomachs and swim-bladders

The LCIA of one tonne of *Pangasius* fishmeal, stomachs and swim-bladders which are produced concurrently can be seen in table 7.2. The LCIA of one tonne of *Pangasius* oil is the same as the fish meal because they have the same economic value and can be compared to the production of salmon oil in chapter 8. The yield of these products from the by-product raw material arriving at the processor gate were 9.72% for fishmeal, 18.3% for fish oil, 0.42% for stomachs and 0.69% for swim-bladders.

Table 7.2 LCIA of 1 tonne of *Pangasius* fishmeal and associated stomach and swim-bladder production, using economic allocation, means and standard deviations after 1000 iterations of Monte Carlo analysis, to 3 significant figures. *DCB= dichlorobenzene. Note that the LCIA of *Pangasius* oil is the same as fishmeal because they have the same economic value per kg.

			Product	
Impact category	**Unit**	***Pangasius* FM, 1000kg**	***Pangasius* stomachs, 43kg**	***Pangasius* swim-bladders, 71kg**
Abiotic depletion, rare elements	kg Sb eq	0.00171 ±0.00071	0.000109 ±0.0000422	0.000198 ±0.0000734
Abiotic depletion, fossil fuels	MJ	70500 ±19200	2110 ±423	360 ±879
Global warming, GWP100	kg CO$_2$ eq	6180 ±1410	230 ±41.5	390 ±89.2
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.00026 ±0.0001	0.0000162 ±0.00000752	0.0000274 ±0.0000105
Fresh water ecotoxicity	kg 1,4-DCB eq*	853 ±522	15.8 ±6.58	27.2 ±9.6
Marine ecotoxicity	kg 1,4-DCB eq*	3900000 ±1630000	67300 ±21400	119000 ±38900
Terrestrial ecotoxicity	kg 1,4-DCB eq*	18.1 ±5.43	0.751 ±0.169	1.29 ±0.337
Photochemical oxidation (high NOx)	kg ethylene eq	2.65 ±1.15	0.11 ±0.306	0.195 ±0.101
Acidification	Kg SO$_2$ eq	44.5 ±10.7	1.67 ±0.306	2.89 ±0.647
Eutrophication	Kg PO$_4^{3-}$eq	45.7 ±8.63	3.03 ±0.593	4.88 ±0.805

The contribution analysis of *Pangasius* meal, farming and commercial feed can be seen in figure 7.3. Major contributions to GWP, ecotoxicity and acidification in oil and meal production were from the use of coal fired boilers at the by-product processor. This was not the case for the stomachs and swim-bladders which were removed prior to the fishmeal and oil production process. For these products, contributions to GWP were more associated with upstream processes such as the fishing effort and electricity consumption to supply fishmeal and other ingredients for *Pangasius* feeds. Carbon dioxide emissions were proportionately much more important for the fishmeal and fish oil production, whereas dinitrogen monoxide was far more important for the stomachs and swim-bladders. The majority of these emissions were from *Pangasius* farming itself, and from agricultural activities to supply feed ingredients, such as US soybean production. This is to be expected as there is little processing of the *Pangasius* by-product before it reaches the fishmeal and oil production process, and what little there is, is mainly manual.

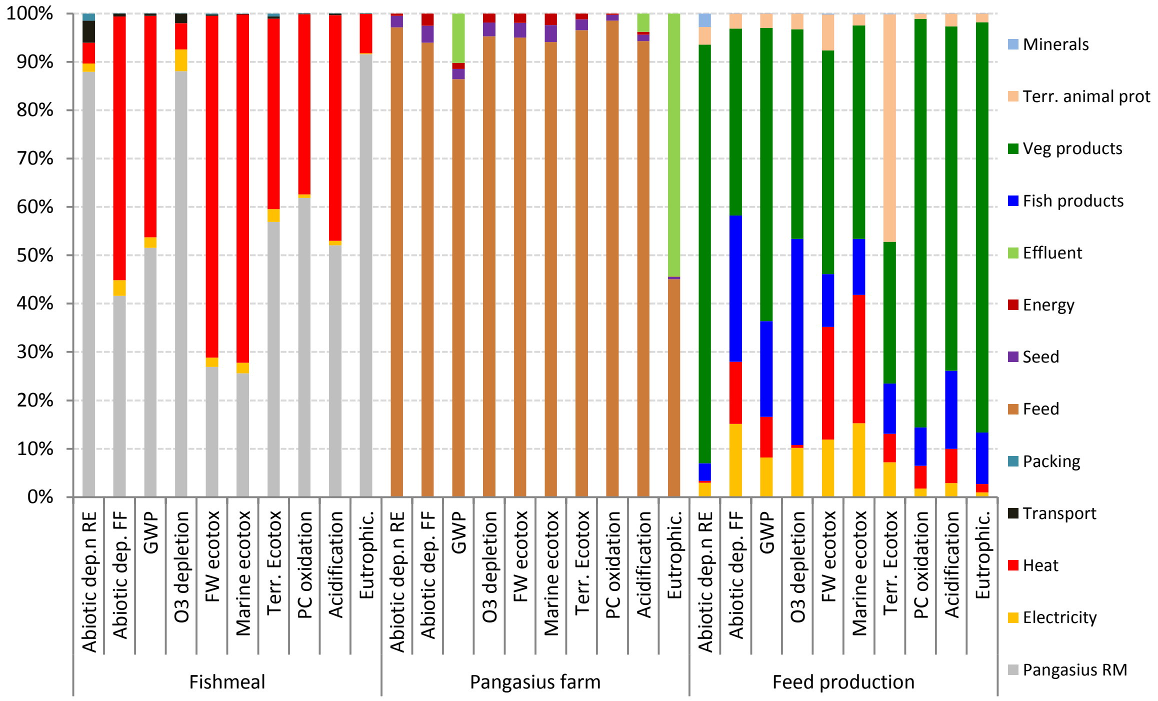


Figure 7.3 Contributions to LCIAs of *Pangasius* fishmeal, large scale *Pangasius* farms and commercial *Pangasius* feeds using economic allocation. Data for farms and feeds collected in collaboration with Henriksson *et al* (2014a). RE = rare elements, FF = fossil fuels, RM = raw material

To produce one tonne of soybean and one tonne of *Pangasius*, 6.42kg and 0.98kg respectively of dinitrogen oxide were directly emitted. For stomachs and swim-bladders, most of the contributions to these impact categories were from transport to supply feed ingredients. As almost all categories in the farming process are dominated by the contribution from feeds, the contributions from *Pangasius* raw material at the by-product processor are roughly proportionate to those found in the production of the feed. For example, significant amounts of carbon monoxide produced from rice production activities and urea for fertilisers were major contributors to photochemical oxidation for all products, post farm. As the contributions to the LCIA are almost totally from the heat source or from the *Pangasius* raw material, major reductions in impact could be made by reducing either of these two inputs. Becoming more efficient with the coal heating source or substituting for a cleaner energy source such as LPG would substantially reduce many impacts. Improving the yield of fishmeal would also substantially improve the impact. However, there was some confusion over the yields given by the processor, as although it was declared in discussions that they had a yield of around 20% fishmeal, the figures given in the survey were substantially less than this.

7.4.2 LCIA of the *Pangasius* catfish value chain

The proportion of impacts between the final products produced from the processing of *Pangasius* and its by-products in proportion to 1 tonne of fillets, by economic and mass allocation, can be seen in figure7.4. There are no alternative uses for the *Pangasius* by-products as data were collected for the fish meal production and fish oil and the subsequent use of the fish meal in pig feeds only. However, the value chains for *Pangasius* will be compared to those of shrimp and salmon in chapter 9. The effect of the different allocation methods can be seen clearly in figure 7.4, where the proportionate contribution from *Pangasius* fillets is much larger by economic allocation than by mass, which is directly related to the lower fillet yields. This is the case for all impact categories except for terrestrial ecotoxicity and ozone depletion. The lower proportion for terrestrial ecotoxicity by economic allocation is linked to the upstream processes in providing feed ingredients. 72% of the terrestrial ecotoxicity by physical allocation is directly linked to cypermethrin use in rice farming, whereas for economic allocation, it is split more evenly between cypermethrin use and heavy metals linked to industrial processes such as diesel use and electricity production. In the case of ozone depletion also, the proportionately higher contribution that *Pangasius* fillets contribute is due to upstream processes, from fisheries for feed provision, whereas for economic allocation there is a higher proportion coming from the provision of electricity. The ratio between *Pangasius* meal and oil is similar for both allocation methods because their economic values are the same and they directly result from the same process. Stomachs and swim-bladders are more valuable per kg, however, their mass is very low and they are removed manually with no further processing after the filleting stage and therefore their contributions to the overall impact are very low. The analysis of the products contributing to US$1000 of product are not evaluated in this chapter because the proportions of impacts between the products are the same as in figure 7.4 and there are no alternative scenarios for the use of the by-products which would result in different proportions as for the shrimp value chain. The contribution to $1000 of products will be compared against the value chains for other species in chapter 9.

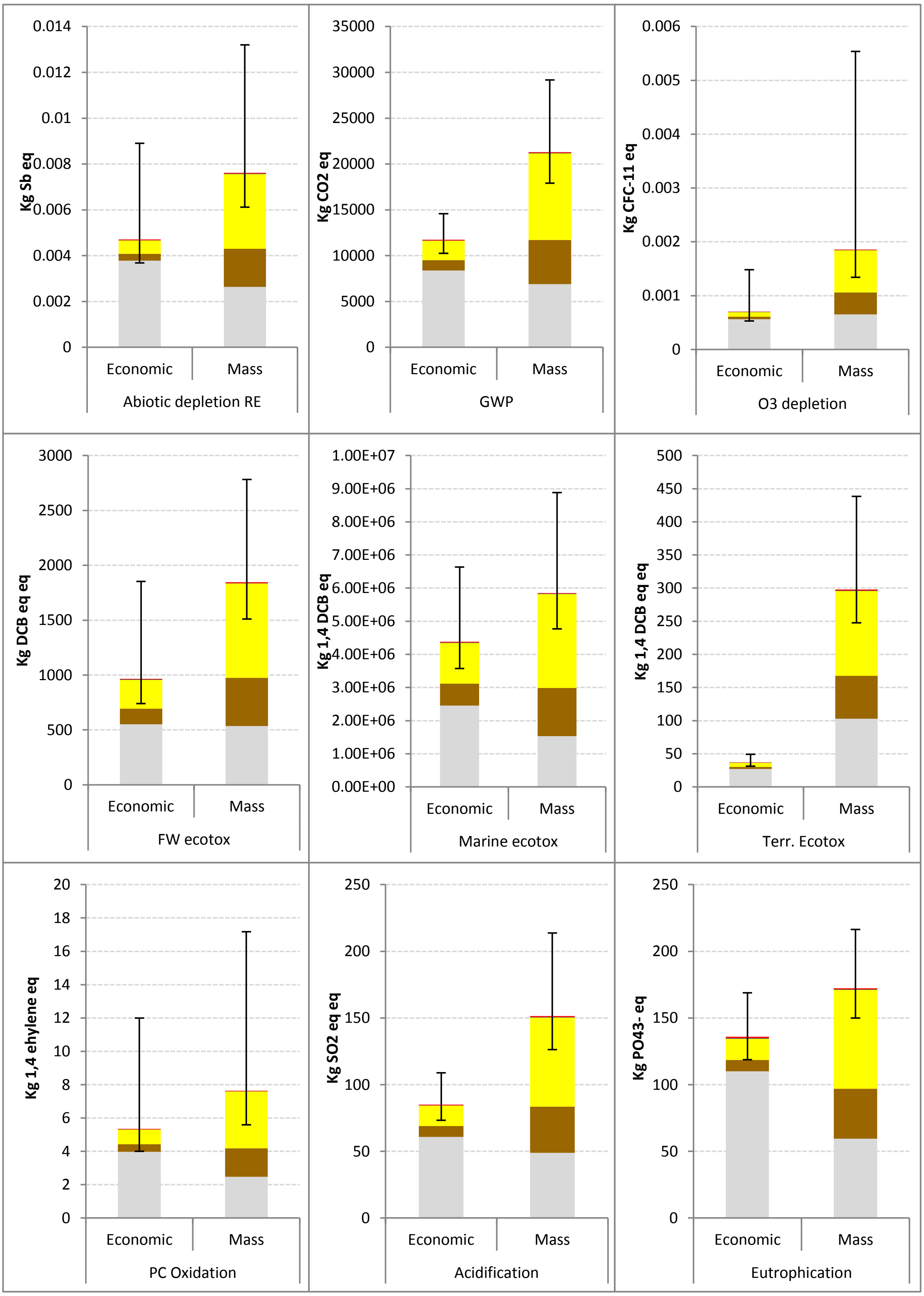


Figure 7.4 LCIA of products resulting from processing activities to produce 1000kg of *Pangasius* fillets and associated by-products by economic and mass allocation. *Pangasius* fillet, 1000kg (grey), *Pangasius* meal, 180kg (brown), *Pangasius* oil, 338 kg (yellow), *Pangasius* stomachs, 7.8 kg (black), *Pangasius* swim-bladders, 12.9 kg (red). 95% confidence levels around geometric mean.

The impacts for the production of *Pangasius* fishmeal are generally lower than those for shrimp meal in Thailand, using data from SM2 which was likely to be the more representative of the two plants. Both the shrimp and *Pangasius* meal plants used coal as a heat source, but the shrimp meal plant used substantially more electricity than the *Pangasius* by-product plant. This could be an artefact of allocation between the two products produced at the plants. The oil and meal have the same value as each other per kilogramme, as do the shrimp meal and hydrolysate at each of the two plants. If it was possible to sub-divide the energy contributions between the products, there may have been different results. However, the energy requirements for shrimp hydrolysate are roughly the same between the two hydrolysate plants and therefore there can be a degree of confidence that the allocation to the shrimp meal from SM2 is roughly correct. There is no way of substantiating the energy consumption contribution to *Pangasius* meal between that and the oil production, however, as only one plant was surveyed. The various contributions from oil centrifuging and pressing the meal cake cannot be separated as the electricity consumptions are given as totals for the plant.

7.4.3 LCIA of pig feed formulated from *Pangasius* by-product meal

The LCIA of a pig feed containing *Pangasius* catfish by-product and a comparative Chinese pig feed can be seen in table 7.3 and the contribution analysis in figure 7.5, both using economic allocation. Table 7.5 shows the results from the statistical analysis between the two feeds using ANOVA on the CMLCA generated Monte Carlo runs. The impacts from Vietnamese pig feed containing *Pangasius* by-product meal are significantly lower than those from Chinese pig feeds in most cases. However, this is mainly due to the vegetable based ingredients, rather than the fish product inclusions. Most notable is the higher variance in the Chinese diet compared to the Vietnamese diet.

Table 7.3 LCIA of 1 tonne of pig feeds including *Pangasius* by-product meal (Vietnam) and a standard formulated Chinese pig feed (Liu *et al* 2012), using economic allocation, means and standard deviations after 1000 iterations of Monte Carlo analysis, to 3 significant figures. *DCB= dichlorobenzene.

		Pig feed	
Impact category	**Unit**	**Vietnamese feed, 1000kg**	**Chinese feed, 1000kg**
Abiotic depletion, rare elements	kg Sb eq	0.00116 ±0.000337	0.00137 ±0.000781
Abiotic depletion, fossil fuels	MJ	11300 ±1350	9380 ±3700
Global warming, GWP100	kg CO_2 eq	1160 ±127	1460 ±547
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.0000870 ±0.0000292	0.0000882 ±0.0000417
Fresh water ecotoxicity	kg 1,4-DCB eq*	136 ±35.9	136 ±55.2
Marine ecotoxicity	kg 1,4-DCB eq*	437000 ±93400	678000 ±33200
Terrestrial ecotoxicity	kg 1,4-DCB eq*	13.2 ±7.26	4.69 ±1.66
Photochemical oxidation (high NOx)	kg ethylene eq	0.904 ±0.281	0.487 ±0.42
Acidification	Kg SO_2 eq	18.2 ±4.27	19.7 ±8.29
Eutrophication	Kg PO_4^{3-}eq	9.9 ±2.0	14.9 ±7.77

The Chinese feed is largely made from unprocessed maize compared to more highly processed ingredients in the Vietnamese diet, such as maize flower and dried distillers grains with solubles (DDGS). The milling of the Vietnamese feed is also much more energy intensive with large heat requirements. Although this is mainly from wood fuelled boilers, which have no net carbon dioxide emissions, it contributes highly to terrestrial ecotoxicity and photochemical oxidation impacts, which are clear in figure 7.3. The FCR for the Chinese feed was 2.8 (Liu *et al* 2012). No specific data were collected on the performance of the Vietnamese diet, however, given an FCR of around 3, which is well around the range which can be expected for pig feeds (MacLeod *et al* 2013), it would be of comparable performance to the Chinese diet in terms of performing the same function for the same level of impact. However, this is not due to the inclusion of the *Pangasius* by-product, but the energy intensity of other ingredients and the performance of replacing the fishmeal in the Chinese diet with *Pangasius* catfish meal cannot be predicted. More data would be required on replacing different ingredients with *Pangasius* by-product meal in more comparable diets to be able to conclude whether it can provide the same performance with less overall impact.

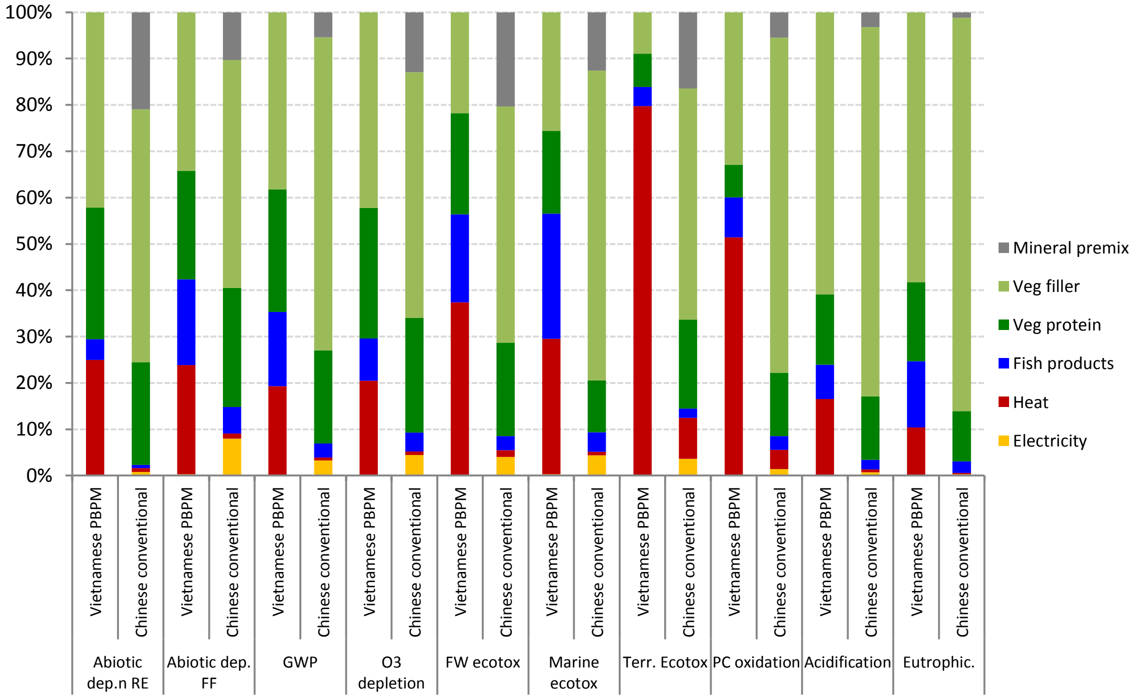


Figure 7.5 Contributions to LCIAs of Vietnamese pig feed including *Pangasius* by-product meal and a standard formulated Chinese pig feed (Liu *et al* 2012), using economic allocation. RE = rare elements, FF = fossil fuels, PBPM = *Pangasius* by-product meal.

Table 7.4 summary of results of statistical analysis of 1000 Monte Carlo runs, ranking the environmental performance of production of Vietnamese pig feed including *Pangasius* by-product meal and conventional Chinese pig feed using ANOVA and economic allocation only. Best performer = 1 to worst = 2. No significance indicated by split ranks

Impact category	**Unit**	**Pangasius meal**	**Chinese conventional**
Abiotic depletion, rare elements	kg Sb eq	1	2
Abiotic depletion, fossil fuels	MJ	2	1
Global warming, GWP100	kg CO_2 eq	1	2
Ozone layer depletion, ODP steady state	kg CFC-11 eq	1.5	1.5
Fresh water ecotoxicity	kg 1,4-DCB eq*	1.5	1.5
Marine ecotoxicity	kg 1,4-DCB eq*	1	2
Terrestrial ecotoxicity	kg 1,4-DCB eq*	2	1
Photochemical oxidation (high NOx)	kg ethylene eq	2	1
Acidification	Kg SO_2 eq	1	2
Eutrophication	Kg PO_4^{3-}eq	1	2

There is no doubt that the by-product industry adds considerable value to the *Pangasius* value chain. However, the processes for producing the fishmeal and oil are quite intensive, using substantial amounts of coal for steam production. This can be seen clearly in figure 7.4 where the proportion of impacts which are attributed to the by-products are large, using both mass and economic allocation, compared to the proportion of impact which is allocated to shrimp by-product industries in figures 6.10 and 6.11. Therefore although there is much to be gained through utilising *Pangasius* by-products for livestock industries, significant improvements could be made by utilising less energy intensive processes and improving the yield. Flesh recovery technology from fish frames has also improved in recent years (WFLO 2008) and the value of the recovered flesh is potentially much higher than the fishmeal and fish oil products (Young pers. comm. 2012). However, there is still by-product left at the end of the recovery process which may have no further value. Therefore there could be further trade-offs in optimising the value from *Pangasius* by-products which need further investigation.

CHAPTER 8 LIFE CYCLE ASSESSMENT OF SALMON BY-PRODUCT VALUE CHAINS

8.1 Introduction

In contrast to *Pangasius* production, the production of Atlantic salmon and its service industries are dominated by a few major companies with a high level of vertical integration (Marine Harvest 2014). Despite this, much of the secondary processing, has been outsourced to other countries leaving a much more fragmented value chain, which is apparent from figure 1.2, where much of the product is exported from the producing companies, having only been eviscerated. There is still little value in the viscera, as the company that supplied the farm and processing LCI data claimed that they were not receiving any payment for the viscera and in effect, it was a free resource. The benefit to the company was that they did not have any disposal costs, similar to those which they were incurring for the disposal of farm mortalities described in chapter 4. Despite this, it is evident that there is value in salmon by-products demonstrated by the markets mentioned in chapter 1. During data collection in Vietnam for other chapters in this thesis, salmon heads could be seen for sale in supermarkets and local markets (figure 8.1). The company which supplied data for this assessment reported that they sold the mixed heads, frames and other trimmings to Russia, but from this point they could not be traced. There is one company in Scotland (Rossyew Ltd) that sources the viscera from the primary processing of salmon from several companies. From this they extract the oil and hydrolyse the by-product to produce a protein concentrate in liquid form. These two products are sold to both the livestock and pet feed markets, domestically and internationally.

Figure 8.1 Farmed salmon heads for sale at a local market in Dong Thap province, Vietnam

8.2 Goal and scope

This chapter seeks to investigate the efficiency of the Scottish salmon viscera by-product resulting from primary processors, in terms of environmental impact and value addition, and to identify hotspots of environmental impact within the production. The boundary for the assessment was the protein concentrate and the salmon oil leaving the extraction and hydrolysis plants and the various salmon products (fresh and frozen fillets, and trimmings) resulting from secondary processing. It would have been desirable to trace the utilisation of the secondary processing trimming by-products further, but unfortunately the one company within the UK that was involved in the selling of these products refused to participate and the trimmings from the secondary processor could not be traced. However, in all, one major feed mill, six grow-out farms, a primary and a secondary processor, and the by-product processing plant were all surveyed for the LCI of this assessment. No hatcheries were surveyed as their overall contribution was assumed to be negligible, as survey data revealed that the smolts are generally supplied at around 80g compared to the final harvest weight of around 4.5kg average.

The functional unit for this assessment was given as one tonne each of salmon oil and protein concentrate, and as the products related to the edible yield and economic value of the total products which could be obtained as described in chapter 5. This allows the performance of the salmon value chain to be compared to both the *Pangasius* and Thai shrimp chains in terms of impact versus value of products. Allocation to products resulting from multi-functional processes was given first by economic value and then secondarily by mass as described in chapter 5. All data were modelled using CMLCA 5.2 software provided by Leiden University and Ecoinvent 2.2 life cycle assessment database.

8.3 Life Cycle Inventory

LCI data for the salmon value chain were collected over a 3 year period from 2012 to 2014. The reference period was the complete year 2012 for the feed mill, primary and secondary processors, the last complete cycle for the grow-out farms (from October 2013) and 2011 for the salmon by-product processor. According to the data, the grow-out phase of production takes approximately twenty-two months from initial stocking of smolts until the final harvest, followed by around 2 months fallowing before restocking begins. The electricity mix for the UK was taken directly from the Ecoinvent 2.2 database, and feed ingredient data were compiled partly from literature and partly from Henriksson *et al* (2014a). The blank surveys used for LCA data collection from the entire value chain described above can be seen in Appendix 4.

8.3.1 Salmon feed production

The LCI data for salmon feed were collected from one large company with feed mills in Scotland and other major salmon producing countries, and which supplies a substantial share of the UK salmon production. The data were confidential and therefore details of the ingredient mix are not given in this thesis. However, aggregated data are shown in table 8.1. The aggregated data represent the averaged total feed ingredients used to manufacture feed for the entire year of production for the survey year (2012). The majority of feed ingredients were sourced from Europe except for fishmeal and vegetable proteins which were mostly from South America. For the standard feed used in this survey, no fishmeal was sourced from the by-products of either fisheries or aquaculture production. However, the company did state that they produced an organic feed, which contained several fishmeal sources, from the trimmings and by-products of fisheries in South America and the UK. The company produced a range of feeds for all stages of salmonid production. However, data were collected for a standard grow out feed only and the producer was able to sub-divide the electricity and heating inputs between the different production lines. The data collection survey for Atlantic salmon feed can be seen in Appendix 4.1

Table 8.1 LCI for the production of one tonne of standard grow out salmon feed produced in a UK feed mill.

Input per 1 tonne of feed	Source	Quantity
Ingredients		
Fishmeals	S. America and Europe	258
Vegetable proteins/fillers	S. America, UK and Europe	448
Fish oils	S. America and Europe	219
Vegetable oils	UK	41
Minerals and premixes	Europe	15
Energy		
Electricity, kWh		81.6
Natural gas, MJ		720
Water, kg		239

8.3.2 Scottish salmon grow-out production

The LCI data for salmon production were collected by survey from six salmon farms on the west coast mainland and Outer Hebrides. The farms ranged in size from around 880 tonnes to 2900 tonnes total production over the two year cycle but all farms were similar in that they used net pens suspended from 90 metre circumference Polar circles. The life cycle inventories for the six farms can be seen in table 8.2.

Table 8.2 LCI of six salmon farms on the west coast of Scotland and Outer Hebrides. *Averaged inputs between more than one site. †Medication given as active ingredient in kg.

	Farm					
	1	2	3	4	5	6
Location	Hebrides	Mainland	Mainland	Hebrides	Hebrides	Hebrides
Production, tonnes	2360	2880	2300	880	940	1710
Inputs						
Feed, tonnes	3024	3023	3015	1007	1100	2049
Electricity, kWh	-	-	14412	8119*	-	8119*
Diesel (feed barge), L	46000*	46000*	-	-	13000	-
Diesel (vehicles), L	1500*	1500*	-	13000	-	16125
Feed transport (road), km	300	150	180	300	260	300
Feed transport (sea), km	40	-	-	60	60	60
Medication† (in-feed), kg	133	230	190	81.1	43.3	144
Medication† (solution), kg	32.5	10	80.3	44	25.6	73

Feed was assumed to be all from the feed mill which supplied LCI data in section 8.3.1, although in reality there will be some differences because farms source feed from different suppliers throughout the growing cycle, there are different feeds for different growth stages and the feed presented in table 8.1 shows aggregated ingredients from a year of production. The feed efficiency is very different between the sites, however this can partly be attributed to shared land-bases between the farms. Overall, the eFCR for the sites is 1.19, which is within the expected range for salmon farming (Tacon and Metian 2008), however the range contributes to large uncertainty values in feed provision. Three of the farm sites used feed barges with on-board silos and pneumatic feed delivery systems, which were powered by diesel generators. The other farms were completely serviced from land with the same feed delivery systems but powered by mains electricity. The cages are 90m circumference, serviced from the shore with mains driven pneumatic feed blowers. There is a computerised management system which allows for good record keeping, and the cameras shown allow for good viewing of the fish and their feeding behaviour. This allows waste feed to be minimised and FCRs to be optimised. Figure 8.2 shows a typical salmon farm set up with the cages in the distance serviced from an on-shore base.

Figure 8.2 Typical land-based net pen salmon farm on the west coast mainland of Scotland, viewed from the office window

Other major inputs to the farms were the road distances required to supply feed to the farms which were estimated using Google Earth 7.1.2.2041. No data were collected on the LCIs of medication inputs, but they were entered to the farm LCIs as a generic pesticide process available in the Ecoinvent 2.2 data base. Responses were only given by two farms on mortality disposal, which were all sent to landfill, however, a visit to one of the other farms revealed that they disposed of theirs on-site in a kerosene fuelled incinerator. No data were given on these processes and consequently mortality disposal was not included in the LCI. The LCIs of capital items such as the infrastructure and cages were not collected. However, some contextual information was collected. All cages were recycled at the end of their life span by the company which supplied them, as were the nets. The barges, where present, are also taken away by the company which makes them for servicing and refitting. All LCI inputs to the farms were horizontally averaged to the production of 1 tonne of live salmon, using the methodology outlined in section 5.2.1.8 and using the Numeral Unit Spread Assessment Pedigree (NUSAP) to define the representativeness of the data, to attach overall uncertainty values according to the methodology outlined by Henriksson *et al* (2014b). As this was primary data from six sites, the representativeness was good, but the horizontal spread included a lot of uncertainty due to the different natures of the sites.

8.3.3 Scottish salmon processing plants

LCI data were collected from two processing plants located in the Outer Hebrides and Scottish mainland which took whole salmon directly from the farms surveyed in section 8.3.2. One of the processors only conducted primary processing to produce head-on gutted salmon (HOG), leaving the viscera as a by-product. The other processor produced a range of products, including HOG, fresh and frozen fillets, trimmings and the viscera by-product. The viscera was all supplied to the protein hydrolysate and oil extraction plant which is described in section 8.3.4, but no price was attached to the viscera and it was supplied as a free resource. The fillets were sold to a range of markets, both internationally and domestically, whereas all of the remaining trimmings from the second processor were sold to Russian markets. It was assumed that these trimmings included heads, frames and bellies and other scraps as identified by Ramírez (2007) but definitive information was not given. Unfortunately data on the final utilisation of the trimming by-products could not be collected in the time frame of this thesis for reasons given above.

Table 8.3 LCI of two farmed Atlantic salmon processing plants in Scotland

	Processor	
	1	2
Inputs		
Whole salmon from farms, tonnes	17000	8000
Electricity, kWh	588000	900000
Diesel, L	122000	6000
Formic acid 3%, L	28100	20000
Refrigerant (HCFC 22), kg	120	120
Water	24000	51000
Transport (sea), km	59.6	6.83
Transport (road), km	200	158
Outputs		
HOG salmon, tonnes	14100	3860
Fresh fillets, tonnes	-	1970
Frozen fillets, tonnes	-	133
Trimmings, tonnes	-	733
Viscera, tonnes	2850	1480
BOD, kg	1700	25400

The transport distances for the supply of whole salmon to the processing plants from the farms were calculated individually and weighted averages were used according to the production at each farm. The LCI data from the two processing plants can be seen in table 8.3. Both processing plants produced around the same yield of viscera per unit input of whole salmon at around 16% to 17%. Major energy inputs were different between the two plants with processor 1 using much more diesel but also far less electricity than processor 2. Plant 2 also produced far greater BOD per unit raw material, and this can be attributed to the higher level of processing and therefore rinsing of products. However, the plants did have good water treatment facilities, drain traps and instructed staff not to wash fish scraps into the drains.

8.3.4 Salmon protein concentrate and oil extraction plant

The final part of the salmon LCA was the extraction of oils and the manufacture of salmon protein concentrate from viscera, obtained from the salmon processors described in section 8.3.3. The reference year for the data collection was 2011. One major producer of salmon protein concentrate and oil from salmon viscera was interviewed for the data used in this assessment, which handled viscera equating to around 85000 tonnes of whole fish produced at Scottish salmon farms, over 50% of Scottish production for that year (Marine Scotland Science 2012). The raw material was macerated before being heated to optimum temperatures for hydrolysis with commercial enzymes for up to twenty-four hours. The exact process was commercially sensitive and details were not provided by the company. The resultant liquid product was then centrifuged to separate the oil and the remaining protein fraction which was then vacuum evaporated to give a thick liquid protein concentrate.

Table 8.4 LCI of salmon protein concentrate and oil extraction plant in Scotland.

Inputs	
Salmon viscera, tonnes	14000
Electricity, MWh	750
Natural gas, MJ	70 million
Diesel, L	123000
Outputs	
Salmon protein concentrate, tonnes	2900
Salmon oil, tonnes	1700
Waste sludge	300

Table 8.5 Proximate analysis and amino acid profile (% of protein) of salmon protein concentrate and amino acids as percentages of those in an ideal grower pig diet, extrapolated from figures given by Boisen *et al* (2000)

Proximate analysis	
Crude protein, %	30
Crude lipid, %	6
Ash, %	3.5
Fibre, %	<1
Moisture, %	55

Amino acid profile	Content, g/100g protein	Ratio to ideal protein %
Lysine	7.8	108
Methionine	3.1	160
Histidine	1.5	46.6
Threonine	3.8	76.2
Isoleucine	3.9	88.6
Valine	4.9	84.7
Typtophan	1.2	96.0
Arginine	6.4	180
Leucine	7.5	-
Serine	6.0	-
Glycine	6.0	-
Proline	4.5	-
Cysteine	0.7	-
Phenylanine	3.8	-
Tyrosine	3.4	-

Both of the products from the process were mainly sold to livestock feeds companies, domestically and internationally. The specific standards which would allow the oil fraction to be directed to human consumption as a nutraceutical, as given by the EU regulations described in chapter 2, were not in place. The protein concentrate was very different in nature to the shrimp head hydrolysate in chapter 6, which was in a dried powdered form. The salmon hydrolysate contained only 45% dry matter and 30% protein according to the specifications issued by the company (unpublished data 2012). The proximate analysis and amino acid profile of the hydrolysate and its ratios to the ideal protein for pigs, described by Boisen *et al* (2000) in chapter 3 is shown in table 8.5. The amino acid profile of the concentrate is comparable to the profiles from other marine fish meals given in table 3.1 in its ability to provide the correct balance to pigs, although it is considerably lower in histidine. This could perhaps be provided by soybean or other vegetable proteins which have higher levels of this amino acid (Boisen *et al* 2000).

Products were sold for animal health reasons as described in chapter 1, such as reproduction and weaning performance in pigs, but also for premium pet foods and as functional ingredients in chicken feeds to produce omega-3 FA rich eggs for human consumption. The resultant waste sludge was sent to an incineration plant for treatment, the impacts of which were adjusted from Ecoinvent 2.2 processes for the incineration of digester sludge. The LCI data can be seen in table 8.4 and the survey questionnaire in appendix 4.2.

8.4 Life cycle impact assessment of Scottish salmon value chains

The LCIA of the whole value chain for Scottish salmon is presented in this section as data were collected from all nodes of the chain for this thesis, whereas LCI data upstream from the by-product processing were collected in collaboration with Henriksson *et al* (2014a) for chapters 6 and 7.

8.4.1 LCIA of Scottish salmon grow-out feeds

The LCIA of one tonne of salmon feed can be seen in table 8.6. The data are presented as the aggregated ingredients and energy consumption required over a full year of production as presented in table 8.1

The contributions to the LCIA can be seen in figure 8.3. Much of the contribution comes from the use of vegetable based ingredients within the diet, especially proteins, despite there being around 48% fish ingredients. This is because some of the plant proteins, such as types of gluten, are extremely energy intensive in their processing (Pelletier *et al* 2009). The individual ingredients cannot be discussed because of confidentiality. However, almost all of the contributions to plant proteins came from processes associated with the production of electricity, including mining to supply coal in the case of ecotoxicity and eutrophication. Pelletier *et al* (2009) also showed that some vegetable ingredients were energy intensive and Papatryphon *et al* (2004) showed that salmonid

Table 8.6 LCIA of one tonne of generic salmon feed at the mill by economic allocation. 1000 iterations of Monte Carlo analysis, means and standard deviations

Impact category		
Abiotic depletion, rare elements	kg Sb eq	0.00211 ±0.00143
Abiotic depletion, fossil fuels	MJ	69100 ±67800
Global warming, GWP100	kg CO_2 eq	5070 ±4400
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.000254 ±0.00022
Fresh water ecotoxicity	kg 1,4-DCB eq*	1560 ±2160
Marine ecotoxicity	kg 1,4-DCB eq*	5270000 ±6280000
Terrestrial ecotoxicity	kg 1,4-DCB eq*	33.0 ±22.1
Photochemical oxidation (high NOx)	kg ethylene eq	1.60 ±0.833
Acidification	Kg SO_2 eq	30.9 ±20.2
Eutrophication	Kg PO_4^{3-}eq	82.9 ±14.9

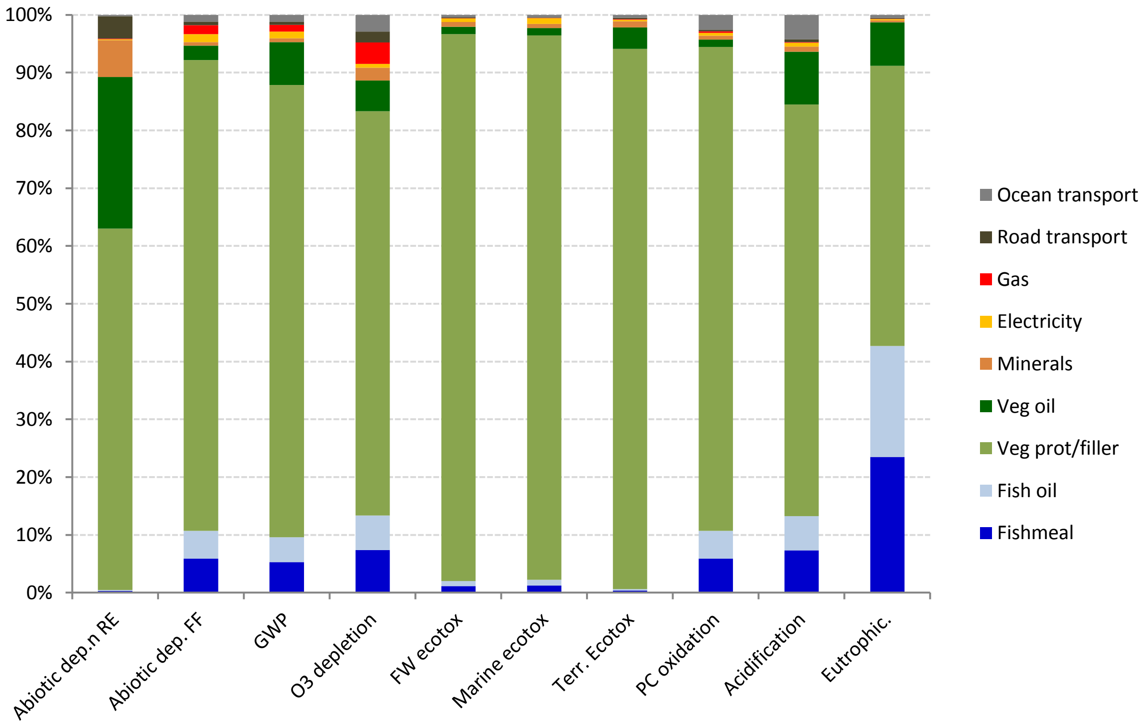


Figure 8.3 Contributions to LCIA in Scottish salmon feeds by economic allocation

feeds containing large quantities of vegetable ingredients had higher impacts than those with high levels of fish ingredients. However, it should be noted that these studies used different methodology in some cases and would have had different inputs to the data presented here.

The fish ingredients perform well in this study compared to plant ingredients in all categories except for eutrophication for which the contributions are more even. Almost all of the eutrophication from fishmeal and fish oil production in this model comes from the waste-water of fishmeal processing. The contributions from energy required to heat and mill the ingredients at the feed mill are negligible compared with their production, as is the contribution from both land and sea transport. This is despite over 40% of the ingredients being sourced from South America and a significant proportion from central Europe. It is therefore worth noting that in terms of LCA impacts, high fishmeal diets are substantially better performing than many plant ingredients but this is of course tempered by the stock status of the fish from which it is produced. The GWP for one tonne of the vegetable protein/filler mix used in the salmon diet assessed in this study was considerably higher than that of one tonne of the fishmeal, at 7250 kgCO_2eq and 844 kgCO_2eq respectively. It follows that the various fishmeal supplies which have been identified in chapter 3 could perhaps be better directed to increase efficiencies and reduce global impact, and a balance needs to be struck between those well managed fishmeal supplies which are regarded as sustainable (such as by IFFO RS etc) and the range of replacements available for less sustainable fishmeal resources. However, as chapter 7 showed, by-product meals can be highly impacting if they use large energy inputs to process them and if the industry from which they came was also highly impacting.

8.4.2 LCIA of Scottish salmon farming

The LCIA of producing one tonne of live salmon is presented in table 8.7 and the contribution analysis can be seen in figure 8.4. Similar to the production of *Pangasius* catfish, the impacts from the production of salmon are dominated by the production of feed and all other contributions are less than 10% except for eutrophication which has a significant contribution from the effluent resulting from the metabolic activities of the fish. The contributions from energy seem particularly low and there may be some error, although farms gave both the quantity of electricity in kWh and the price, which tallied according to the price of electricity at the time. It is also broadly in agreement with Pelletier *et al* (2009) who found the contributions from feeds were the dominant input to farm impacts in the UK.

Table 8.7 LCIA of one tonne of live salmon at farm by economic allocation

Impact category	**Unit**	
Abiotic depletion, rare elements	kg Sb eq	0.00211 ±0.00143
Abiotic depletion, fossil fuels	MJ	69100 ±67800
Global warming, GWP100	kg CO_2 eq	5070 ±4400
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.000254 ±0.00022
Fresh water ecotoxicity	kg 1,4-DCB eq*	1560 ±2160
Marine ecotoxicity	kg 1,4-DCB eq*	5270000 ±6280000
Terrestrial ecotoxicity	kg 1,4-DCB eq*	33.0 ±22.1
Photochemical oxidation (high NOx)	kg ethylene eq	1.60 ±0.833
Acidification	Kg SO_2 eq	30.9 ±20.2
Eutrophication	Kg PO_4^{3-}eq	82.9 ±14.9

Therefore, the overall performance of salmon farms, and many other aquaculture operations, is fundamentally connected to their efficiency of feed provision and survival of the stock to provide good eFCRs. More efficient feeding will also reduce the impacts from the farm effluent. The delivery of feed has improved significantly in a short space of time, from cages with computer controlled automatic feeders to individually fed cages, monitored by camera as the fish are feeding. The feeders can then be shut off when the fish stop their feeding response so that little feed is wasted (Hawkins pers. comm. 2011). This has now become the norm for salmon grow out farms where feed is the main expense and contributes most to the environmental impact of the farm. Advances in feed formulation have also contributed significantly to improving FCRs which can be expected in salmon farming (Tacon and Metian 2008).

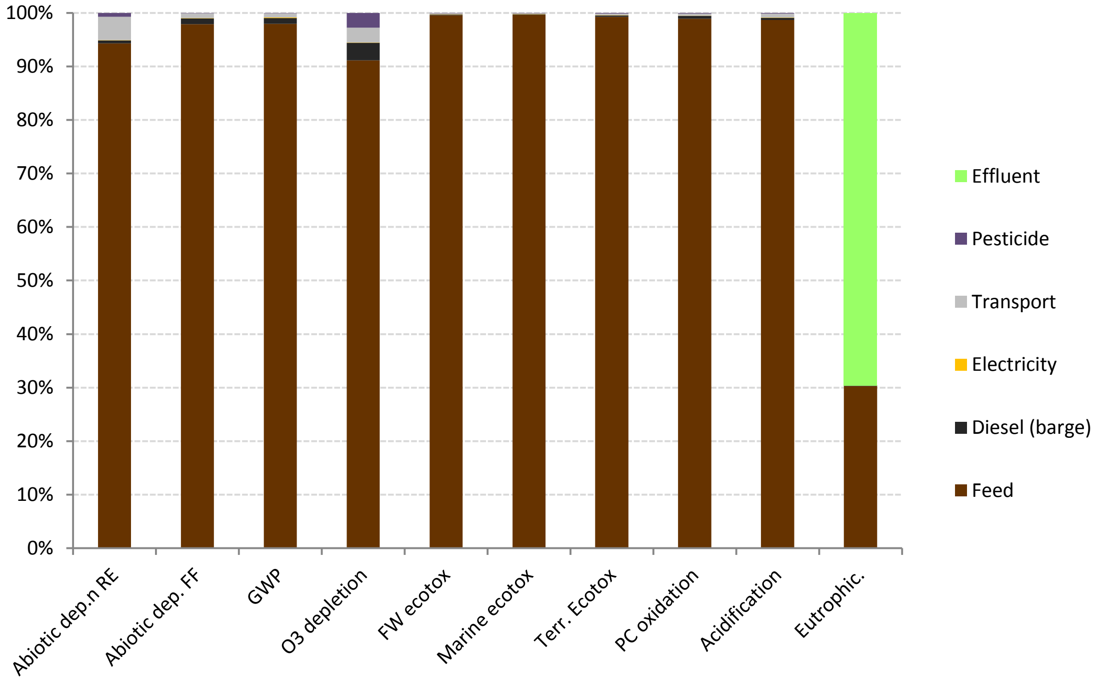


Figure 8.4 Contributions to the LCIA of producing Scottish farmed salmon at the farm. Transport incudes the delivery of feed and the boat used for servicing the farm.

8.4.3 LCIA of Scottish Salmon processing plants

The LCIAs of the two processors is presented in table 8.8 and the contribution analysis in figure 8.5. The overall impact is dominated by the contribution from the salmon raw material, as it is for *Pangasius* and therefore feed provision is still the most important factor within the value chain. The only other contributions of note are to ozone depletion from chemicals, mainly HCFC (hydrochlorofluorocarbon) refrigerants, and from transport from the farm to the processor. The HCFC used for refrigeration at the processors surveyed was R-22, which is currently in the process of being phased out in some countries including the USA and the EU (U.S. Environmental Protection Agency, no date; DEFRA 2011) and it is only permissible to use recycled R-22 in the EU (DEFRA 2011). The use of other refrigerants such as R-410A may improve the impact from ozone depletion, however, there may be trade-offs in other impact categories, but different refrigerants were not explored for this thesis.

Due to the higher impact to produce one tonne of whole live fish at the farm for salmon than for *Pangasius*, the impact for the production of fillets is also higher. The proportion of economic value attached to the edible yield from salmon and *Pangasius* at the processing stage is 72.7% and 82.4% respectively. The similar economic proportions result in both the impact from farming and producing fillets of salmon to be approximately double that of *Pangasius*. The HOG and fillet products have similar impacts to each other, despite their different values, with similar contributions from the salmon raw material. The higher electricity consumption to produce fillets is evident from processor 2 but the use of diesel at processor 1 has negligible contribution.

Data on nitrogen loading within the effluent were not provided, but it may be that the fillets would have had higher eutrophication potential than the HOG salmon, as processor 2 had much higher BOD than processor 1 (table 8.3). The nitrogen loading of the effluent is dependent on many factors within a processor including if the fish is soaked in water and for how long, the amount of rinsing and whether fish scraps are prevented from entering the drains (ENTEC 1999). The processors declared that they had measures to lower the effluent impact and water treatment facilities but because of the different factors involved, it is not possible to estimate the nitrogen or other solutes within it.

Table 8.8 LCIA of products from two Scottish farmed salmon processors using economic allocation. The head on gutted fish are from the combined production of the two processors, proportionate to their total production. Fish fillets are combined fresh and frozen fillets from processor 2. Viscera had no economic value and therefore no impact in this assessment.

Impact category		**HO gutted 1000kg**	**Fillets 1000kg**	**Trimmings 1000kg**
Abiotic depletion, rare elements	kg Sb eq	0.00229 ±0.00192	0.00674 ±0.00553	0.000501 ±0.000325
Abiotic depletion, fossil fuels	MJ	69100 ±60600	207000 ±194000	15500 ±12500
Global warming, GWP100	kg CO_2 eq	5070 ±3990	15300 ±12800	1130 ±803
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.000268 ±0.000185	0.000808 ±0.000627	0.0000603 ±0.0000425
Fresh water ecotoxicity	kg 1,4-DCB eq*	1530 ±2090	4730± 7250	344 ±382
Marine ecotoxicity	kg 1,4-DCB eq*	529000 ±6564832	16400000 ±23200000	1220000 ±1333000
Terrestrial ecotoxicity	kg 1,4-DCB eq*	34.3 ±29.5	100 ±78.8	7.63 ±4.83
Photochemical oxidation (high NOx)	kg ethylene eq	1.61 ±0.758	4.80 ±2.77	0.351 0.178
Acidification	Kg SO_2 eq	31.1 ±18.66	93.0 ±62.3	6.83 ±0.395
Eutrophication	Kg PO_4^{3-}eq	84.1 ±13.6	248 ±95.6	18.3 ±7.29

The contribution from transport is proportionately higher from processing than other nodes of the value chain for salmon and processes for other species. This is because there are only two processors which service the whole production for this company, with farm sites over 200km away in some circumstances. Most of this must be conducted by road due to the remote nature of the farm sites and processors, with some transport by boat from the island sites.

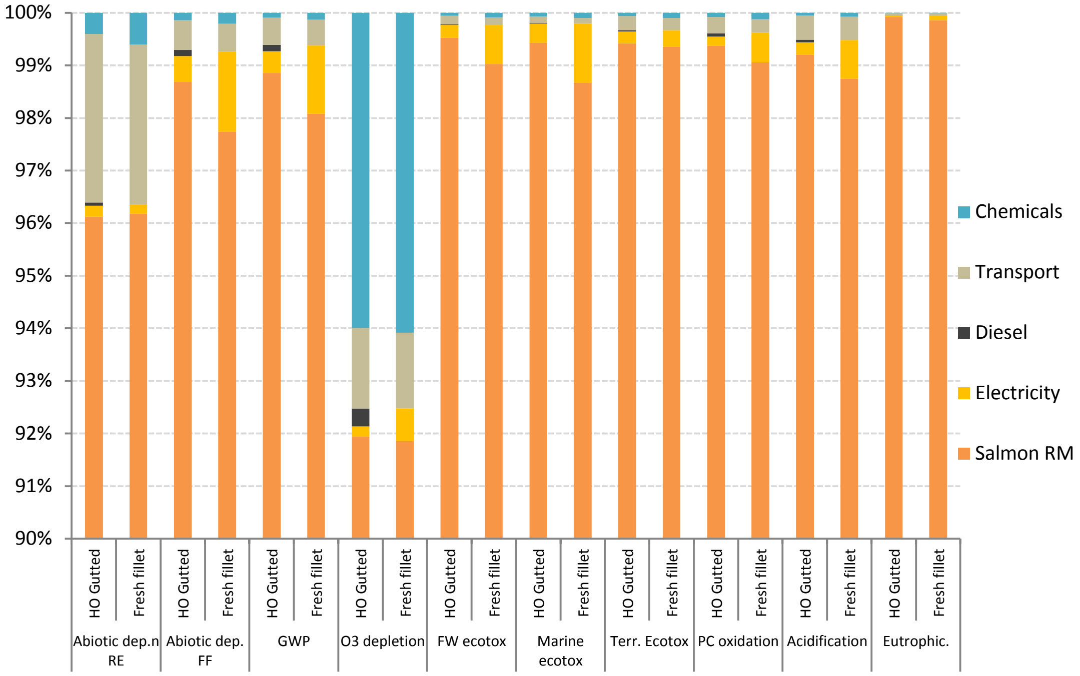


Figure 8.5 Contributions to the LCIA of farmed salmon processing at 2 processors using economic allocation. HOG is from the primary processor only and does not include that from processor 2 which conducts secondary processing also. Fish fillets are fresh fillets only, from processor 2. RM = Raw material

8.4.4 LCIA of protein concentrate and oil extraction from salmon by-products

The viscera from the two salmon processing plants is provided to the salmon hydrolysate and salmon oil extraction company at no charge. Therefore, using economic allocation, all of the impacts from this by-product processing are associated with the energy, heat and transport which it requires, with none coming from the upstream processes of salmon production. The LCIA of the protein concentrate and salmon oil extraction are given in table 8.9 with the contribution analysis in figure 8.6.

Table 8.9 LCIA of salmon protein concentrate and salmon oil extracted from farmed salmon viscera by economic allocation. Means and standard deviation.

Impact category	**Unit**	**Salmon protein concentrate 1000kg**	**Salmon oil 1000kg**
Abiotic depletion, rare elements	kg Sb eq	0.00014 ±0.0000454	0.000300 ±0.000101
Abiotic depletion, fossil fuels	MJ	14600 ±3550	31600 ±7910
Global warming, GWP100	kg CO_2 eq	843 ±117	1800 ±255
Ozone layer depletion, ODP steady state	kg CFC-11 eq	0.000114 ±0.0000414	0.000246 ±0.0000880
Fresh water ecotoxicity	kg 1,4-DCB eq*	25.9 ±19.1	55.2 ±17.3
Marine ecotoxicity	kg 1,4-DCB eq*	96300 ±28800	208000 ±50200
Terrestrial ecotoxicity	kg 1,4-DCB eq*	0.731 ±0.221	1.58 ±0.457
Photochemical oxidation (high NOx)	kg ethylene eq	0.0671 ±0.0149	0.145 ±0.0340
Acidification	Kg SO_2 eq	0.989 ±0.157	2.13 ±0.358
Eutrophication	Kg PO_4^{3-}eq	0.246 ±0.909	0.533 ±0.212

The impacts from salmon oil are approximately double those of the protein concentrate and proportionately the same for each category because they originate from the same process and are separated by the same allocation factor. The value of the oil is just over double that of the protein concentrate per kg. The impacts of the protein concentrate are much lower than those of the shrimp hydrolysate in chapter 6, however, they are not directly comparable because the salmon protein concentrate is in a liquid form with only

45% dry matter compared to the powdered shrimp hydrolysate. The drying process was also one of the most energy intensive phases of producing the shrimp product. The effects of economic allocation are also very important in this case as the shrimp hydrolysate took the majority of the impact compared to the shell by-product, whereas the protein concentrate took only around a third of the impacts from the combined protein concentrate production and oil extraction process. Also there is no contribution from the salmon raw material because it is a free resource. These issues will be investigated more in chapter 9.

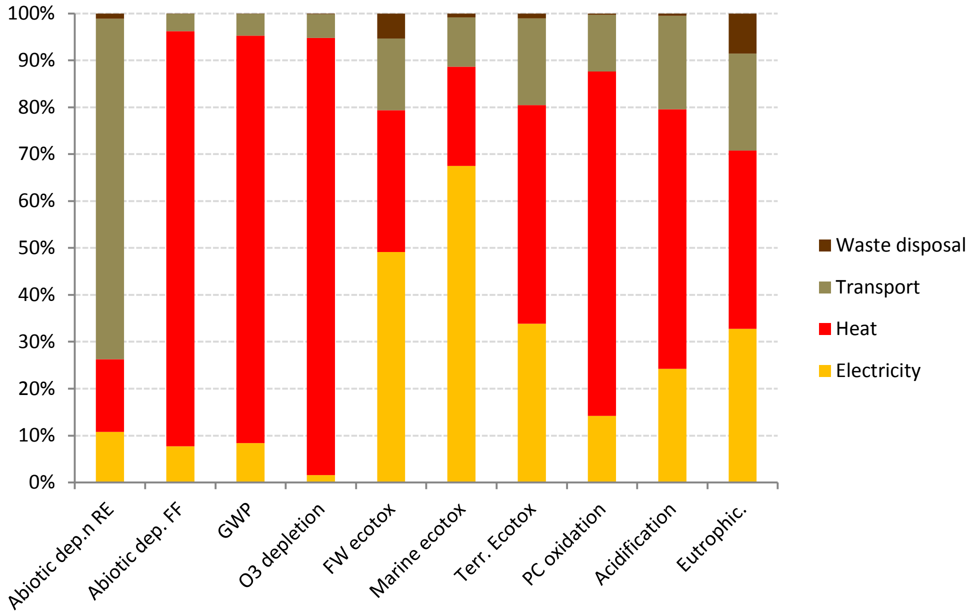


Figure 8.6 Contribution analysis of producing salmon protein concentrate and salmon oil from Scottish farmed salmon viscera by economic allocation.

The most significant contributions to impacts from salmon protein concentrate and oil production are from heating using natural gas boilers. Electricity consumption is also a substantial contributor to ecotoxicity impacts, acidification and eutrophication, which come mainly from the burning of fossil fuels, and associated coal mining and gas production activities. Transport also contributes to a noticeable proportion of the impacts and this is expected considering the long distances involved from remote processors to the plant's location in the "Central Belt" of Scotland. However, the processors and the extraction plant are all close to the sea and it is possible that impacts from transport could be reduced by transporting more of the salmon raw material by sea. Considering economic allocation for this process, this company has the best opportunity of any of the other companies or nodes of production to affect its impact. It is unlikely that the impacts from transport could be much reduced and would have little effect except for on abiotic depletion of rare elements. The exact processes involved in the production were confidential so it is difficult to pin-point areas in which efficiency could be improved. However, by improving energy efficiency, especially with regards to gas consumption, this company could substantially reduce its impact. This could mean the inclusion of heat exchangers or more efficient boilers.

8.4.5 LCIA of the Scottish farmed salmon value chain

Figure 8.7 shows the contributions from the various salmon products which are associated with one tonne of products that are directed to human consumption by economic and mass allocation. The contribution to $1000 of production is included in the comparison with other value chains in chapter 9. For salmon, the products directed to human consumption include the HOG salmon as well as fillets and no attempt has been made to separate the total edible yield from the HOG fraction. This could be estimated with the remaining by-product being added to the trimmings which are sold to Russian markets. Using economic allocation, the salmon protein and oil fractions make very little contribution to overall impact of the value chain because they carry no upstream impacts with them. Using mass allocation, the combined impact of the salmon protein concentrate and oil contributes close to 20% in all impact categories. However, the uncertainty attributed to the overall impact of the value chain is very large with either allocation method. This is mainly due to the range of inputs at the farming stage, between farms which had large ranges of feed utilisation and which used mains electricity for land based feeding systems compared to diesel powered feed barges at other sites. Considering the large contribution of feed to the production of salmon at the farm, it is the uncertainty in feed provision which contributes most to the overall uncertainty of the model.

Generally it must be concluded that the use of the by-products from primary processing is highly beneficial as otherwise it is most likely that they would be discarded due to their low value. Their overall contribution to the impacts of the value chain is very small, especially using economic allocation. The further utilisation of the protein concentrate and oil in other industries was not assessed and it would be of interest to compare the performance of the protein concentrate to the shrimp hydrolysate in livestock and aquafeeds as it is likely that it would perform well in a comparative LCA. Like the other species, the overall, LCA of the salmon industry is dominated by the provision of feed, with energy intensive vegetable ingredients contributing most highly. Therefore the findings of chapter 3 are of considerable note and it may be more beneficial for feed companies to drive the provision of sustainable fishmeal resources from the by-products

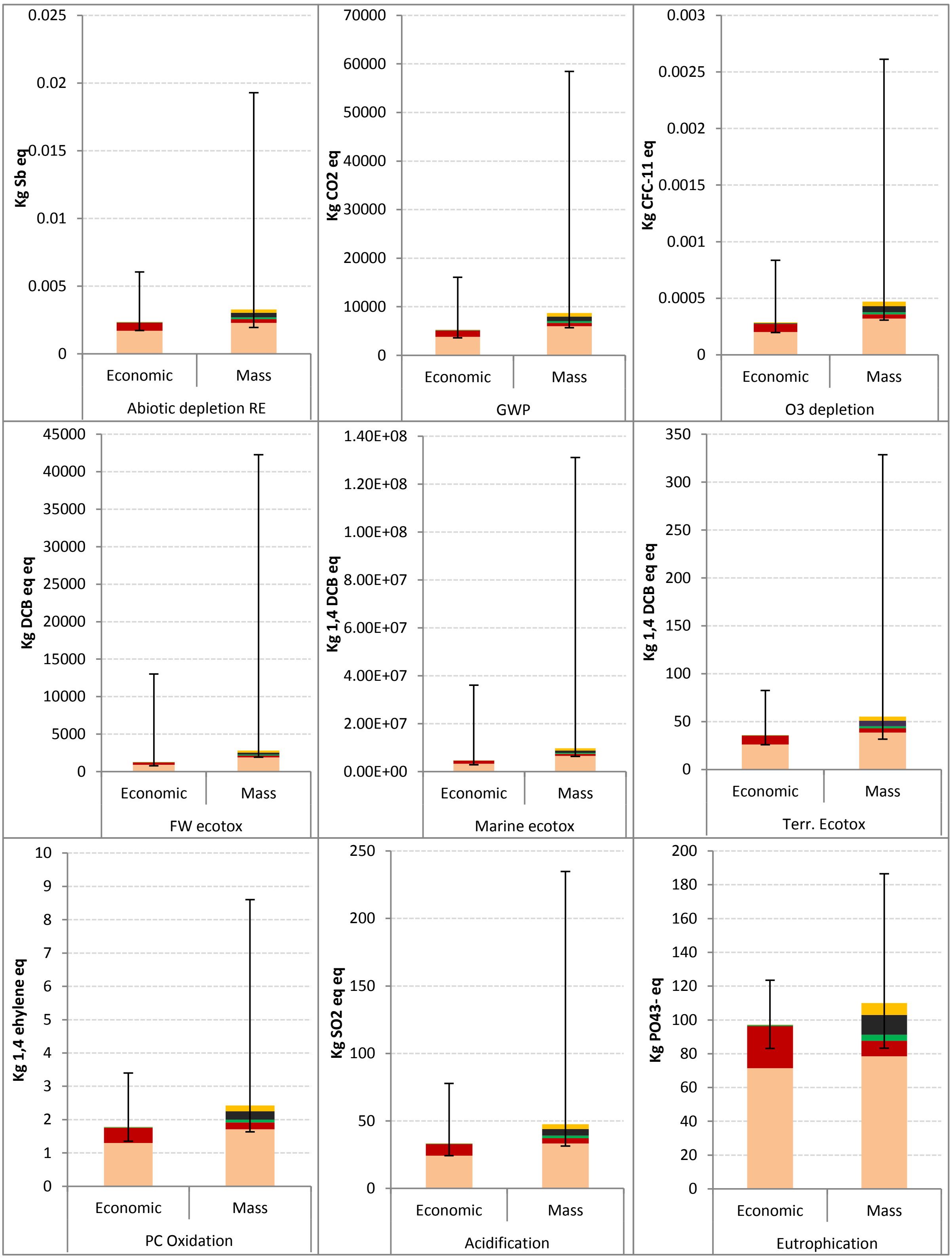


Figure 8.7 LCIA of products resulting from processing activities to produce 1000kg of salmon directed to human consumption and associated by-products by economic and mass allocation. Salmon HOG, 856kg (pink), combined fresh and frozen fillets, 107kg (red), salmon trimmings, 37.1kg (green), salmon protein concentrate, 41.3kg (black), salmon oil, 24.1kg (yellow).

of marine capture fisheries, to provide less impacting feed ingredients compared to substituting for the more impacting vegetable sources, such as corn gluten. However, some of these ingredients perform other functions within the diet apart from nutrition such as pellet binding. Therefore it is simplistic to suggest that the high impacting vegetable ingredients may all be replaced with less energy intensive ingredients, or that many vegetable proteins could be simply be replaced with the lesser impacting of the fish ingredients without other consequences on the performance of the diet. For example, different fishmeals have shown to perform differently when included in formulated diets, affecting the hardness and durability of pellets (Samuelsen *et al* 2013). In which case poorer quality fishmeals, which may be less energy intensive in their production and be nutritionally comparable in many respects, could have trade-offs such as the requirement for more energy intensive binders or possibly higher eFCRs due to higher wastage at the farm. Therefore the trade-offs of utilising different ingredients would need much more investigation in nutrition studies which are beyond the scope of this thesis, however, many feed companies carry out their own comparative LCA assessments when sourcing the ingredients for their formulations.

CHAPTER 9 COMPARING VALUE CHAINS AND GENERAL DISCUSSION

9.1 Introduction

The aim of this thesis was to identify the current by-product utilisation strategies, to compare their environmental performance against each other, and the trade-offs between the value added and the additional environmental impact from these industries. A major part of it was to develop LCA methodology that can adequately assess the broad range of by-product applications and compare between diverse value chains. This chapter brings together the findings and discussion from the previous LCA chapters, which assessed the environmental impacts associated with individual species value chains and compared them against each other using the methodologies outlined and discussed in chapter 5. This section will primarily focus on the overall economic value of the industries including their by-product processing activities but also comparing the co-products in relation to one tonne of edible yield from the processor gate. In chapter 6, two alternative scenarios for shrimp by-product utilisation were compared with each other. It was found that the scenario producing chitosan and shrimp hydrolysate in separate industries performed better than the scenario which produced only shrimp meal, in terms of eco-efficiency and also in terms of the utilisation of equal amounts of by-product obtained from one tonne of edible yield. In this chapter, the same methodology will be used to test the chitosan and hydrolysate scenario against the *Pangasius* and salmon value chains to assess which is most efficient in its economic return versus its environmental impact.

The final part of this chapter will take those findings, and those of other chapters, and discuss them in the broader context of global environmental sustainability discussed throughout the thesis.

9.2 Comparison of LCAs of shrimp, *Pangasius* and salmon value chains

Figure 9.1 shows the comparison between the utilisation strategies to generate total product value of $1000 from the co-products from the three study species. For Thai shrimp scenario b), in chapter 6.4, producing chitosan and hydrolysate was chosen as the best performing strategy to compare against the other two species. Statistical analysis was performed by pairwise ANOVA on the log transformed data generated from 1000 Monte Carlo runs of the LCIA data in CMLCA 5.2 for each of the species. Analysis was carried out on all of the impact categories separately. All species were significantly different from each other in all categories ($p = <0.0001$ apart from ozone depletion $p = 0.0410$, shrimp and salmon), except for eutrophication where salmon and *Pangasius* were not significantly different ($p = 0.2240$).

Scottish salmon performs badly compared to other species in the ecotoxicity impact categories where it is the worst performer followed by *Pangasius* then shrimp for all three ecotoxicity categories. Shrimp is consistently the best performer in terms of least emissions for all categories except for ozone depletion for which salmon is the best performer. *Pangasius* is the worst performer in most cases apart from ecotoxicity and eutrophication. For the eutrophication, there is no significant difference between *Pangasius* and salmon but they both perform worse than shrimp.

Figure 9.2 shows the same analysis as figure 9.1 but with mass allocation. Statistical analysis of the Monte Carlo runs from CMLCA 5.2 broadly agree with those using economic allocation in that *Pangasius* is the worst performer in all but two categories, followed by salmon and then shrimp ($p = <0.0001$). For freshwater and marine ecotoxicity salmon is the worst performer, followed by *Pangasius* and then shrimp but for terrestrial ecotoxicity, there is no significant difference between salmon and shrimp ($p = 0.9241$) which are both better performers than *Pangasius* ($p = <0.0001$). For ozone depletion, *Pangasius* is the worst performer, followed by shrimp and then salmon ($p = <0.0001$). The results of the two analyses are summarised in table 9.1

Table 9.1 summary of results of statistical analysis of 1000 Monte Carlo runs, ranking the environmental performance of production of US$1000 of Vietnamese *Pangasius*, Thai shrimp and Scottish salmon products using ANOVA. Best performer = 1 to worst = 3.

		Product					
		Shrimp		**Salmon**		***Pangasius***	
Impact category	**Unit**	Economic	Mass	Economic	Mass	Economic	Mass
Abiotic depletion, rare elements	kg Sb eq	1	1	2	2	3	3
Abiotic depletion, fossil fuels	MJ	1	1	2.5	2	2.5	3
Global warming, GWP100	kg CO_2 eq	1	1	2	2	3	3
Ozone layer depletion, ODP steady state	kg CFC-11 eq	2	2	1	1	3	3
Fresh water ecotoxicity	kg 1,4-DCB eq*	1	1	3	3	2	2
Marine ecotoxicity	kg 1,4-DCB eq*	1	1	3	3	2	2
Terrestrial ecotoxicity	kg 1,4-DCB eq*	1	1.5	3	1.5	2	3
Photochemical oxidation (high NOx)	kg ethylene eq	1	1	2	2	3	3
Acidification	Kg SO_2 eq	1	1	2	2	3	3
Eutrophication	Kg PO_4^{3-}eq	1	1	2.5	2	2.5	3

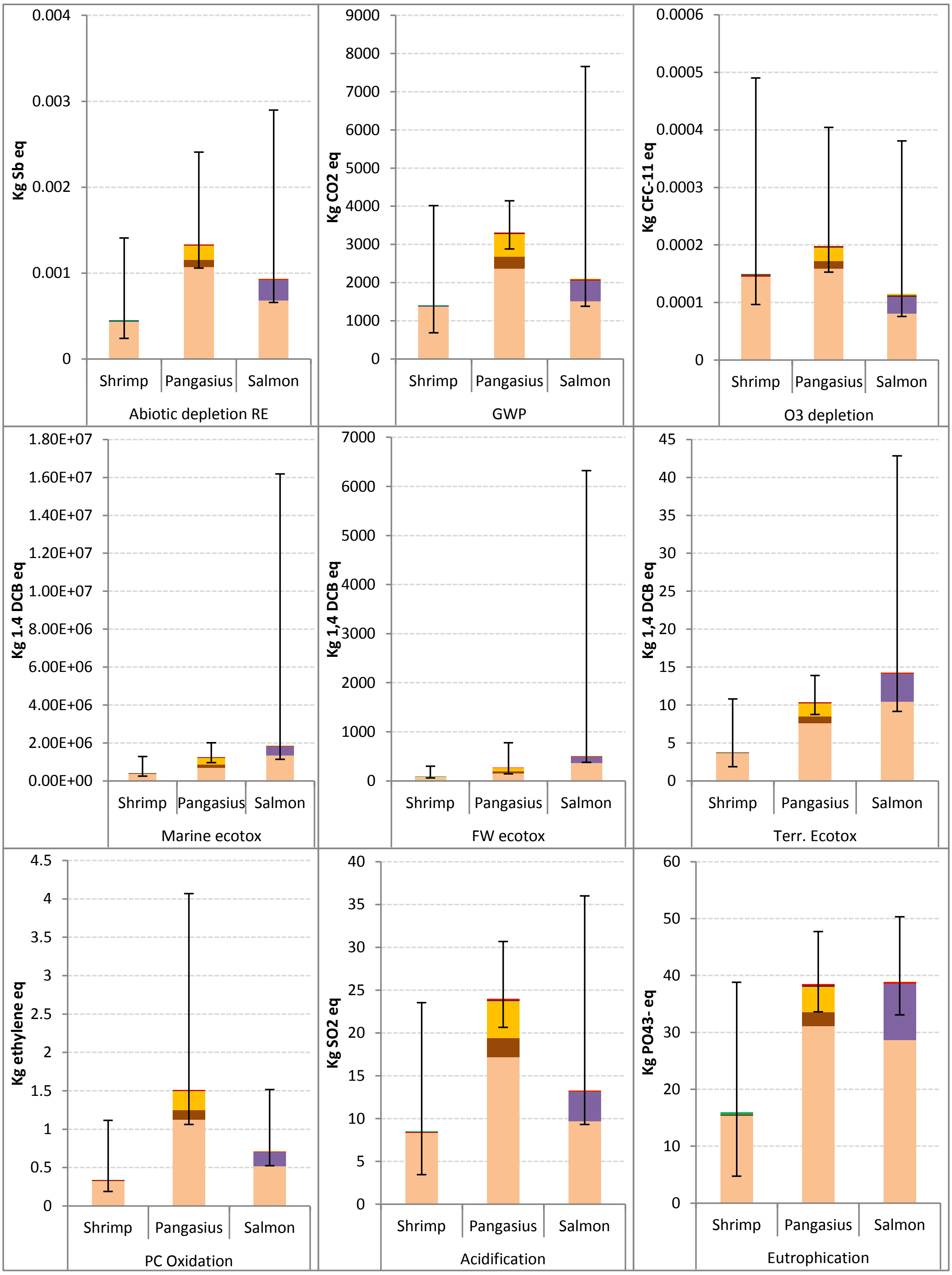


Figure 9.1 LCIA of products resulting from processing activities to produce US$1000kg of total shrimp, *Pangasius* and salmon products by economic allocation. Edible portion (pink), for salmon edible portion separated into HOG (pink) and total fillets (purple), stomachs, swim-bladders, trimmings (red), fishmeal (brown), protein concentrate and hydrolysate (dark blue), fish oils (yellow), chitosan (green). 95% confidence levels around geometric mean of log normal distribution.

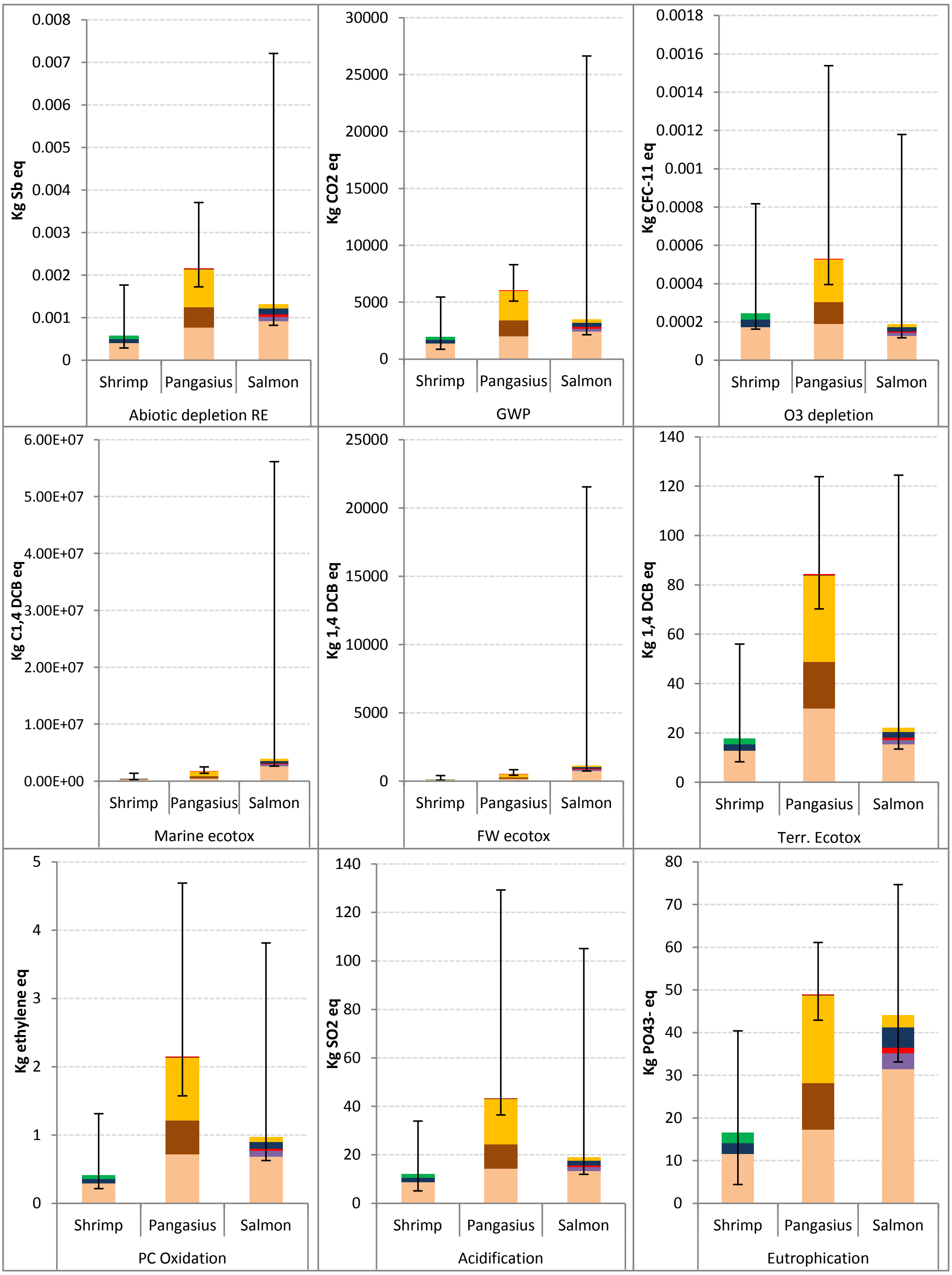


Figure 9.2 LCIA of products resulting from processing activities to produce US$1000kg of total shrimp, *Pangasius* and salmon products by mass allocation. Edible portion (pink), for salmon edible portion separated into HOG (pink) and total fillets (purple), stomachs, swim-bladders, trimmings (red), fishmeal (brown), protein concentrate and hydrolysate (dark blue), fish oils (yellow), chitosan (green). 95% confidence levels around geometric mean of log normal distribution.

The allocation method only has a slight effect on the relative performances of the different species value chains, with different ranks in just three of the impact categories which were investigated. This strengthens the overall findings of the analysis, however, it is important to realise that the findings are very much subject to how the various products are valued, which may be extremely volatile and differ from region to region (Guinée *et al* 2004). The edible portion is the largest contributor to the overall value of the combined products for all species except for *Pangasius* using mass allocation and therefore, this is the dependent factor in the assessment. The price of shrimp, for example, has been steadily rising since April 2013 in the wake of the EMS outbreak and the prices of *Pangasius* and salmon have also been subject to volatility (Nguyen 2008, Indexmundi, online resource 2014). How much effect this has on the performance of the different species is not known as prices were only taken from the survey data as they were collected and several years' worth of data would be needed for comparison, which was beyond the scope of this thesis.

Figures 9.3 and 9.4 show the same analyses as figures 9.1 and 9.2, but for a tonne of edible product at the processor gate and the co-products associated with that fraction, after further processing, for each species. There are clear differences in the performances of the species compared to their total economic value. The high value of chitosan and the shrimp product, has a major effect on the overall performance of shrimp value chain. Whereas it is the most eco-efficient in terms of the impact per unit value of the combined products, to produce a tonne of edible product and the associated co-products, salmon is least impacting. Table 9.2 shows a summary of the ranking of each species after statistical analysis of the Monte Carlo runs from the CMLCA models.

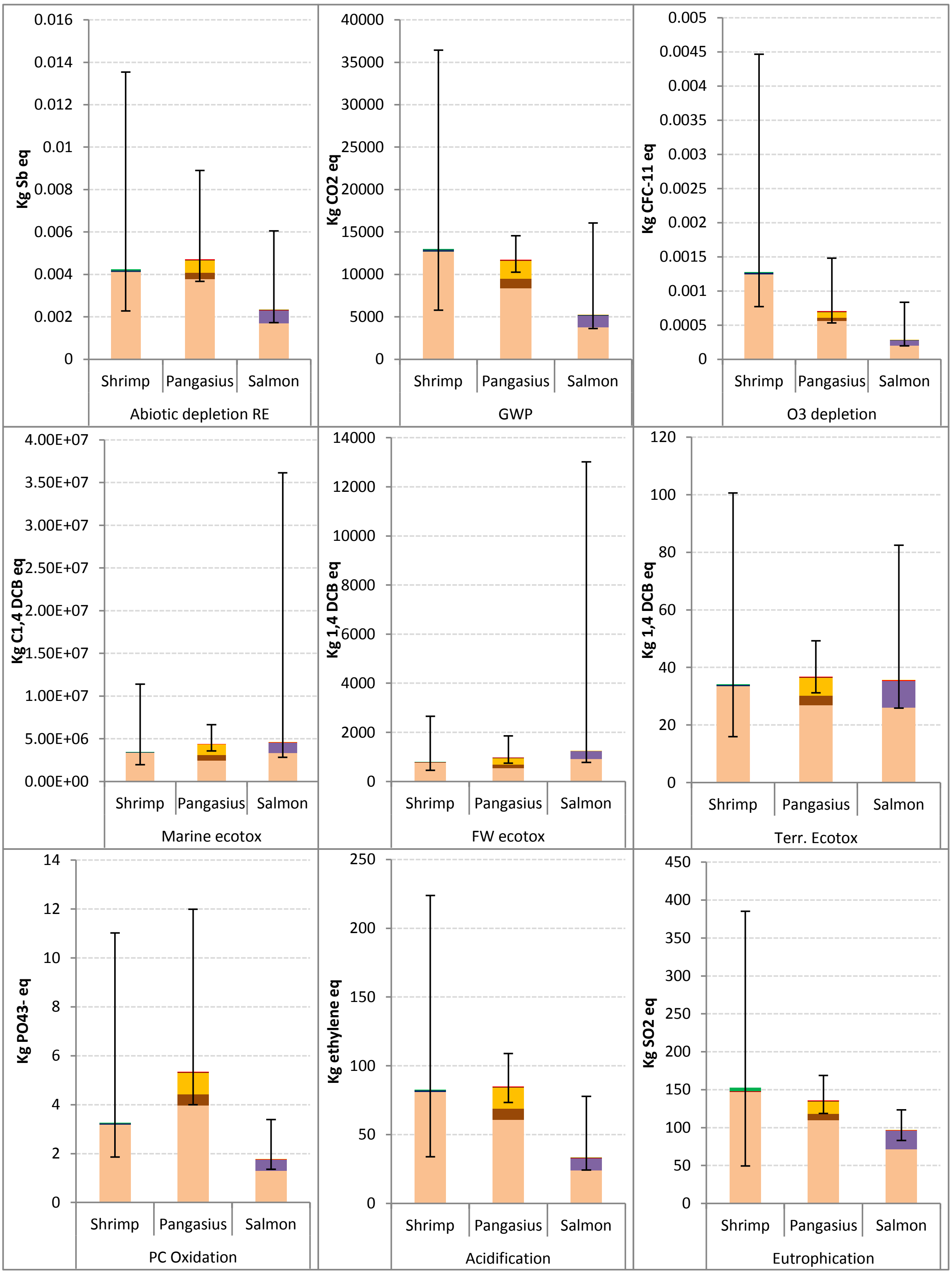


Figure 9.3 LCIA of products resulting from processing activities related to production of one tonne edible yield of shrimp, *Pangasius* and salmon production by economic allocation. Edible portion (pink), for salmon edible portion separated into HOG (pink) and total fillets (purple), stomachs, swim-bladders, trimmings (red), fishmeal (brown), protein concentrate and hydrolysate (dark blue), fish oils (yellow), chitosan (green). 95% confidence levels around geometric mean of log normal distribution.

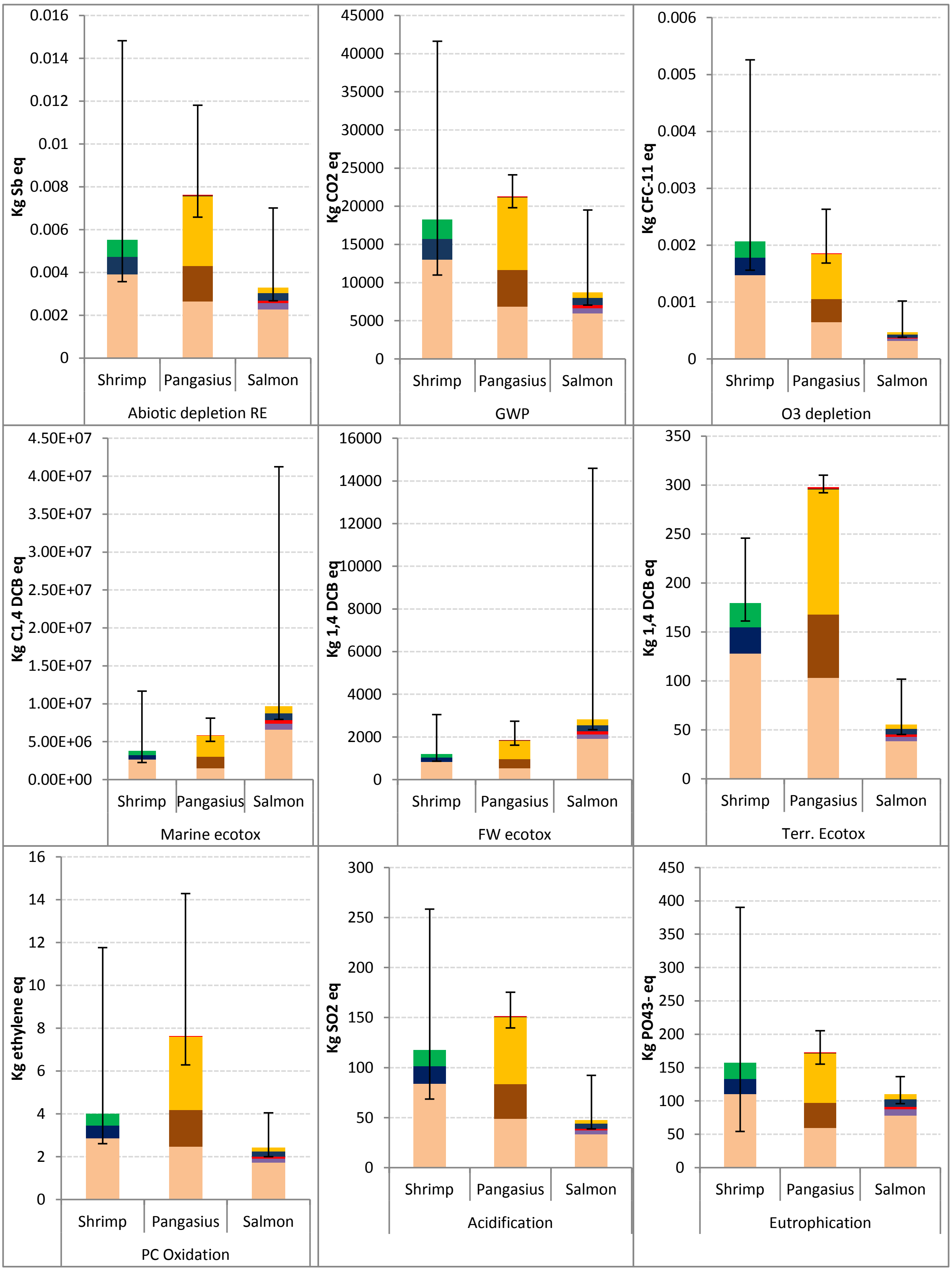


Figure 9.4 LCIA of products resulting from processing activities related to production of one tonne edible yield of shrimp, *Pangasius* and salmon production by mass allocation. Edible portion (pink), for salmon edible portion separated into HOG (pink) and total fillets (purple), stomachs, swim-bladders, trimmings (red), fishmeal (brown), protein concentrate and hydrolysate (dark blue), fish oils (yellow), chitosan (green). 95% confidence levels around geometric mean of log normal distribution.

Table 9.2 summary of results of statistical analysis of 1000 Monte Carlo runs, ranking the environmental performance of production of one tonne of edible portions of Vietnamese *Pangasius*, Thai shrimp and Scottish salmon, and associated products using ANOVA. Best performer = 1 to worst = 3.

		Product					
		Shrimp		**Salmon**		***Pangasius***	
Impact category	**Unit**	Economic	Mass	Economic	Mass	Economic	Mass
Abiotic depletion, rare elements	kg Sb eq	2	2	1	1	3	3
Abiotic depletion, fossil fuels	MJ	3	2.5	1	1	2	2.5
Global warming, GWP100	kg CO_2 eq	3	2	1	1	2	3
Ozone layer depletion, ODP steady state	kg CFC-11 eq	3	3	1	1	2	2
Fresh water ecotoxicity	kg 1,4-DCB eq*	1	1	3	3	2	2
Marine ecotoxicity	kg 1,4-DCB eq*	1	1	2.5	3	2.5	2
Terrestrial ecotoxicity	kg 1,4-DCB eq*	2	2	2	1	2	3
Photochemical oxidation (high NOx)	kg ethylene eq	2	2	1	1	3	3
Acidification	Kg SO_2 eq	2.5	2	1	1	2.5	3
Eutrophication	Kg PO_4^{3-}eq	2	2	1	1	3	3

There were significant differences between all species for all impact categories except abiotic depletion of fossil fuels marine ecotoxicity and acidification, and from table 9.2, it can be seen that salmon is the best performer by both mass and economic allocation in all impact categories except for the three ecotoxicity categories. There was no difference between salmon and *Pangasius* marine ecotoxicity by economic allocation or between shrimp and pangasius abiotic depletion of fossil fuels and acidification by mass and economic allocation respectively. It is less clear between shrimp and *Pangasius* which is the better performer. However, it is clear from figures 9.3 and 9.4 that the actual edible portion of *Pangasius* is less impacting than that of shrimp in many categories and it is the further utilisation of the large by-product fraction that is responsible for a large proportion of the impact. This is especially notable when using physical allocation, as would be expected because of the low fillet yield of *Pangasius*.

However, it should be noted that the full value chain of the salmon is not represented, with a disproportionate amount of the impacts associated with HOG. This includes the head and frame of the fish. Similarly, the shrimp edible yield, which has been modelled, is that which is directed to human consumption at the processor and not necessarily fully edible. Therefore, more production is required by both the shrimp and salmon industries to achieve the same function as the pangasius chain which produces mostly fillets. This is not true of the scenario where total values of products are compared. However, a single level of processing can change the value of the by-product significantly. For example the price of shrimp shells is a fraction of the value of chitosan that can be made from them (Trung 2010). Therefore the point at which the value of the commodity is taken is critical in evaluating the whole value chain. Within this thesis, one level of further processing has been added from the point of by-product production at the primary processor apart from for salmon where data from the secondary processing of HOG, particularly, could not be obtained.

The benefits of further utilisation are difficult to gauge because at each stage of processing there are different choices, such as those to which chitosan could be directed in agriculture, food processing and medical technology described in chapter 6 (Rabea *et al* 2003, Benhamou *et al* 1994, Jeon *et al* 2002, Appendini and Hotchkiss 2002, Beach *et al* 2012). Similarly choices exist between using *Pangasius* oil in biofuels or animal feeds (Nguyen 2010). Separate studies would need to be conducted on each of the different strategies which ultimately adds complexity to the model but does not necessarily provide any extra insight. Table 9.1 shows that salmon is least impacting in providing an edible yield, whereas table 9.2 shows that shrimp is most eco-efficient. The choice between the two interpretations is subjective. It can be argued that the eco-efficiency is the dominant result because the economic value acts as a proxy for the potential for further utilisation of the by-products. However, from figure 9.1 it can be seen that the proportion of economic value is dominated by the edible portion rather than the chitosan and hydrolysate fractions. Alternatively, the production of edible yield could be argued to be the most important factor, with food production being the primary driver of aquaculture industries as argued by Pelletier and Tyedmers (2007). However, this would not be comparing like with like in the case of the shrimp export industry because shrimp are often considered luxury food products (Hensler and Bremer 2013) and therefore economic value could be seen as a legitimate functional unit for such comparisons.

Interesting methodological issues are raised by the salmon by-products which have no economic value. ISO 14044 (ISO 2006b) states that co-products which have a value should be allocated according to the hierarchy outlined in chapter 5, but wastes which have no economic value should not have any allocation factor attributed to them, whichever allocation method is chosen. As a utilised by-product, but with no value, the salmon by-product should perhaps still be regarded as a waste and have no allocation of upstream impacts attached to it, even when using mass allocation methodology. Some previous LCA studies have failed to recognise the transition from waste to utilisation as discussed in chapter 5 and this has had important consequences for the interpretation of the study. The choice of functional unit and allocation throughout the LCA study have a direct bearing on the interpretation and the conclusions that can be drawn. Although there is no ideal partitioning method, because they rely on artificial and subjective divisions of processes (Heijungs and Guinée 2007), methodology should be chosen that minimises complex problems but may be applied to best direct the use of resources. Pelletier and Tyedmers (2007) discussed at length the implications of different allocation approaches in upstream inputs for comparison between salmon feeds. It was argued that gross nutritional energy represented the material and energy flows related to the co-products, as the underlying purpose of food production is to provide nutritional energy. However, the situation regarding the drivers of food production is more complicated than just providing energy. Food choices are influenced by other factors; primarily by food safety, taste and price, the hierarchy of which is dependent upon such factors as location, social status, age, gender and if they have children. Ethical concerns are usually further down the list (Chambers et al 2008; Prescott et al 2002). The economic value of a food product is determined by its cost of production in terms of inputs, transport, availability and demand (Armah et al 2009). In the case of fish, they are often valued as sources of low fat protein and in some cases valuable nutrients such as ω-3 fatty acids (Domingo 2007). These factors may also have different priorities in the perceptions of different stakeholders e.g. the producers and retailers who seek to maximise profit compared to the consumers who seek to buy food based on the above criteria.

Pelletier and Tyedmers (2011) expanded on the reasoning for choosing physical allocation in food LCAs in previous work and is one of the most extensive discussions on the choice of allocation method in this field. They claimed that market forces gave a distorted impression of the impacts that could exacerbate existing sustainability issues. It was further stated that the allocation decision should inform on material and energy flows to meet human needs, with the goal being to limit human activities within the bio-capacity of the Earth. In general, this may be considered as beyond the scope of any conventional product focussed LCA, as they are unable to assess the broad inter-relationships of human activity and production systems at any time in enough detail.

The argument that physical allocation is a long-term solution compared to economic allocation, does not necessarily hold because physical relationships may fluctuate, and industrial technology and practices are constantly changing. For example the seasonality of capture fisheries (Thrane 2004, Davies *et al* 2009) and the ratios of aquaculture feed ingredients according to quality, current price and availability (Naylor *et al* 2009). Therefore, uncertainties related to physical allocation are similar to those of economic allocation (Guinée *et al* 2004). Consequently, the LCA will require frequent updating in response to annual and seasonal fluctuations, and changing industrial practices and technology, to remain relevant. Therefore, on this basis, economic allocation is just as valid. Ultimately this has to be contextualised with other sustainability issues that LCA does not measure directly, towards finding a balance in decision making which drives the better utilisation of current resources. Ayer *et al* (2007) and Pelletier and Tyedmers (2010) claimed that using gross energy allocation will reduce waste as it will drive producers to utilise all of the co-products more efficiently rather than wasting them. Conversely however, this could discourage an industry from utilising a product which has high environmental burdens attached to it, i.e. producers are encouraged to sell on their un-utilised co-product but buyers are discouraged from buying it (Svanes *et al* 2011). Therefore, gross energy content may be regarded as giving contradictory messages for similar situations. For example, Pelletier and Tyedmers (2010) advocate that tilapia by-products should be utilised to reduce waste, whereas Pelletier and colleagues (2009, 2007) highlight the increased environmental impact associated with fishery by-products used as fishmeal. If the same methodology was used for investigating the production of fish fillets from capture fisheries, using gross-energy content as an allocation factor, it may perhaps been concluded that the by-products should be fully utilised to avoid waste, as for Pelletier (2010). This shows the somewhat contradictory nature of physical allocation methods and the need to more fully explore the use of the by-products within the LCA in these circumstances.

The examples above by Pelletier and colleagues (2009, 2007), using energy content as an allocation factor, showed the use of fishery by-products to be much more impacting than virgin fishmeal from reduction fisheries as inputs in salmonid feeds. While a fishery may be environmentally inefficient, and one may not wish to encourage those practices by improving their profitability through buying their by-products, fishery by-products will most likely still exist if they are not used in other industries and then require subsequent disposal as demonstrated in chapter 3. This has also been demonstrated by the beef industry when the use of ruminant by-products was prohibited for the use in animal feeds post BSE crisis in Europe. Although initially the beef industry suffered huge losses, the industry continued to supply beef and the by-products were treated as waste until another market could be found (Atkinson 2000). By-products from pelagic processors are only worth very little compared to the edible fraction and their sale is not a main driver of the industry (Be-Fair 2007). The figures shown in chapter 3 demonstrate this to be the case with a large number of fisheries and aquaculture, where by-products have traditionally been considered a waste rather than been well utilised.

Using economic allocation in the sensitivity analysis of Pelletier and Tyedmers (2007) showed that using fisheries trimmings were less impacting than the reduction fisheries. Therefore in contrast to the above, it may be considered that using a biophysical allocation factor may encourage waste and exacerbate sustainability issues if the LCA suggests that these wastes should not be utilised. In the authors' view the purpose of LCA is to direct stakeholders to make the best choices on most environmentally sustainable practices, whether it be identifying hotspots in one value chain, or comparing between different production systems or value chains. Using economic allocation, the utilisation of a by-product will still be more environmentally attractive to the producer compared to wasting it, and as the value of the by-product rises with more valuable applications, its sale will become increasingly attractive, both environmentally and economically, thus driving better utilisation. Hence, it follows that economic allocation may be viewed as the logical progression from waste (allocated zero burdens) to co-products of increasingly significant application as their economic value increases. This compared to the unrealistic example of *Pangasius* where the burdens attached to *Pangasiu*s by-products will increase from nothing to over 65% of the production, at the point in time that the by-product begins to be utilised. Fish oil is a good example of how the value of a co-product has changed according to its demand. Chronologically it was a target product used as a fuel oil, then as a by-product of fishmeal production for industrial purposes such as machine lubricants and for hydrogenation into "hardened" fats in the margarine industry, as a co-target product for aquafeeds and most recently as the target product for encapsulated fish-oil nutritional supplements (Hjaltason and Hf 1990; Jackson and Shepherd 2010; Snyder 2010). The value of the commodity over time has often reflected these applications but needs to be taken in context with prices of other available edible oils with which it competes (Hjaltason and Hf 1990).

One of the most crucial factors in the decisions concerned with fish by-product utilisation may be more concerned with the status of the fish stock and the impacts on biodiversity

(Alder *et al* 2008), which LCA does not currently measure. For example, the use of by-products from herrings may be less energy efficient but also less impacting on biodiversity than using anchovetta. Conversely industry may not wish to encourage utilisation of by-products from Atlantic blue-fin tuna when this species is thought to be heavily over-fished (Fromentin and Powers 2005). However, not using the by-products may not have any effect on the catch of that species, considering its overall value. The different scenarios concerning these resources are therefore very complex and raise important questions about how LCA models should be constructed. It is currently the view of many standard setters that by-products from fisheries should not be included when calculating the “fish in / fish out” ratios (GAA 2012, GlobalGAP 2012, IFFO 2011, Jackson 2009, ASC 2010) although most standards also state that fish for reduction should be sourced from sustainable stocks. The EU by product regulations regarding animal by-product utilisation in fish-feeds were relaxed in 2013 (EC 2013) in recognition that the protein resources used for feed in competing livestock value chains are limited. Therefore it is important not to send conflicting messages. The recent PAS2050 (BSI 2012) standards for aquaculture and fisheries have advocated using mass allocation, but the logic behind this choice should be questioned given the points above.

Discussion around the choice of FU is very much dependent upon the goal and scope of the study for which a live weight at farm gate is often appropriate when only comparing between different production systems for a species. This thesis has shown that live weight is inappropriate for comparing between very different species which have the potential to provide very different functions. Ultimately the goal of the industry is to produce an edible yield, but along with this, the utilisation of the unavoidable co-product will have a significant effect on the efficiency of that production. The size of the global chitosan industry is small (Trung 2010). However, the economic value attached to it could conceivably make the by-product more valuable than the edible yield if chitosan applications and markets grow. This concept is acknowledged by Guinée *et al* (2004), who discussed the changing relationship between co-products such as given in the fishmeal and fish oil example above.

The studies presented in this thesis have attempted to address the issues of FU and allocation within them, and the contribution that by-products can make to the efficient use of the entire aquaculture product. This is the first time that this methodology has been applied to aquaculture processing co-products. There are outstanding issues in that full value chains for the species could not be obtained because of the global nature of seafood processing discussed in chapter 3. The final products of the salmon processing were not obtained because a large fraction of trimmings were exported to Russia, where there could have been many options for further processing. Similarly the use of *Pangasius* skins in the manufacture of gelatine was not modelled. This is most important in the comparison between the function of the different species. It is assumed in the case of edible yield that they are comparable, whereas in reality they are very different in their nutritional value and their perception to consumers. Whereas Pangasius is considered a white fish substitute (Little *et a*l 2012), salmon is considered a healthy source of omega-3 FAs (Domingo 2007) and shrimp are considered a luxury food item (Hensler and Bremer 2013). Therefore it is perhaps inappropriate to compare equal quantities of edible yield as shown in figures 9.3 and 9.4 and figure 9.2. Ultimately, the comparison between them is quite subjective in this regard and the overall economic value of the products may be considered the best proxy for the various functions that can be aspired to. The most misleading aspect of the presentation of LCAs in the past has been to present single figures for the different impact categories in only one context, with a dogmatic methodology that sticks rigidly to the practitioners own interpretation of the ISO standards (ANEC 2012). By presenting the data using several different procedures, a more robust decision can be made, depending on the goal of the decision makers involved.

It is hoped that the methodology can be developed further to be useful in comparing the environmental impact and trade-offs with value addition for diverse value chains in the agriculture sector. However some improvements could be made. The ISO standards state that LCAs should measure the impacts of the products, from extraction of raw materials to final disposal (ISO 2006a, 2006b). This thesis did not, for example, measure the comparative nutritional performance of the two different protein concentrates from salmon and shrimp or the oils from salmon and *Pangasius*. Similarly, the different performances were not measured for the different chitosan plants that produced different grades of chitosan. There are a huge number of different options and potential trade-offs between the various products for all species which could have altered their overall performance. A more in depth study of one species and how the boundaries are set for the different products in LCA scenarios of subsequent industries would be of value. This was ultimately beyond the scope and timeframe of this thesis which attempted to introduce a new way of thinking about how LCAs should be constructed and put the findings into context with other sustainability issues which LCA does not measure well.

9.3 Conclusions

There have been few studies into the environmental impact of aquaculture by-products and the interactions and synergies between different livestock industries. Previous studies on the impacts of aquaculture have often been obsessive about the perceived dependencies on fishmeal and countless nutrition studies have been made into substituting fishmeal for other proteins, often with little regard as to the sustainability of the substitutes. The findings of this thesis clear in highlighting the environmental impact of certain vegetable ingredients, especially in salmon feeds (chapter 8), which many nutrition studies have proposed should replace marine ingredients. In previous studies, this has largely been on the understanding that marine ingredients are finite and have consequences for marine ecosystems (Alder *et al* 2008, Naylor *et al* 2009). However, many of the reduction fisheries are well regulated, especially those which contribute to salmonid diets, whereas there have been growing fears over the possible replacements, such as soybean, which contribute to habitat loss (Fearnside 2001) and products such as wheat gluten which have proven to be very energy intensive, in this study and others such as Pelletier *et al* (2009).

Although much of the by-product is in Asia and possibly unavailable due to consumption attitudes, substantial quantities of prime marine fish by-products are under-utilised in Europe and North America which could be used to manufacture additional fishmeal supply. As the Be-fair project (2007) highlighted, this is more of an issue of logistics and economics to direct this material most efficiently, especially regarding discarding by-products from on-board processing vessels. However, market forces may eventually prove favourable for fishmeal manufacturers to drive greater demand of fisheries by-products as the recent trend in their increased utilisation suggests. Although aquaculture by-products have the advantage of being uniform and already concentrated at processors in large quantities, they may be of lower quality than traditional sources, with amino acid profiles different from the ideal ratios and low in omega-3 fatty acids in some circumstances. Therefore, they may be of little value in supplying the carnivorous aquafeeds industry unless supplemented by other protein and lipid sources. The provision of high quality fishmeal from the by-products of aquaculture species is most likely to come from *salmonid* and other carnivorous fish production, as the amino acid profile of the hydrolysed protein concentrate assessed for LCA in chapter 8 suggested, and where production is concentrated and high enough to allow for the by-product quantities to be of economic interest. Demand for fishmeal may also be highest amongst salmonids in the salmonid processing locations. Therefore, they are precluded from being used where the demand is highest, because of the intra-species feeding ban according to EU regulations and many international standards. However, according to the salmon protein concentrate producer, much of their product was sold to Thai shrimp feeds manufacturers. It was stated that the demand from the shrimp industry could account for their entire production but they chose to sell to several diverse livestock markets domestically and internationally to provide more security. The protein concentrate producer accounted for approximately half of the supply of salmon raw material but was at capacity. However, the company had only been producing for under a decade and were expecting to expand their production. Therefore the development of the by-products industry may be several years behind the demand for its products, which is being driven by the ever increasing competition for feeds ingredients, albeit developing in parallel.

The pressure on feed ingredient supplies is demonstrated by the switch to more vegetable ingredients such as soybean and the relaxation of the EU legislation on the use of meat-and-bone (MBM) meal in aquafeeds. While the inclusion of soybean has been readily accepted by feeds manufacturers and consumers, despite its impact on the environment in some circumstances, the use of MBM in aquafeeds is firmly rejected by major retailers in the UK. However, MBM is being used in Asian aquafeeds according to data collected for the SEAT project in collaboration with Henriksson *et al* (2014a). The data were collected around the time that the ban on its use in EU products was relaxed. It is not certain whether MBM was being used prior to the lifting of the ban or whether the aquaculture products which may have been raised on these feeds were destined for Europe. In any case the current and future use of MBM by Asian producers may give them a competitive advantage over European producers in the short to medium term. The Asian value chains provide a good example of full utilisation in many cases however both regions are subject to entrenched consumer perceptions and behaviour which prevents optimum efficiencies. In Europe, the barriers over perceptions of practices in intensive animal production and in Asia, consumer attitudes to fish consumption may mean that by-products cannot be directed to the best markets despite legislation sanctioning these practices. While in Europe, this mainly concerns the utilisation of terrestrial animal by-products, the use of any animal by-product is met with some trepidation.

It is clear that the biggest opportunities for aquaculture by-product utilisation are in Asia, and specifically in China. It represents around two thirds of global aquaculture production and has the industrial infrastructure to take full advantage of the resource. Industries for collagen, chitosan, peptides and gelatine have all developed over the last few years as well as the increasing demand for fishmeal. According to the Fishstat (2013) database, the production of fishmeal from “fish waste” has been growing substantially over the past few years to several hundred thousand tonnes, although according to Jackson (pers comm 2013) it is vastly over estimated. However, it is likely that there has been substantial growth in several industries, utilising the by-products from aquaculture products destined for international markets such as tilapia fillets. These industries are likely to continue growing as more by-product becomes available and as the demand for the products grows, but ultimately the increased production may be driven by vertically integrated companies which wish to maximise their profit potential and which have the ability to influence markets and consumer attitudes.

The growth in industries such as chitosan may also offer more opportunities for mortality utilisation, but the quantities of routine mortalities from shrimp farms may not provide enough material to be of economic interest. However, “middle-men” may be able to collect enough material to be of interest in some circumstances as demonstrated in Vietnam. It was not clear where the “middle-men” were selling the mortalities and it is possible that *Pangasius* catfish were being directed to fishmeal as the only established by-product industry in Vietnam. In most circumstances *Pangasius* fishmeal was being used in terrestrial livestock feeds, but some *Pangasius* oil was found to be present in the *Pangasius* feed from one producer. In which case, the EU regulations (EC 2009) are being broken on two counts; firstly in directing mortalities to livestock feeds and secondly by intra-species feeding. Traceability is not strong enough in Vietnam to know which feeds are being used for *Pangasius* that is being directed to European markets but the Vietnamese industry should be aware of the regulations and engage with feed mills and farmers to prevent this practice. The promotion of international standards which involve whole value chains such as GlobalGAP and BAP could aid in the industry's ability to conform to EU and other international regulations and guidelines.

In conclusion, the prospects for by-product utilisation are good with the possibility of adding substantial value in diverse markets with broad application. In the short term the desire to satisfy the increasing demands for feed ingredients in all livestock sectors is paramount and aquaculture has the ability to contribute to this requirement if the infrastructure is in place, traceability is observed and enforced, and if proper regard is paid to food security in developing nations which depend on the raw material resources. In the longer term the prospects for higher end products such as chitosan, nutraceuticals and cosmetics may also be good but markets may be slow to develop for such products and standards need to be put in place to ensure consistent quality in many cases.

LITERATURE CITED

Abdussamad E and Thampy D, 1994. Cannibalism in the Tiger Shrimp *Panaeus monodon fabricus* in the nursery rearing stage. Journal of Aquaculture in the Tropics, vol. 9, 1, pp 67-75.

Agriviet.com. 2009. Dầu sinh học – Sản phẩm triển vọng xuất khẩu của ĐBSCL. http://agriviet.com/nd/1716-dau-sinh-hoc-%E2%80%93-san-pham-trien-vong-xuat-khau-cua-dbscl/ Accessed 5/3/2010. 1pp. (in Vietnamese).

AIC. 2009, Compound Feed Audit Checklist Attachments, Compound Feed Operations Manual.Agricultural Industries Confederation. 5 pp.

Aidos I, Lie O, and Espe M. 1999, Collagen content in farmed Atlantic salmon (*Salmo salar L*.), Journal of Agricultural Food Chemistry, vol. 47, pp. 1440-1444.

Akazawa N. 2013. Environmental Trigger For EMS/AHPNS Identified In Agrobest Shrimp Ponds. global aquaculture advocate July - August 2013, pp 16-17.

Aksnes A, Hope B, J_nsson E, B_rnsson B T, and Albrektsen S. 2006, Size-fractionated fish hydrolysate as feed ingredient for rainbow trout (*Oncorhynchus mykiss*) fed high plant protein diets. I: Growth, growth regulation and feed utilization, Aquaculture, vol. 261, pp. 305-317.

Alder J, Campbell B, Karpouzi V, Kaschner K, and Pauly D. 2008, Forage Fish: From Ecosystems to Markets, Annual Reviews in Environment and Resources, vol. 33, pp. 153-166.

Amal M and Zamri-Saad M. 2011, *Streptococcosis* in Tilapia (*Oreochromis niloticus*): A Review, Pertanika Journal of Tropical Agriculture Science, vol. 34, no. 2, pp. 195-206.

ANEC, 2012. ANEC Position: Environmental Assessment goes Astray: A Critique of Environmental Footprint Methodology and its Ingredients. ANEC-ENV-2012-G-008final. ANEC, Brussels, Belgium. 39pp.

Appendini P. and Hotchkiss J.H. 2002, Review of antimicrobial food packaging, Innovative Food Science and Emerging Technologies, vol. 3, pp. 113-126.

Applegate T. 2008, Protein and Amino Acid Requirements for Poultry. United States Department of Agriculture. 11pp.

Arala-Chaves M. and Sequeria T. 2000, Is there any kind of adaptive immunity in invertebrates? Aquaculture, vol. 191, pp. 247-258.

Araujo P, Lucena E, Yang Y, Ceemala B, Mengesha Z, Holen E, 2014. The impact of exogenous ω-6 and ω-3 polyunsaturated fatty acids on the induced production of pro- and anti-inflammatory prostaglandins and leukotrienes in Atlantic salmon head kidney cells using a full factorial design and LC–MS/MS. Journal of Chromatography B, vol. 964, pp 164-171.

Arason S, Thoroddsson G, and Valdimarsson G, 1990. The production of silage from waste and industrial fish: the Icelandic experience, International By-Products Conference, Anchorage, Alaska. 26pp.

Archer M, Watson, R, and Denton, J W, 2001. Fish Waste Production in the United Kingdom - The Quantities Produced and Opportunities for Better Utilisation. SR537. Seafish. Edinburgh, UK. 57pp.

Arena U, Mastellone M L, and Perugini F, 2003. The environmental performance of alternative solid Waste Manage options: a life cycle assessment study. Chemical Engineering Journal, vol. 96, pp 207-222.

Armah, P, Archer, A, and Phillips, G C, 2009. Drivers leading to higher food prices: biofuels are not the main factor. In Vitro Cellular Developmental Biolology - Plant, 45, pp 330-341.

Armenta R E and Guerrero-Legarreta I. 2009, Amino acid profile and enhancement of the enzymatic hydrolysis of fermented shrimp carotenoproteins, Food Chemistry, vol. 112, pp. 310-315.

Armenta-Lopez R, Guerrero L, and Huerta S. 2002, Astaxanthin extraction from shrimp waste by lactic fermentation and enzymatic hydrolysis of the carotenoprotein complex, Journal of Food Science, vol. 67, no. 3, pp. 1002-1006.

ASC. 2010. ASC Pangasius Standard (version 1.0). Aquaculture Stewardship Council. www.ascworldwide.org. 61pp.

ASC. 2012, ASC Tilapia Standard (version 1.0). Aquaculture Stewardship Council. www.ascworldwide.org. 44pp.

ASC. 2012, ASC Salmon Standard (version 1.0). Aquaculture Stewardship Council. www.ascworldwide.org. 103pp.

Atkinson N. 2000, Impact of BSE on the economy. Ministry of Food and Fisheries, London. http://www.veterinaria.org/revistas/vetenfinf/bse/14Atkinson.html . Accessed 20/3/14. 16pp.

Aubin J, Papatryphon E, Van der Werf H M G. and Chatzifotis S, 2009. Assessment of the environmental impact of carnivorous finfish production systems using life cycle assessment. Journal of Cleaner Production, 17, pp 354-361.

Aubin J, Papatryphon E, Van der Werf H M G, Petit J and Morvan Y M, 2006. Characterisation of the environmental impact of a turbot (*Scophthalmus maximus*) re-circulating production system using Life Cycle Assessment. Aquaculture, 261, pp1259-1268.

Aye K and Stevens W, 2004, Technical note: Improved chitin production by pre-treatment of shrimp shells, Journal of Chemical Technology and Biotechnology, vol. 79, pp. 421-425.

Ayer N W, Tyedmers P H, Pelletier N L, Sonesson U and Scholz A, 2007. Co-Product Allocation in Life Cycle Assessments of Seafood Production Systems: Review of Problems and Strategies. International Journal of Life Cycle Assessment, vol. 12, 7, pp 480-487.

Ayer N W and Tyedmers P H, 2009. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. Juornal of Cleaner Production, 17, 3, pp 362-373.

Babu C M, Chakrabarti R, and Sambasivarao K R S. 2008. Enzymatic isolation of carotenoid-protein complex from shrimp head waste and its use as a source of carotenoids, LWT- Food Science and Technology, vol. 41, pp. 227-235.

Badii F and Howell N K. 2006. Fish gelatin: Structure, gelling properties and interaction with egg albumen proteins, Food Hydrocolloids, vol. 20, pp. 630-640.

Bansbeck B. 2006. Independent review of the Fallen stock scheme and company. Department of Environment Food and Rural Affairs, UK. 120pp.

Bare J C, Hofstetter P, Pennington D W, and Udo de Haes Helias. 2000, Life Cycle Impact Assessment Workshop Summary Midpoints versus Endpoints: The Sacrifices and Benefits, International Journal of Life Cycle Assessment, vol. 6, pp. 319-326.

Beach E S, Eckelman M J, Cui Z, Brentner L, and Zimmerman J B. 2012, Preferential technological and life cycle environmental performance of chitosan flocculation for harvesting of the green algae Neochloris oleoabundans. Bioresource Technology, vol. 121, pp. 445-449.

Be-Fair. 2007, Report on the availability and conditions of the discards and by-products generated by the fleets under consideration. LIFE Project Deliverable D1.2. LIFE05 ENV/E000267. 80pp.

Belton B, Haque M, and Little D C. 2012. Does Size Matter? Reassessing the Relationship between Aquaculture and Poverty in Bangladesh, Journal of Development Studies, vol. 1, pp. 1-19.

Belton B, Murray F, Young J, Telfer T, and Little D C. 2010, Passing the Panda Standard: A TAD Off the Mark?, Ambio, vol. 10, pp. 2-13.

Benfey T. 2001. Use of sterile triploid Atlantic salmon (*Salmo salar L.*) for aquaculture in New Brunswick, Canada, ICES Journal of Marine Science, vol. 58, pp. 525-529.

Benhamou N, Lafontaine P J, and Nicole M 1994, Induction of Systemic Resistance to Fusarium Crown and Root Rot in Tomato Plants by Seed Treatment with Chitosan, Phytopathology, vol. 84, pp. 1432-1444.

Benjakul S, Binsan W, Visessanguan W, Osako K, and Tanaka M. 2009, Effects of flavourzyme on yield and some biological activities of mungoong, an extract paste from the cephalothorax of white shrimp, Journal of Food Science, vol. 74, 2, pp. 73-80.

Bimbo A P. 2007. Current and future sources of raw materials for the long-chain omega-3 fatty acid market", Lipid Technology, vol. 19, 8, pp. 176-179.

Binsan W, Benjakul S, Visessanguan W, Roytrakul S, Faithong N, Tanaka M, and Kishimura H. 2008. Composition, antioxidative and oxidative stability of mungoon, a shrimo extract paste from the cephalothorax of white shrimp, Journal of Food Lipids, vol. 15, pp. 97-118.

BMU. 2013, Renewable Energy Sources in Figures. Federal Ministry for the Environment, Mature Conservation and Nuclear Safety (BMU), Berlin, Germany. 111pp.

Boisen S, Hvelplund T, and Weisbjerg M. 2000. Ideal amino acid profiles as a basis for feed protein evaluation, Livestock Production Science, vol. 64, pp. 239-259.

Bondari K. and Sheppard D C. 1987. Soldier fly, Hermetia illucens L., larvae as feed for channel catfish, *Ictalurus punctatus* (Rafinesque), and blue tilapia, *Oreochromis aureus (Steindachner)*, Aquaculture and Fisheries Management, vol. 18, pp. 209-220.

Boonlertnirun S, Boonraung C, and Suvanasara R. 2008. Application of Chitosan in Rice Production, Journal of Metals, Materials and Minerals, vol. 18, no. 2, pp. 47-52.

Boran G, Lawless H T, and Regenstein J M. 2010. Effects of Extraction Conditions on the Sensory and Instrumental Characteristics of Fish Gelatin Gels, Journal of Food Science, vol. 75, 9, pp. 469-476.

Borch O-J. 1999. New organizational forms within the aquaculture industry: The fish farming enterprise as a 'virtual' organization, Aquaculture Economics and Management, vol. 3, 2, pp. 105-120.

Bosma R, Anh, P.T. and Potting J, 2011. Life cycle assessment of intensive striped catfish farming in the Mekong Delta for screening hotspots as input to environmental policy and research agenda. International Journal of Life Cycle Assessment, 16, 5, pp 903-915.

Bostock J, McAndrew B, Richards R, Jauncey K, Telfer T, Lorenzen K, Little D, Ross L, Handisyde N, Gatward I, and Corner R. 2010, Aquaculture: global status and trends, Philosophical Transactions of the Royal Society B, vol. 365. pp. 2897-2912.

Bourseau P, Vandanjon L, Jaouen P, Chaplain-Derouiniot M, Massé A, Guérard F, Chabeaud A, Fouchereau-P éron M., Le Gal Y, Ravallec-Plé R, Berg_J-P, Picot L, Piot J-M, Batista I, Thorkelsson G, Delannoy C, Jakobsen G, and Johansson I. 2009, Fractionation of fish protein hydrolysates by ultrafiltration and nanofiltration: impact on peptidic populations, Desalination, vol. 244, pp. 303-320.

Brandão M, Milà i Canals L, 2013. Global characterisation factors to assess land use impacts on biotic production. International Journal of Life Cycle Assessment, vol. 18, pp 1243–1252.

Brentrup F, Küsters J, Lammel J, Kuhlmann H, 2002. Life Cycle Impact Assessment of land use based on the Hemeroby Concept. International Journal of Life Cycle Assessment, vol. 7, 6, 339-348.

Briggs M, Funge-Smith S, Subasinghe R P, and Phillips M. 2005. Introductions and movement of two penaeid shrimp species in Asia and the Pacific, FAO fisheries technical paper 476.FAO, Rome. 63pp.

British Standards Institution. 2011. PAS2050: 2011 - Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI, London, UK. 38pp.

BSI. 2010, PAS 110: 2010 - Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials. British Standards Institution, London UK. 50pp.

BSI 2011. PAS2050: 2011 - Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI. London, UK. 37pp.

BSI, 2012. PAS2050-2: 2012 - Assessment of life cycle greenhouse gas emissions. Supplementary requirements for the application of PAS 2050:2011 to seafood and other aquatic food products. BSI. London, UK. 39pp.

Bush S, van Zwieten P A M, Visser L, Van Dijk H, Bosma R, De Boer W F, and Verdegem M. 2010. Scenarios for Resilient Shrimp Aquaculture in Tropical Coastal Areas, Ecology and Society, vol. 15, 2. (article 15, no page numbers).

Cancre I, Ravallec R, Van Wormhoudt A, Stenberg E, Gildberg A, and Le Gal Y. 1999. Secretagogues and Growth Factors in Fish and Crustacean Protein Hydrolysates, Marine Biotechnology, vol. 1, pp 489-494.

Cao W, Zhang C, Hong P, Ji H, Hao J, and Zhang J. 2009. Autolysis of shrimp head by gradual temperature and nutritional quality of the resulting hydrolysate, LWT - Food Science and Technology, vol. 42. pp 244-249.

Cao L, Diana J, Keoleian G A and Lai Q, 2011. Life Cycle Assessment of Chinese Shrimp Farming Systems Targeted for Export and Domestic Sales. Environmental Science and Technology, 45. pp 6531-6538.

Carswell B, Willow K, and Ekkart J. 1990. Ensiling Salmon Mortalities: Suggested Guidelines for B.C. Farmers, Report no. 90-3. Ministry of Agriculture and Fisheries, Aquaculture and Commercial Fisheries Branch, British Columbia, Canada. 50pp.

Chambers S, Lobb, A, Butler L T and Traill B W. 2008. The influence of age and gender on food choice: a focus group exploration. International Journal of Consumer Studies, 32, pp 356-365.

Cherubini F, Bargigli S, and Ulgiati S. 2009. Life cycle assessment (LCA) of Waste Manage strategies: Landfilling, sorting plant and incineration. Energy, 34, pp 2116-2123.

Chitmanat C. 2009, Risk Analysis of Diseases for Tilapia Cage Culture Raised in Upper Ping River, Report no. 13 / P 34. Faculty of Fisheries Technology and Aquatic Resources, Maejo University, Chiangmai. 9pp.

Chiu A, Luping L, Shujing G, Junfei B, Fedor C, and Naylor R. 2013. Feed and fishmeal use in the production of carp and tilapia in China, Aquaculture, vol. 414-415, pp. 127-134.

Choi S-S and Regenstein J M. 2000. Physicochemical and Sensory Characteristics of Fish Gelatin, Food Chemistry and Toxicology, vol. 65, no. 2, pp. 194-199.

Clarke S. 2009, Understanding China's Fish Trade and Traceability System. TRAFFIC East Asia Report, Hong Kong, China. 99pp.

Conley D. 1998, Environmental Concerns: The Anti-Salmon Farming Lobby in British Columbia. Aquaculture Magazine, July/August 1998, Volume 24, 4, pp 36-51.

Cordova-Murueta J H and Garcia-Carreno F L. 2002, Nutritive value of squid and hydrolysed protein supplement in shrimp feed, Aquaculture, vol. 210, pp 371-384.

COT. 2006. Statement on organic chlorinated and brominated contaminants in shellfish, farmed and wild fish. Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment. 20pp. http://cot.food.gov.uk/pdfs/cotstatementfishsurveys.pdf . Accessed 12/12/2009.

Coutteau P and Goossens T. 2013. Functional feeds as effective strategies against EMS. AQUA Culture Asia Pacific Magazine July/August 2013, pp 31-33.

Coward-Kelly G, Agbogbo F, and Holtzapple M. 2006, Lime treatment of shrimp head waste for the generation of highly digestible animal feed, Bioresource Technology, vol. 97, pp. 1515-1520.

Cruz-Suarez E, Ricque-Marie D, Martinez-Vega J, and Wesche-Ebeling P. 1993, Evaluation of two shrimp by-product meals as protein sources in diets for *Penaeus vannamei*, Aquaculture, vol. 15, pp. 53-62.

Czeczuga B, Czezuga-Semeniuk E, and Vala Tyggvadottir S. 2005, Carotenoid content in various body parts of Atlantic salmon (*Salmo salar L.*) and Arctic charr (*Salvelinus alpinus L.*) specimens from an ocean ranching farm, Oceanological and Hydrobiological Studies, vol. XXXIV, no. 1, pp. 31-42.

Damude H and Kinney A. 2007, Engineering Oilseed Plants for a Sustainable, Land-Based Source of Long Chain Polyunsaturated Fatty Acids, Lipids, vol. 42, pp. 179-185.

Davies R W D, Cripps S J, Nickson A and Porter G. 2009. Defining and estimating global marine fisheries bycatch, Marine Policy, 33, pp 661-672.

de Koning A, Schowanek D, Dewaele J, Weisbrod A. and Guinée J. 2010. Uncertainties in a carbon footprint model for detergents; quantifying the confidence in a comparative result. International Journal of Life Cycle Assessment, 15, pp 79-89.

De Silva S and Turchini G. 2008, Towards Understanding the Impacts of the Pet Food Industry on World Fish and Seafood Supplies, Journal of Agricultural and Environtal Ethics, vol. 21, pp. 459-467.

Dexter, 2005. Shrimp Derived Chitosan GRAS (Generally Recognised as Safe) Notification submitted to the US FDA on behalf of Primex ehf, Siglufjordur, Iceland. Provided by Lee B. Dexter and Associates, Technology Consultants, Austin, USA. 327pp.

Debio. 2009, Standards for Organic Aquaculture.Debio, Bjørkelangen, Norway. 41pp.

DEFRA. 2011. Information Sheet RAC 8 – R22 Phase-out. DEFRA, London, UK. 7pp.

Delgado C, Wada N, Rosegrant M, Meijer S, and Ahmed M. 2003, Fish to 2020: Supply and Demand in Changing Global Markets, World Fish Center Technical Report 62. International Food Policy Research Institute, Washington USA. World Fish Center Penang, Malaysia. 226 pp.

Department of Fisheries (Thailand). 2009, Fisheries Statistics Thailand 2007, No. 5/2009.Information Technology Center, Dept. Fisheries, Ministry of Agriculture and Cooperatives, Bangkok, Thailand. 91pp.

Dierberg, F. E., and Kiattisimkul, W., 1996. Issues, impacts and implications of shrimp aquaculture in Thailand. Environmental Management, 20, 5, pp 649-666.

Domingo J L. 2007. Omega-3 fatty acids and the benefits of fish Consumption: Is all that glitters gold?, Environmental International, vol. 33, pp. 993-998.

Dong S Y, Zheng M Y, Wang D F, Liu Z Y, Zhao Z H, and Yang H H 2008, Antioxidant and biochemical properties of protein hydrolysates prepared from Silver carp (*Hypophthalmichthys molitrix*), Food Chemistry, vol. 107, no. 4, pp. 1485-1493.

Eckhoff K, Aidos I, Hemre G-I, and Lie O. 1998, Collagen content in farmed Atlantic salmon (*Salmo salar, L.*) and subsequent changes in solubility during storage on ice, Food Chemistry, vol. 62, no. 2, pp. 197-200.

Edwards P. 2004, A survey of marine trash fish and fish meal as aquaculture feed ingredients in Vietnam, Working paper no. 57.Australian Centre for International Agricultural Research, Canberra, Australia. 56 pp.

Einen O and Roem A J. 1997. Dietary protein/energy ratios for Atlantic salmon in relation to fish size: growth, feed utilization and slaughter quality. Aquaculture Nutrition, vol. 3, pp. 115-126.

Ekvall T, and Finnveden G, 2001. Allocation in ISO 14041—a critical review. Journal of Cleaner Production, vol. 9, pp 197-208.

El Hag E.A. 1984. Food and food selection of the Penaeid prawn *Penaeus monodon (Fabricus).* Hydrobiologia, vol. 110, 1, pp 213-217.

Ellingsen H, and Aanondsen S A, 2006. Environmental impacts of wild caught cod and farmed salmon - A comparison with chicken. International Journal ofLife Cycle Assessment, vol. 1, 1, pp 60-65.

ENTEC, 1999. Reducing Water and Effluent Costs in Fish Processing. Environmental Technology Best Practice Programme, Guide GG187. ENTEC UK. 41pp.

Erkkila A, Matthan N R, Herrington D M, Lichtenstein A H, 2006. Higher plasma docosahexaenoic acid is associated with reduced progression of coronary atherosclerosis in women with CAD. Journal of Lipid Research, vol. 47, pp. 2814-2819.

European Commission. 1976. Council Directive of 27 July 1976 on the approximation of the laws of the Member States relating to cosmetic products (76/768/EEC). http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1976L0768:20080424:en:PDF. 129 pp.

European Commission. 2001. Regulation (EC) No 999/2001 of the European Parliament and of the Council of 22 May 2001 Laying Down Rules for the Prevention, Control and Eradication of Certain Transmissible Spongiform Encephalopathies. http://ec.europa.eu/food/fs/bse/bse36_en.pdf. 40pp.

European Commission. 2002a. Regulation (EC) No 1774/2002 of the European Parliament and of the Council, Laying Down Health Rules Concerning Animal By-Products Not Intended for Human Consumption. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002R1774andrid=3. 95pp.

European Commission. 2002b. Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January2002 Laying Down the General Principles and Requirements of Food Llaw, Establishing the European Food Safety Authority and Laying Down Procedures in Matters of Food Safety. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:031:0001:0024:EN:PDF. 24pp.

European Commission. 2003. Commission Regulation (EC) No 811/2003, Implementing Regulation (EC) No 1774/2002 of the European Parliament and of the Council as Regards the Intra-Species Recycling Ban for Fish, the Burial and Burning of Animal By-Products and Certain Transitional Measures. http://faolex.fao.org/docs/pdf/eur38605.pdf. 5pp.

European Commission. 2004. Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 Laying Down Specific Hygiene Rules for on the Hygiene of Foodstuffs. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:139:0055:0205:EN:PDF. 151pp.

European Commission. 2004. The Fish Meal and Fish Oil Industry Its Role in the Common Fisheries Policy. EU Working Paper, FISH 113 EN 02-2004. EU. Luxemburg. 148pp.

European Commission. 2005. Regulation (EC) No 183/2005 of the European Parliament and of the Council of 12 January 2005 Laying Down Requirements for Feed Hygiene. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2005:035:0001:0022:EN:PDF. 22pp.

European Commission. 2007. Council Regulation (EC) No 834/2007 of 28 June 2007 on Organic Production and Labelling of Organic Products and Repealing Regulation (EEC) No 2092/91. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:189:0001:0023:EN:PDF. 23pp.

European Commission. 2008. Council Regulation (EC) No 1005/2008 of 29 September 2008 establishing a Community system to prevent, deter and eliminate illegal, unreported and unregulated fishing, amending Regulations (EEC) No 2847/93, (EC) No 1936/2001 and (EC) No 601/2004 and repealing Regulations (EC) No 1093/94 and (EC) No 1447/1999. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:286:0001:0032:EN:PDF. 32pp.

European Commission. 2009a. Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 Laying Down Health Rules as Regards Animal By-Products and Derived Products Not Intended for Human Consumption and Repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R1069andfrom=EN. 33pp.

European Commission. 2009b. Commission Regulation (EC) No 710/2009 of 5 August 2009 Amending Regulation (EC) No 889/2008 Laying Down Detailed Rules for the Implementation of Council Regulation (EC) No 834/2007, as Regards Laying Down Detailed Rules on Organic Aquaculture Animal and Seaweed Production. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R0710andfrom=EN. 20pp.

European Commission. 2010. International Reference Life Cycle Data System (ILCD) Handbook, General Guide for Life Cycle Assessment - Detailed Guidance. First Edition. Joint Research Centre, Institute for Environment and Sustainability, European Union. Ispra, Italy. 394pp.

European Commission. 2011. Commission Regulation (EU) No 142/2011 of 25 February 2011 Implementing Regulation (EC) No 1069/2009 of the European Parliament and of the Council Laying Down Health Rules as Regards Animal By-Products and Derived Products Not Intended for Human Consumption and Implementing Council Directive 97/78/EC as Regards Certain Samples and Items Exempt from Veterinary Checks at the Border Under that Directive. http://faolex.fao.org/docs/pdf/eur109216.pdf. 252pp

European Commission. 2013. Commission Regulation (EU) No 56/2013 of 16 January 2013 amending Annexes I and IV to Regulation (EC) No 999/2001 of the European Parliament and of the Council laying down rules for the prevention, control and eradication of certain transmissible spongiform encephalopathies . http://www.eurl.craw.eu/img/page/Legislation/56-2013_EN.pdf. 14pp.

European Union. 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098andfrom=EN. 28pp.

Eysturskarð J, Haug I J, Ulset A-S, and Draget K I. 2009, "Mechanical properties of mammalian and fish gelatins based on their weight average molecular weight and molecular weight distribution", Food Hydrocolloids, vol. 23, pp. 2315-2321.

Fanimo A O, Susenbeth A, and Sudekum K-H, 2006. Protein utilisation, lysine bioavailability and nutrient digestibility of shrimp meal in growing pigs, Animal Feed Science and Technology, vol. 129, pp 196-209.

FAO. 1986, The Production of Fishmeal and Fish Oil, Fisheries Technical Paper 142.FAO, Rome, Italy. 63pp.

FAO. 1989, Yield and Nutritional Value of the Commercially More Important Fish Species. FAO Fisheries Technical Paper. No. 309. FAO, Rome. 187pp.

FAO. 1995, Code of Conduct for Responsible Fisheries. FAO, Rome, Italy. 41pp.

FAO. 1997, Aquaculture Feed and Fertilizer Resource Atlas of the Philippines, FAO Fisheries Technical Paper 366. FAO, Rome. 259pp.

FAO. 2002a, The State of the World Fisheries and Aquaculture 2002. Part 1, World Review of Fisheries and Aquaculture (SOFIA). FAO, Rome. 52pp.

FAO. 2002b, Use of Fishmeal and Fish Oil in Aquafeeds: Further Thoughts on the Fishmeal Trap, Fisheries Circular 975. FAO, Rome. 61pp.

FAO. 2004, Introductions and Movements of Penaeus vannamei and Penaeus sylirostris in Asia and the Pacific, RAP publication 2004/10. FAO, Rome. 32pp.

FAO. 2009, The State of World Fisheries and Aquaculture 2008. FAO, Rome. 176 pp.

FAO. 2010. The State of World Fisheries and Aquaculture 2010. FAO, Rome, Italy. 197pp.

FAO. 2012, The State of the World Fisheries and Aquaculture 2012.FAO, Rome. 209 pp.

Fishstat 2013. Fisheries and aquaculture software. FishStat Plus - Universal software for fishery statistical time series. In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 28 November 2013. http://www.fao.org/fishery/statistics/software/fishstat/en

Fearnside P M. 2001. Soybean cultivation as a threat to the environment in Brazil, Environmental Conservation, vol. 28, no. 1, pp. 23-38.

Fernandes A, Smith F, Petch R, Bradley E, Brereton N, Panton S, Carr M, and Rose M. 2009. Investigation into the Levels of Environmental Contaminants in Scottish Marine and Freshwater Fin Fish and Shellfish, FD 09 /01. Food Standards Agency Scotland. 193pp.

Ferreira N, Bonett C, and Seiffert W. 2011. Hydrological and water quality indices as management tools in marine shrimp culture, Aquaculture, vol. 318, pp425- 433.

Finnveden G, Hauschild M Z, Ekvall T, Guinée J, Heijungs R, Hallweg S, Koehler A, Peenington D and Suh S, 2009. Recent developments in Life Cycle Assessment. Journal of Environmental Management, 91, 1, pp1-21.

Fisheries Research Services. 2010. Nuisance species in aquaculture: jellyfish. http://www.marlab.ac.uk/Delivery/standalone.aspx?contentid=773 . Marlab, Crown. Accessed 10/11/2009. 2 pp.

Fishmeal Information Network. 2001, Fishmeal for pigs - a feed with a very healthy future. Grain and Feed Trade Association. London, UK. 6 pp.

Fishmeal Information Network. 2008, Annual Review of the feed grade fish stocks used to produce fishmeal and fish oil for the UK market, Dossier 2008. FIN, Grain and Feed Trade Association. London UK. 77pp.

Fitzpatrick J, Akbarashandiz H, Sakhrani D, Biagi C, Pitcher T, and Devlin R. 2011, Cultured growth hormone transgenic salmon are reproductively out-competed by wild-reared salmon in semi-natural mating arenas, Aquaculture, vol. 12, pp. 185-191.

Focken U, Groth A, Coloso R M, and Becker K. 1998. Contribution of natural food and supplemental feed to the gut content of *Penaeus monodon* Fabricius in a semi-intensive pond system in the Philippines, Aquaculture, vol. 164, pp. 105-116.

Fox C, Brown J, Blow P, and Watson I. 1994. The effect of various processing methods on the physical and biochemical properties of shrimp head meals and their utilization by juvenile *Penaeus monodon* Fab., Aquaculture, vol. 122, pp. 209-226.

Frazer N. L., 2008. Sea-cage aquaculture, sea lice, and declines of wild fish. Conservation Biology, vol. 23, 3, pp 599-607.

Frederick L., Harris R., Peterson L., and Kehrmeyer S. 1989. The Compost Solution to Dockside Fish Wastes. University of Wisconsin Sea Grant Advisory Services. 20pp.

Friends of the Earth. 2007. Briefing Anaerobic Digestion. Friends of the Earth. 7pp.

Fromentin J-M and Powers J E, 2005. Atlantic bluefin tuna: population dynamics, ecology, fisheries and management. Fish and Fisheries, vol. 6, pp 281-306.

Funge Smith. 1996. Water and Sediment Quality in Different Intensive Shrimp Culture Systems in Southern Thailand. Project Technical Report. University of Stirling, Scotland. 27 pp.

GAA. 2008, Tilapia Farms Guidelines for BAP Standards. Global Aquaculture Alliance, St. Louis, USA. 29pp.

GAA. 2010, Aquaculture Facility Certification - Feed Mills Best Aquaculture Practice Certification Standards, Guidelines. Global Aquaculture Alliance, St. Louis, USA. 13pp.

GAA. 2010, Aquaculture Facility Certification - Pangasius Farms Best Aquaculture Practices Certification Standards, Guidelines. Global Aquaculture Alliance, St. Louis, USA. 19pp.

GAA. 2011, Aquaculture Facility Certification - Salmon Farms Best Aquaculture Practices Certification Standards, Guidelines.Global Aquaculture Alliance, St. Louis, USA. 22pp.

GAIN. 2007, Norway Fishery Products Annual 2007, GAIN report number NO7006. Global Agriculture Information Network, USA. 10pp.

Garcia M L and Angenent L T, 2009. Interaction between temperature and ammonia in mesophilic digesters for animal waste treatment, Water Research, vol. 43, pp. 2373-2382.

Gelman A, DrabkinV, and Glatman A. 2001. Evaluation of lactic acid bacteria, isolated from lightly preserved fish products, as starter cultures for new fish-based food products, Innovative Food Science and Emerging Technologies, vol. 1, pp. 219-226.

General Statistics Office,Vietnam. 2014. Number of pigs as of annual 1st October by province. http://www.gso.gov.vn/default_en.aspx?tabid=469andidmid=3andItemID=14266 . Accessed 4/2/2014.

Gildberg A, Johansen A, and B›gwald J. 1995. Growth and survival of Atlantic salmon (*Salmo salar*) fry given diets supplemented with fish protein hydrolysate and lactic acid bacteria during a challenge trial with *Aeromonas Salmonicida*, Aquaculture, vol. 138, pp. 23-34.

Giménez B, Gomez-Guillen M C, and Montero P. 2005a. Storage of dried fish skins on quality characteristics of extracted gelatin , Food Hydrocolloids, vol. 19, pp. 958-963.

Giménez B, Turnay J, Lizarbe M A, Montero P, and Gomez-Guillen M C. 2005b. Use of lactic acid for extraction of fish skin gelatin, Food Hydrocolloids, vol. 19, pp. 941-950.

Glanville T D, Richard T L, Harmon J D, Reynolds D L, Ahn H K, and Akinc S. 2006. Environmental Impacts and Biosecurity of Composting for Emergency Disposal of Livestock Mortalities (Final Report).Iowa Department of Natural Resources. 71 pp.

Glanville T D, Ahn H K, Richard T L, Shiers L E, and Harmon J D. 2009. Soil contamination caused by emergency bio-reduction of catastrophic livestock mortalities, Water Air Soil Pollution, vol. 198, pp. 285-295.

Glatman A, Drabkin V, and Gelman A. 2000. Using lactic acid bacteria for developing novel fish food products, Journal of the Science of Food and Agriculture, vol. 80, pp. 375-380.

GlobalGAP. 2011. Control Points and Compliance Criteria: Compound Feed Manufacture, Code Ref: CFM 2.1 CPCC. GlobalGAP, Cologne, Germany. 35pp.

GlobalGAP. 2012, GlobalGAP Aquaculture.GlobalGAP, Cologne, Germany. http://www.globalgap.org/export/sites/default/.content/.galleries/documents/120924-InfoKIT_Aqua_web_en.pdf. 20pp.

GlobalGAP. 2012, GlobalGAP Integrated Farm Assurance, Aquaculture Module: Control Points and Compliance Criteria.GlobalGAP, Cologne, Germany. 49pp.

Goddard S, Al-Shagaa G, and Ali A. 2008. Fisheries by-catch and processing waste meals as ingredients in diets for Nile tilapia, *Oreochromis niloticus*, Aquaculture Research, vol. 39, pp. 518-525.

Gomez X, Cuetos M J, Tartakovsky B, Martinez-Nunez M F, and Moran A. 2010. A comparison of analytical techniques for evaluating food waste degradation by anaerobic digestion, Bioprocess Biosystems Engineering, vol. 33, pp. 427-438.

Gong Y, Krabbenhoft D, Ren L, Egelandsdal B, Richards M, 2011. Mercury distribution and lipid oxidation in fish muscle: effects of washing and isoelectric protein precipitation. Journal of Agricultural and Food Chemistry, vol. 59, pp 11050–11057.

Goycoolea F, Argoelles-Monal W, and Higuera-Ciapara I. 2000. Chitin and Chitosan, in Novel Macromolecules in Food Systems (Doxastakis G, Kiosseoglou V eds.), Ch. 11, pp 265-308. Elsevier BV, Amsterdam.

Grönroos J, Seppaia J, Silvenius F and Makinen T, 2006. Life cycle assessment of Finnish cultivated rainbow trout. Boreal Environmental Research, vol 11, pp 401-414.

Guerin M., Huntley M.E., and Olaizola M. 2003. *Haematococcus* astaxanthin: applications for human health and nutrition, Trends in Biotechnology, vol. 21, no. 5, pp. 210-216.

Guinée J B, Goree M, Heijungs R, Huppes G, Kleijn R, de Koning A, von Oers L, Sleeswijk A, Suh S, Udo de Haes H A , de Bruijn H, van Duin R, Huijbegts M A J , Lindeijer E, Roorda A A H, van der Ven B L , and Weidema B P. 2002. Handbook on Life Cycle Assessment: Operational Guide to ISO Standards. Kluwer Academic Publishers, Dordrecht.

Guinée, J., Heijungs, R. and Huppes, G., 2004. Economic allocation: Examples and derived Decision Tree. International Journal of Life Cycle Assessment, vol. 9, 1, pp 23-33.

Hanson A, Cui H, Zou L, Clarke S, Muldoon G, Potts J, and Zhang H. 2011, Greening China's Fish and Fish Products Market Supply Chains. International Institute for Sustainable Development, Winnipeg, Canada. 140pp.

Hardy R W, Sealey W M, and Gatlin D M. 2005. Fisheries by-catch and by-product meals as protein sources for rainbow trout (*Oncorhynchus mykiss*), Journal of the World Aquaculture Society, vol. 36, no. 3, pp. 393-400.

Hawkins L, Armstrong J, and Magurran A. 2005. Aggregation in juvenile pike (*Esox lucius*): interactions between habitat and density in early winter, Functional Ecology, vol. 19, pp. 794-799.

He H-L, Chen X-L, Wu H., Sun C-Y, Zhang Y-Z, and Zhou B-C. 2007. High throughput and rapid screening of marine protein hydrolysates enriched in peptides with angiotensin-I-converting enzyme inhibitory activity by capillary electrophoresis, Bioresource Technology, vol. 98, pp. 3499-3505.

He P. 2010. Anaerobic digestion: an intriguing long history in China, Waste Management, vol. 30, pp. 549-550.

Heijungs R. and Frischknecht R. 2005. Representing statistical distributions for uncertainty parameters in LCA, International Journal of Life Cycle Assessment, vol. 10, no. 4, pp. 248-254.ecomed publishers

Heijungs R. and Guinée J. 2007. Allocation and "what if" scenarios in life cycle assessment of waste management systems, Waste Management, vol. 27, pp. 997-1005.

Henriksson P, Zhang W, Nahid S, Newton R, Phan L, Hai D, Zhang Z, Andong R, Jaithang J, Chiamanuskul K, Son V, Hien H, Haque M, Kruijssen F, Satapornvanit K, Nguyen P, Phan L T, Liu Q, Liu L, Wahab M, Murray F, Little D C, and Guinée J. 2014a. Final LCA Case Study Report Primary Data and Literature Sources Adopted in the SEAT LCA Studies, SEAT Deliverable Ref: D 3.5. EU FP7 Funded Project 222889. Available at: http://media.leidenuniv.nl/legacy/d35-annexreport.pdf. 121pp.

Henriksson P, Guinée J, Klein R. and de Snoo G, 2012. Life cycle assessment of aquaculture systems - a review of methodologies. International Journal of Life Cycle Assessment, vol. 17, pp 304-313.

Henriksson P, Guinée J, Heijungs R, de Koning A, Green D, 2014b. A protocol for horizontal averaging of unit process data—including estimates for uncertainty. International Journal of Life Cycle Assessment, vol. 19, pp 429–436.

Hensler L and Bremer S, 2013. An Organic Future for Bangladeshi Shrimp? World Aquaculture Magazine, March 2013, pp 28-35.

Hernández C, Olvera-Novoa M A, Smith D M, Hardy R, Gonzalez-Rodriguez B, 2011. Enhancement of shrimp *Litopenaeus vannamei* diets based on terrestrial protein sources via the inclusion of tuna by-product protein hydrolysates. Aquaculture, vol. 317, pp 117-123.

Hevrøy E M, Espe M, Waagbø R, Sandnes K, Ruud M, and Hemre G-I. 2005. Nutrient utilization in Atlantic salmon (*Salmo salar* L.) fed increased levels of fish protein hydrolysate during a period of fast growth, Aquaculture Nutrition, vol. 11, pp. 301-313.

Hickman D, Sims T J, Miles C A, Bailey A J, de Mari M, and Koopmans M. 2000, Isinglass/collagen: denaturation and functionality, Journal of Biotechnology, vol. 79, pp. 245-257.

Higgs D A, Balfry S K, Oakes J D, Rowshandeli M, Skura B J, and Deacon G. 2006. Efficacy of an equal blend of canola oil and poultry fat as an alternate dietary lipid source for Atlantic salmon (*Salmo salar* L.) in sea water. I: effects on growth performance, and whole body and fillet proximate and lipid composition, Aquaculture Research, vol. 37, pp. 180-191.

Hilbert G, Lillemark L, Balchen S, and Schriver Hojskov C. 1998. Reduction of Organochlorine Contaminants from Fish Oil During Refining, Chemosphere, vol. 37, no. 7, pp. 1241-1252.

Hischier R., Weidema B., Althaus H-J., Bauer C., Doka G., Dones R., Frishknecht R., Hellweg S., Humbert S., Jungbluth N., Kollner T., Loerincik Y., Margni M, and Nemecek T. 2010. Implementation of Life Cycle Impact Assessment Methods. Ecoinvent report No. 3. Swiss Centre for Life Cycle Inventories. St. Gallen, Switzerland.

Hites R A, Foran J A, Carpenter D O, Hamilton M C, Knuth B A, and Schwager S J. 2004, Global Assessment of Organic Contaminants in Farmed Salmon, Science, vol. 303, pp. 226-229.

Hjaltason B, and Hf L. 1990. New Products, Processing Possibilities and Markets for Fish Oil. Proceedings of the International By-products Conference, pp131-142. April 25-27 1990. Alaska Sea Grant College Program, Report no. 90-07. Anchorage, USA.

Holub D J and Holub B J. 2004. Omega-3 fatty acids from fish oils and cardiovascular disease, Molcular and Cellular Biochemistry, vol. 263, pp. 217-225.

Hong S and Secombes C J. 2009. Two peptides derived from trout, IL-1ƒ have different stimulatory effects on immune gene expression after interperitoneal administration, Comparative Biochemistry and Physiology, Part B, vol. 153, pp. 275-280.

Hospido A, and Tyedmers P, 2005. Life cycle environmental impacts of Spanish tuna fisheries. Fisheries Science, 76, pp 174-186.

Hospido A, Vasquez M E, Cuevas A F and Moreira M T, 2006. Environmental assessment of canned tuna manufacture with a life-cycle perspective. Resource Conservation and Recycling, vol. 47, 56-72.

Hulan H, Proudfoot F, and Zarkados C. 1979. The nutritional value and quality of squid (*Illex illecebrosus*) meal as source of dietary protein for broiler chicken, Journal Broiler Research, vol. 41, pp. 163-173.

Hung LT, Suhenda N, SlembrouckJ, Lazard J, and Moreau Y. 2004. Comparison of dietary protein and energy utilization in three Asian catfishes (*Pangasius bocourti, P. hypophthalmus and P. djambal*), Aquaculture Nutrition, vol. 10, pp. 317-326.

IEA, 2011. IEA Annual Report 2010.International Energy Authority, Paris. 141pp.

IFFO. 2011, Global Standard for Responsible Supply: Requirements for Certification. IFFO, St. Albans, UK. 25pp.

IFOAM. 2012, The IFOAM norms for organic production and processing. International Federation of Organic Agriculture Movements, Germany. 132pp.

Imsland A K, Handeland S O, Sefansson, S O, 2014. Photoperiod and temperature effects on growth and maturation of pre- and post-smolt Atlantic salmon. Aquaculture International, vol.22, pp 1331–1345.

Indexmundi. 2014. http://www.indexmundi.com/commodities/?commodity=food-price-index . Accessed 21/2/14.

Inter Trade Ireland. 2009, Market Report on the Composting and Anaerobic Digestion Sectors. Inter Trade Ireland, Newry, Co. Down, Ireland. 27pp.

International Monetary Fund. 2011. IMF Primary Commodity Prices. http://www.imf.org/external/np/res/commod/index.asp . Accessed 15/3/2011.

IPCC. 2006. Wastewater Treatment and Discharge, IPCC Guidelines for National Greenhouse Gas Inventories: Waste, Ch. 6. International Panel on Climate Change, Geneva, Switzerland. 28pp.

Iribarren D, Moreira M T, and Feijoo G. 2012, Life Cycle Assessment of Aquaculture Feed and Application to the Turbot Sector, International Journal of Environmental Research, vol. 6, no. 4, pp. 837-848.

Irish Sea Fisheries Board. 2002, Information Note on the Composting of Organic Waste from Seafood Processing, Info note series no 2.Bord Iascaigh Mhara, Dublin, Ireland. 25pp.

ISO, 2006a. Environmental Management - life cycle assessment - principles and framework (ISO 14040:2006). ISO. Geneva, Switzerland. 20pp.

ISO, 2006b.Environmental Management - life cycle assessment - requirements and guidelines (ISO 14044:2006). ISO. Geneva, Switzerland. 45pp.

Jackson A. 2009, Fish in fish out ratios explained, Aquaculture Europe, vol. 34, no. 3, pp. 5-34

Jackson, A. and Shepherd J., 2010. Connections between farmed and wild fish: Fishmeal and fish oil as feed ingredients in sustainable aquaculture, in: Advancing the Aquaculture Agenda (Paris 15-16 April 2010): Workshop Proceedings, pp331 – 343. OECD Publishing.

Jafarpour A and Jorczyca E. 2008. Alternative Techniques for Producing a Quality Surimi and Kamaboko from Common Carp (*Cyprinus carpio*), Journal of Food Science, vol. 73, no. 9, pp. 415-424.

Je J, Park P, Kwon J, and Kim S. 2004. A novel angiotensin I converting enzyme inhibitory peptide from Alaska pollack (*Theragra chalcogramma*) frame protein hydrolysate, Journal of Agricultural and Food Chemistry, vol. 52, pp. 7842-7845.

Jeon Y, Kamil J, and Shahidi F. 2002. Chitosan as an edible invisible film for quality preservation of herring and Atlantic cod, Journal of Agricultural and Food Chemistry, vol. 50, pp. 5167-5178.

Kabahenda M and Hüsken S. 2009. A review of low-value fish products marketed in the Lake Victoria region: Regional Programme Fisheries and HIV/AIDS in Africa: Investing in Sustainable Solutions. Project report 1974.World Fish Center, Zambia. 24pp.

Karim A A and Bhat R. 2009. Fish gelatin: properties, challenges, and prospects as an alternative to mammalian gelatins, Food Hydrocolloids, vol. 23, pp. 563-576.

Kim J-S, Park J W, 2007. Mince from seafood processing by-product and surimi as food ingredients, in Maximising the value of marine by-products (Shahidi F, ed.),Ch. 9, pp 196-228. Woodhead Publishing, Cambridge, UK.

Kim S and Mendis E. 2006. Bioactive compounds from marine processing byproducts - A review, Food Research International, vol. 39, pp. 383-393.

Kim M-H and Kim W-K, 2010. Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Science of the Total Environment, vol. 408, pp 3998-4008.

Klemetsena A, Amundsena P, Grotnesa P, Knudsen R, Kristoffersena R, and Svenning M. 2002. Takvatn through 20 years: long-term effects of an experimental mass removal of Arctic charr, *Salvelinus alpinus*, from a subarctic lake, Environmental Biology of Fishes, vol. 64, pp. 39-47.

Kouba M and Mourot J. 2010. A review of nutritional effects on fat composition of animal products with special emphasis on n-3 polyunsaturated fatty acids, Biochimie pp. 1-5.

Krause V. 2010, Research on Contaminants in Farmed Salmon: Science or Marketing? Special Committee on Sustainable Aquaculture of the Legislative Assembly of B.C., British Columbia, Canada. 21pp.

Kristinsson H G and Rasco B. 2000. Biochemical and Functional Properties of Atlantic Salmon (*Salmo salar*) Muscle Proteins Hydrolyzed with Various Alkaline Proteases, Journal of Agricultural and Food Chemistry, vol. 48, pp. 657-666.

Lallemont A. 2008, A study on chitosan manufacturing plants: case studies in Thailand and Ecuador, AIT report SM 07 08. Asian Institute of Technology, Bangkok, Thailand. 51pp.

Lam P T, Tam M B, Thuy T T N, Gooley G J, Ingram B A, Nguyen H V, Nguyen P T, and De Silva S S. 2009. Current status of farming practices of striped catfish, *Pangasianodon hypophthalmus* in the Mekong Delta, Vietnam. Aquaculture, vol. 296, 227-236.

Laos F, Mazzarino M J , Walter I, Roselli L, Satti P, and Moyano S. 2002. Composting of fish offal and biosolids in northwest Patagonia, Bioresource Technology, vol. 81, pp. 179-186.

Le Nguyen D K, 2007. Description of the Pangasius value chain in Vietnam. CAS Discussion paper No 56. Centre for ASEAN Studies, Singapore. 49pp.

Leceta I, Guerrero P, Cabezudo S, and de la Caba K. 2013. Environmental assessment of chitosan-based films, Journal of Cleaner Production, vol. 41, pp. 312-318.

Lee C H, Singla A, and Lee Y. 2001. Biomedical applications of collagen, International Journal of Pharmaceutics, vol. 221, pp. 1-22.

Lertsutthiwong P, How N, Chandrkrachang S, and Stevens W. 2002. Effect of Chemical Treatment on the Characteristics of Shrimp Chitosan, Journal of Metals, Materials and Minerals, vol. 12, no. 1, pp. 11-18.

Li G Y, Fukunaga S, Takenouchi K, and Nakamura F. 2005. Comparative study of the physiological properties of collagen, gelatin and collagen hydrolysate as cosmetic materials, International Journal of Cosmetic Science, vol. 27, pp. 101-106.

Lian P Z, Lee C M, and Park E. 2005. Characterization of squid-processing byproduct hydrolysate and its potential as aquaculture feed iIngredient, Journal of Agricultural and Food Chemistry, vol. 53, pp. 5587-5592.

Liao P H, Jones L, Lau A K, Walkemeyer S, Egan B, and Holbek N. 1997, Composting of fish wastes in a full-scale in-vessel system, Bioresource Technology, vol. 59, pp. 163-168.

Little D C, Bush S R, Belton B, Nguyen P T, and Young J A. 2012. Whitefish Wars: Pangasius politics and consumer confusion in Europe, Marine Policy no. 36, pp. 738-745.

Liu S-L, Liu Y, Yang H-S, You K, Chen M-Y, and Yu L-D. 2006. Effects of *Perineris aibuhitensis* and *Eisenia foetida* on growth and immune parameters of the shrimp *Litopenaeus vannamei*, Journal of Fisheries Sciences of China, vol. 13, no. 4, pp. 561-562.

Liu M *et al*, 2012. Life Cycle Assessment of Environmental Impacts from Finishing Pig Production in Liaoning Province, China(In Chinese). Journal of Agro-Environment Science, vol. 3, 6, pp.1250-1255.

Local Government Association. 2008, LGA Landfill tax report: June 2008.

Local United. 2011, Energy farms - anaerobic digestion: How to develop a community led agricultural anaerobic digester. NESTA, London UK. 16pp.

Lorenz R T and Cysewski G R. 2000. Commercial potential for *Haematococcus* microalgae as a natural source of astaxanthin, Trends in Biotechnology, vol. 18, pp. 160-167.

Lotz J. 1997. Special topic review: Viruses, biosecurity and specific pathogen-free stocks in shrimp aquaculture, World Journal of Microbiology and Biotechnology pp. 405-413.

Lückstädt C. 2008. Effects of dietary acidifiers in aquaculture - a review. Feed Technology Update, Feedlink Magazine, October 2008.

Lundie S and Peters G. 2005. Life cycle assessment of food waste manage options. Journal of Cleaner Production, vol. 13, pp 275-286.

MacLeod M, Gerber P, Mottet A, Tempio G, Falcucci A, Opio C, Vellinga T, Henderson B, and Steinfeld H. 2013, Greenhouse gas emissions from pig and chicken supply chains - A global life cycle assessment. FAO, Rome, Italy. 171pp.

Maitland J R G. 1887, The History of Howietoun. Edinburgh University Press, UK.

Marchbank T, Elia G, and Playford R J. 2009. Intestinal protective effect of a commercial fish protein hydrolysate preparation, Regulatory Peptides, vol. 155, pp. 105-109.

Marine Harvest, 2014. Salmon Farming Industry Handbook 2014. Marine Harvest, Fort William, UK. 83pp.

Marine Scotland Science. 2013, Scottish Fish Farm Production Survey, 2012 Report. Scottish Government, Edinburgh, UK. 54pp.

Mathiesen B V, Munster M and Fruergaard T., 2009. Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. Journal of Cleaner Production, vol. 17, pp 1331-1338.

Matsuno Y, Daigo I, and Adachi Y, 2007. Application of Markov Chain Model to calculate the average number of times of use of a material in society, an allocation methodology for open-loop recycling, Part 2: case study for steel. International Journal of Life Cycle Assessment, vol. 12, 1, pp 34-39.

Maynard L, Saghaian S, and Nickoloff M. 2008. Buyer and seller responses to an adverse food safety event: the case of frozen salmon in Alberta", International Food and Agribusiness Management Review, vol. 11, no. 1, pp. 77-96.

Mendez-Acosta H O, Palacios-Ruiz B, Alcaraz-Gonzalez V, Gonzalez-Alvaraz V, and Garcia-Sandoval J P. 2010. A robust control scheme to improve the stability of anaerobic digestion processes, Journal of Process Control, vol. 20, pp. 375-383.

Miller D, Jessel A, and Mariani S. 2012. Seafood mislabelling: comparisons of two western European case studies assist in defining influencing factors, mechanisms and motives, Fish and Fisheries, vol. 13, pp. 345-358.

Mizani A and Aminlari B. A New Process for Deproteinization of Chitin from Shrimp Head Waste, Proceedings of European Congress of Chemical Engineering (ECCE-6), Copenhagen, 16-20 September 2007.

Muggli R. 2006. Fortified Foods: A Way to Correct Low Intakes of EPA and DHA, in Handbook of Functional Lipids (Akoh C C, ed.), pp389-401. Taylor and Francis.

Mungkung R T, Udo de Haes H A and Clift R, 2006. Potentials and limitations of Life Cycle Assessment in setting ecolabelling criteria: a case study of Thai shrimp aquaculture production. International Journal of Life Cycle Assessment, vol. 11, 1, pp 55-59.

Murray A G, Smith R J, and Stagg R M, 2002. Shipping and the spread of Infectious Salmon Anaemia in Scottish aquaculture, Emerging Infectious Diseases, vol. 8, no. 1, pp. 1-5.

Murray F, Nietes-Satapornavit A, Lam P T, Mahfujul Haque M, Henrikkson P, and Little D C. 2011. Draft Report on Boundary Issues, SEAT Deliverable Ref: D2.8.EU FP7 Funded Project 222889.

Muyonga J H, Cole C G B, and Duodu K G. 2004. Characterisation of acid soluble collagen from skins of young and adult Nile perch (*Lates niloticus*), Food Chemistry , vol. 85, pp. 81-89.

Nagai T and Suzuki N. 2000. Isolation of collagen from fish waste material - skin, bone and fins, Food Chemistry, vol. 68, pp. 277-281.

National Organic Programme. 2008. Proposed Organic Aquaculture Standards: Fish Feed and Related Management Issues. National Organic Standards Board (NOSB), USA. Available at: http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5072721

Naylor R, Hardy R, Bureau D, Chiu A, Elliot M, Farrell A, Forster I, Gatlin D, Goldburg R, Hua K and Nichols P. 2009. Feeding aquaculture in an era of finite resources. Proceedings of the National Academy of Sciences, vol. 106, 36, pp 15103-15110.

Newton L G, Booram C V, Barker R W, and Hale O M. 1977. Dried *Hermetia illucens* larvae meal as a supplement for swine, Journal of Animal Science, vol. 44, pp. 395-400.

Nguyen D A T, Nguyen A P, Nguyen N L, Ta T K V, Tran T T, Phan D H, Vi V H, and Ha V C. 2009. Status and Potential for the Development of Biofuels and Rural Renewable Energy Viet Nam. Asian Development Bank, Greater Mekong Subregion Economic Cooperation Program, Philippines. 60pp.

Nguyen H, Tu B M, Kajiwaran N, Kunisue T, Iwata H, Pham H, Nguyen P, Bui C T, and Tanabe S. 2006. Contamination by polybrominated diphenyl ethers and persistent organochlorines in catfish and feed from Mekong River Delta, Vietnam. Environmental toxicology and chemistry, vol. 25, 10, pp2700-2708.

Nguyen H T M, Pérez-Gálvez R, Bergé J P, 2012. Effect of diets containing tuna head hydrolysates on the survival and growth of shrimp *Penaeus vannamei*. Aquaculture vol. 324-325, pp 127-134.

Nguyen T T 2010, Evaluation of Catfish (*Pangasius hypophthalmus*) By-Products as Protein Sources for Pigs in the Mekong Delta of Viet Nam, PhD thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Nguyen T.V.A., Prem Ananth A., Visvanathan C., and Anbumozhi V. 2009. Techno policy aspects and socio-economic impacts of eco-industrial networking in the fishery sector: experiences from An Giang province, Vietnam, Journal of Cleaner Production, vol. 17, pp. 1272-1280.

Nguyen, B. 2008. December catfish processing down 6 per cent. Available online at: http://pangasius-vietnam.com/Plus.aspx/en/News/114/0/9/0/562/December_catfish_processing_down_6_per_cent. Accessed 23/5/2011.

Nomura M, Sloman K A, von Keyserlingk M A G, Farell A P, 2009. Physiology and behaviour of Atlantic salmon (*Salmo salar*) smolts during commercial land and sea transport. Physiology nd Behaviour, vol. 96, pp 233-243.

Norwegian Directorate of Fisheries. 2013, Nøkkeltall fra norsk havbruksnæring. Norwegian Directorate of Fisheries, Bergen. 28pp.

Norwegian Seafood Export Council. 2009. Record high export of Salmon and Trout. http://www.seafoodfromnorway.com/Fishlovers/Seafood+facts/View+article?key=44473 . Norwegian Seafood Export Council. Accessed 10/12/2009.

Nwanna L C. 2003. Nutritional value and digestibility of fermented shrimp head waste meal by African catfish *Clarias gariepinus*, Pakistan Journal of Nutrition, vol. 6, pp339-345.

Nyland C A, Modahl I S, Raadal H L and Hanssen O J, 2003. Application of LCA as a Decision-Making Tool for Waste Manage Systems. International Journal of Life Cycle Assessment, vol. 8, 8, pp 331-336.

OIE, 2013. Control of Hazards in Aquatic Animal Feed, Section 6.1, Animal Health Code. World Organisation for Animal Health, Paris France. 8pp.

Orcutt M W, Forrest J C, Judge M D, Schinckel A P and Kuei C H, 1990. Practical means for estimating pork carcass composition. Journal of Animal Science, vol. 68, pp 3987-3997.

Ouraji H, Shabanpour B, Kenari A A, Shabani A, Nezami S, Sudagar M, and Faghani S. 2009. Total lipid, fatty acid composition and lipid oxidation of Indian white shrimp (*Fenneropenaeus indicus*) fed diets containing different lipid sources, Journal of the Science of Food and Agriculture, vol. 89, pp 993-997.

Pacheco N, Garnica-Gonzalez M, Ramirez-Hernandez J Y, Flores-Albino B, Gimeno M, Barzana E, and Shirai K. 2009. Effect of temperature on chitin and astaxanthin recoveries from shrimp waste using lactic acid bacteria, Bioresource Technology, vol. 100, pp 2849-2854.

Papatryphon E, Petit J, Kaushik S J and Van der Werf H M G, 2004. Environmental Impact Assessment of Salmonid Feeds Using Life Cycle Assessment (LCA). Ambio, vol. 33, 6, pp 316-323.

Parker R W R and Tyedmers P H, 2012. Life cycle environmental impacts of three products derived from wild-caught Antarctic krill (*Euphausia superba*), Environmental Science and Technology, vol. 46, pp 4958-4965.

Parker R, 2012. Review of Life Cycle Assessment Research on Products Derived from Fisheries and Aquaculture: A Report for Seafish as Part of the Collective Action to Address Greenhouse Gas Emissions in Seafood. Seafish Industry Authority. Edinburgh, UK. 22pp.

Peigne J and Girardin P. 2004. Environmental Impacts of Farm-Scale Composting Practices, Water Air and Soil Pollution, vol. 153, pp 45-68.

Pelletier N L, and Tyedmers P H, 2010. Life Cycle Assessment of Frozen Tilapia Fillets From Indonesian Lake-Based and Pond-Based Intensive Aquaculture Systems. Journal of Industrial Ecology, vol. 14, pp 467-481.

Pelletier N L, and Tyedmers PH, 2007. Feeding farmed salmon: is organic better? Aquaculture. Vol. 272, 399-416.

Pelletier N L, and Tyedmers P H, 2011. An ecological economic critique of the use of market information in Life Cycle Assessment research. Journal of Industrial Ecology, vol. 15, 3, pp 342-354.

Pelletier N L, Tydmers P H, Sonesson U, Scholz A J, Ziegler F, Flysjo A, Kruse S A, Cancino B and Silverman H. 2009. Not all salmon are created equal: Life Cycle Assessment (LCA) of global salmon farming systems. Environmental Science Technology, vol. 43, pp 8730-8736.

Percot A, Viton C, and Domard A. 2003. Optimization of Chitin Extraction from Shrimp Shells, Biomacromolecules, vol. 4, pp 12-18.

Pérez R. 1995, Fish Silage for Feeding livestock, World Animal Review, vol. 82, 1.

Perez-Galvez A, 2009. Le Compactage: Une solution pour un meilleu management des bioresources marine. Applicationaux rejet et co-produits de poisson, PhD. Thesis, Universite de Nantes. 287pp.

Phong L T, de Boer I J M, and Udo H M J, 2011. Life cycle assessment of food production in integrated agriculture–aquaculture systems of the Mekong Delta. Livestock Science, vol. 139, 1-2, pp 80-90.

Phong L T, Tri L Q, Udo H M J, Nhan D K, van Mensvoort M E F, van der Zijpp A J and Bosma R H, 2007. Integrated agriculture-aquaculture systems in the Mekong Delta, Vietnam: an analysis of recent trends. Asian Journal of Agriculture and Development, vol. 4, 2, pp 51-66.

Piccolo T. 2007. Aquatic Biofuels. Globefish, Fish Utilization and Marketing Service. 14pp.

Pichyangkura R, 2010. Application of Chitin-Chitinosan from Marine by Products in Thailand, in The FFTC-KU Joint Seminar on "Improved Utilization of Fishery By-product as Potential Nutraceuticals and Functional Foods, 21st October 2010, Kasetsart University, Bangkok, Thailand.

Polak-Juszczak L. 2007, Chemical Characteristics of Fishes New to the Polish Market, Acta scientiarum Polonorum, Piscaria, vol. 6, no. 2, pp. 23-32.

Prescott C, Brown S, Zabek L, Staley C, and Tolland L. 1997. Organic Fertilization Trials in Conifer Plantations in Coastal British Columbia, in Forest Alternative: Principles and Practice of Residuals Use (Cole L. ed.), Ch 16, pp 94-104.

Prescott J, Young O, O' Neill L, Yau N J N and Stevens R, 2002. Motives for food choice: a comparison of consumers from Japan, Taiwan, Malaysia and New Zealand. Food Quality and Preference, vol. 13, pp 489-495.

Preto F, Zhang F, and Wang J. 2007. A study on using fish oil as an alternative fuel for conventional combustors", Fuel, vol. 87, pp. 2258-2268.

Rabea E, Badawy M, Stevens C, Smagghe G, and Steurbaut W. 2003, "Chitosan as antimicrobial agent: applications and mode of action", Biomacromolecules, vol. 4, 6, pp1457-1465.

Racotta I S, Palacios E, and Ibarra A M, 2003. Shrimp larval quality in relation to broodstock condition, Aquaculture, vol. 227, pp. 107-130.

Raghavan S and Kristinsson H G. 2009. ACE-inhibitory activity of tilapia protein hydrolysates, Food Chemistry, vol. 117, pp. 582-588.

Ramírez. 2007. Salmon By-Product Proteins, Fisheries Circular No. 1027. FAO, Rome. 30pp.

Reap J, Roman F, Duncan S, and Bras B. 2008. A survey of unresolved problems in life cycle assessment, International Journal of Life Cycle Assessment, vol. 13, pp 290-300.

Regenstein J M and Zhou P. 2007. Collagen and gelatin from marine by-products, in Maximising the value of marine by-products (Shahidi F, ed.),Ch. 13, pp 279-303. Woodhead Publishing, Cambridge, UK.

Roque, d'Orbcastel E, Blancheton J-P and Aubin J, 2009. Towards environmentally sustainable aquaculture: comparison between two trout farming systems using Life Cycle Assessment. Aquaculture Engineering, vol. 40, pp 113-119.

Roy P, Neil D, Orikasa T, Xu Q, Okadome H, Nakamura N and Shiina T, 2009. A review of life cycle assessment (LCA) on some food products. Journal of Food Engineering, vol. 90, pp 1-10.

RUBIN. 2009, Laksebein i fôr til torsk: Biologisk evaluering av laksebeinmel som alternativ proteinkilde i torskefôr, Rapport nr. 178. RUBIN, Trondheim, Norway.

Ruttanapornvareeskul Y, Ikeda M, Hara K, Osako K, Kongpun O, and Nozaki Y 2005. Effect of shrimp head protein hydrolysates on the state of water and denaturation of fish myofibrils during dehydration, Fisheries Science, vol. 71, pp. 220-228.

Sachindra N M, Bhaskar N, and Mahendrakar N S. 2006. Recovery of carotenoids from shrimp waste in organic solvents, Waste Management, vol. 26, pp. 1092-1098.

Sachindra N M, Bhaskar N, and Mahendrakar N S 2005. Carotenoids in different body components of Indian shrimps, Journal of the Science of Food and Agriculture, vol. 85, pp. 167-172.

Sachs I. 2007. The Biofuels Controversy, United Nations Conference on Trade and Development, Report no. UNCTAD/DITC/TED/2007/12, UNCTAD, Geneva, Switzerland. 28pp.

Sadowska M and Kolodziejska I. 2005. Optimisation of conditions for precipitation of collagen from solution using j-carrageenan. Studies on collagen from the skin of Baltic cod (*Gadus morhua*), Food Chemistry, vol. 91, pp 45-49.

Saito M, Kiyose C, Higuchi T, Uchida N, and Suzuki H. 2009, Effect of Collagen Hydrolysates from Salmon and Trout Skins on the Lipid Profile in Rats, Journal of Agricultural Food Chemistry, vol. 57, pp 10477-10482.

Salta E, Panagiotidis C, Teliousis K, Petrakis S, Eleftheriadis E, Nikolaos Grigoriadis, Eleni Kaldrymidou, Anna Nicolaou, Grigorios Krey, and Theodoros Sklaviadis. 2009. Evaluation of the Possible Transmission of BSE and Scrapie to Gilthead Sea Bream (*Sparus aurata*)", PLoS ONE, vol. 4, no. 7, pp 1-13.

Samuelsen T.A., Mjøs S.A., and Oterhals Å, 2013. Impact of variability in fishmeal physicochemical properties on the extrusion process, starch gelatinization and pellet durability and hardness, Animal Feed Science and Technology, vol. 179, pp. 77-84.

Sarabia A I, Gomez-Guillen M C, and Montero P, 2000. The effect of added salts on the viscoelastic properties of fish skin gelatin. Food Chemistry, vol. 70, pp. 71-76.

Schau E M and Fet A M, 2008. LCA Studies of Food Products as Background for Environmental Product Declarations. International Journal of Life Cycle Assessment, vol. 13, 3, pp 255-264.

Scottish Parliament, 2013. Rural Affairs, Climate Change and Environment Committee 1st Report, 2013 (Session 4) Stage 1 Report on the Aquaculture and Fisheries (Scotland) Bill , SP Paper 260. Scottish Parliament, Edinburgh Uk. 89pp.

Seafish, 2008. Use of waste as a biofuel and fertiliser in Orkney (C008), SR609. Sea Fish Industry Authority. 51pp.

Seafish, 2009a. 2008 Survey of the UK Seafood Processing Industry. Sea Fish Industry Authority, Edinburgh, UK. 103pp.

Seafish, 2009b. Fishmeal and fish oil facts and figures. Sea Fish Industry Authority, Grimsby UK. 28pp.

Seafish. 2010, Fishmeal and fish oil figures. Sea Fish Industry Authority, Grimsby UK. 30pp.

Sechena R, Nakano C, Liao S, Polissar N, Lorenzana R, Truong S, and Fenske R. 1999. Asian and Pacific Islander Seafood Consumption Study, EPA Report 910/R-99-003.EPA Environmental Justice Community, Washington, USA. 75pp.

Seoka M, Kurata M, Tamagawa R, Kumar Biswas A, Kumar Biswas B, Yong A, Kim Y-S, Ji S-C, Takii K, and Kumai H. 2008. Dietary supplementation of salmon roe phospholipid enhances the growth and survival of Pacific bluefin tuna (*Thunnus orientalis*) larvae and juveniles, Aquaculture, vol. 275, pp 225-234.

SEPA. 2004. Evaluation of Fish Waste Manage Techniques. SEPA Contract reference 230/4198. Scottish Environmental Protection Agency, Edinburgh, UK. 48pp.

SETAC. 1999, Best Available Practice Regarding Impact Categories and Category Indicators in Life Cycle Impact Assessment, International Journal of Life Cycle Assessment, vol. 4, no. 3, pp. 167-174.

Shahidi F. 2007. Chitin and chitosan from marine by-products, in Maximising the Value of Marine Products (Shahidi F, ed.), Ch. 16, pp340-373. Woodhead Publishing , Cambridge, UK.

Shahiri Tabarestani H, Maghsoudlou Y, Motamedzadegan A, and Sadeghi Mahoonak A R. 2010. Optimization of physico-chemical properties of gelatin extracted from fish skin of rainbow trout (*Onchorhynchus mykiss*), Bioresource Technology, vol. 101, pp 6207-6214.

Shepherd J. 2013. Changing Supply and Demand for Fish Oil. Unpublished work.

Singh P, Benjakul S, Maqsood S, and Kishimura H. 2011, Isolation and characterisation of collagen extracted from the skin of striped catfish (*Pangasianodon hypophthalmus*), Food Chemistry, vol. 124, pp 97-105.

Šližytë, Mozuraitytė, R., Martinez-Alvarez O, and Falch E. 2009. Functional, bioactive and antioxidative properties of hydrolysates obtained from cod (*Gadus morhua*) backbones, Process Biochemistry, vol. 44, pp. 668-677.

Smail D A, Garden A, Thompson F, Smith M J, Cronje_ A, and Heyworth A. 2009. Inactivation of the Fish Pathogens *Lactococcus garvieae* and Infectious Pancreatic Necrosis Virus in an Aerobic Composting Silo Incorporating Shellfish, Marine Scotland Science Collaborative Report 06/09, Marine Scotland Science, Aberdeen, UK. 18pp.

Smail D A, Huntly P K, and Munro A L S. 1993. Fate of four fish pathogens after exposure to fish silage containing fish farm mortalities and conditions for the inactivation of infectious pancreatic necrosis virus, Aquaculture, vol. 113, 3, pp 173-181.

Smith S R, Lang N L, Cheung K H M, and Spanoudaki K. 2005. Factors controlling pathogen destruction during anaerobic digestion of biowastes, Waste Management, vol. 25, pp 417-425.

Snyder, J., 2010. Feed, supplement industries maximize use of fish oil production. Seafood Business Magazine. Available online: http://www.seafoodbusiness.com/articledetail.aspx?id=4294994216. Accessed 20/5/2011.

Soares S, Green D, Turnball J, Crumlish M, and Murray A. 2011. A baseline method for benchmarking mortality losses in Atlantic salmon (*Salmo salar*) production, Aquaculture, vol. 314, pp 7-12.

Sobhi B, Adzahan N M, Karim M S A, and Karim R. 2010. Physiochemical and sensory properties of a traditional chilli shrimp paste, Journal of Food Agriculture and Environment, vol. 8, 1, pp 38-40.

Soil Association. 2010, Soil Association Organic Standards: Aquaculture. The Soil Association, Edinburgh, UK. 59pp.

Sriket P, Benjakul S, Visessanguan W, and Kijroongrojana K. 2007. Comparative studies on chemical composition and thermal properties of black tiger shrimp (*Penaeus monodon*) and white shrimp (*Penaeus vannamei*) meats, Food Chemistry, vol. 103, pp 1199-1207.

SSPO. 2009, Scottish Salmon Farming Industry Research Report. Scottish Salmon Producers Organisation, Perth, UK. 18pp.

SSPO. 2010. Scottish farmed salmon export figures, 2008. Unpublished data.

Statistics Norway. 2009, Fishery Statistics 2007, Official Statistics of Norway D 428. Statistics Norway, Oslo. 13pp.

St-Hilaire S, Cranfill K, McGuire M A, Mosley E E , Tomberlin J K , Newton L , Sealey W, Sheppard C, and Irving S. 2007. Fish offal recycling by the black soldier fly produces foodstuff high in omega-3 fatty acids, Journal of the World Aquaculture Society, vol. 38, 2, pp 309-313.

Stubhaug I, Lie Ø, and Torstensen B E. 2007. Fatty acid productive value and b-oxidation capacity in Atlantic salmon (*Salmo salar* L.) fed on different lipid sources along the whole growth period, Aquaculture Nutrition, vol. 13, pp 145-155.

Sudaryono A, Tsvetnenko E, and Evans L H. 1996. Digestibility studies on fisheries by-product based diets for *Penaeus monodon*, Aquaculture, vol. 143, pp 331-340.

Sun T, Piggot G M, and Herwig R P. 2002. Lipase-Assisted Concentration of n-3 Polyunsaturated Fatty Acids from Viscera of Farmed Atlantic Salmon (*Salmo salar* L.), Journal of Food Science, vol. 67, 1, pp 130-136.

Sun T, Xu Z, and Prinyawiwatkul W. 2006. FA Composition of the Oil Extracted from Farmed Atlantic Salmon (*Salmo salar* L.) Viscera, Journal of the American Oil Chemists' Society, vol. 83, 7, pp 615-619.

Sustainable Fisheries Partnership, 2010. FishSource, Reduction Fisheries and Aquaculture, Sustainable Fisheries Partnership Briefing, March 2010. Hawaii, USA. Available online: http://cmsdevelopment.sustainablefish.org.s3.amazonaws.com/2011/03/21/SFP_Brief_FS_Reduc-3-193919e6.pdf. 10pp.

Svanes E, Vold M, and Hannsen O J, 2011. Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such results. International Journal of Life Cycle Assessment, vol 16, pp 512-521.

Synowiecki J and Al-Khateeb N A A Q. 2000. The recovery of protein hydrolysate during enzymatic isolation of chitin from shrimp *Crangon crangon* processing discards, Food Chemistry, vol. 68, pp 147-152.

Synowiecki, J. and Al-Khateeb, N. A. A. Q. 2003. Production, properties, and some new applications of chitin and its derivatives. Critical Reviews in Food Science and Nutrition, vol. 43, 2, pp 145-171.

Tacon A G J and Metian M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. Aquaculture, vol. 285, pp. 146-158.

Tacon A G J. 2002. Thematic Review of Feeds and Feed Management Practices in Shrimp Aquaculture. Report prepared under the World Bank, NACA, WWF, FAO, Consortium program on shrimp farming and the environment. 69 pp.

Tacon A G J, Hasan M R, Metian M, 2011. Demand and Supply of Feed Ingredients for Farmed Fish and Crustaceans. FAO Fisheries and Aquaculture Technical Paper 564. FAO, Rome. 87pp.

Teeransuntonwat P and Raksakulthai N, 2000, Production of Flavouring Agent from Shrimp Heads, ASEAN Food Journal, vol. 10, pp 131-138.

Thai Frozen Foods Association. 2014. Export Shrimp of Thailand. Available online: http://www.thai-frozen.or.th/webdatas/stats_ex_im/208.pdf . Accessed 7/2/2014

The Independent, 2012, 5 February. Meat trade emissions equal to half of all Britain's cars. Independent Print Ltd. London, UK.

Thistle Environmental Partnership. 2008, Strategic Waste Management and Minimisation in Aquaculture. SARF, Pitlochry, UK. 74pp.

Thorkelsson G and Kristinsson H G. 2009. Bioactive Peptides from Marine Sources. State of Art. Report to the NORA fund. Matis Food Research, Innovation and Safety, Norway. 19pp.

Thrane, M., 2004. Environmental Impacts from Danish Fish Product - Hot spots and Environmental Policies. Department of Development and Planning. PhD thesis. Aalborg University. Aalborg, Denmark. 490pp.

Thrane M, Nielsen E and Christensen P. 2009. Cleaner production in Danish fish processing - experiences, status and possible future strategies. Journal of Cleaner Production, vol. 17, pp380-390.

Trung S T. 2010, "The innovative use of fishery by-products in Vietnam", in The FFTC-KU Joint Seminar on Improved Utilization of Fishery By-Products as Potential Nutraceuticals and Functional Foods, 21st October 2010, Faculty of Fisheries, Kasetsart University, Bangkok, Thailand.

Treasurer J W, Hannah F, and Cox D. 2003. Impact of a phytoplankton bloom on mortalities and feeding response of farmed Atlantic salmon, *Salmo Salar*, in West Scotland, Aquaculture, vol. 218, pp. 103-113.

UNEP and SETAC, 2011. Towards a Life Cycle Sustainability Assessment - Making Informed Choices on Products. UNEP/SETAC Life Cycle Initiative, DTI/1412/PA. UNEP/SETAC joint publication. 67pp.

US Environmental Protection Agency. No date, Phasing Out HCFC Refrigerants To Protect The Ozone Layer. EPA, Washington, USA. 2pp. Available online: http://www.epa.gov/ozone/title6/downloads/EPA.homeowners.9-06-06.pdf

Vandanjon L, Grignon M, Courois E, Bourseau P, and Jaouen P. 2009. Fractionating white fish fillet hydrolysates by ultrafiltration and nanofiltration, Journal of Food Engineering, vol. 95, pp 36-44.

VASEP. 2010, Statistics of Vietnam Seafood Exports 1998 – 2008 (CD ROM). Vietnamese Association of Seafood Exporters and Producers. Ha Noi, Vietnam.

Vasquez-Rowe I, Villanueva-Rey P, Hospido A, Moreira M T, and Feijoo G. 2014. Life Cycle Assessment of European pilchard (*Sardina pilchardus*) consumption. A case study for Galicia (NW Spain), Science of the Total Environment, vol. 475, pp. 48-60.

Vietnamese Ministry of Agriculture and Rural Development. 2014. Review on the achievements of 2013 plan and implementation of 2014 plan (in Vietnamese), Vietnamese Ministry of Agriculture and Rural Development ,Ha Noi, Vietnam.

VIFE (Sub institute for Fisheries Economics and Planning in Southern Vietnam). 2009 Project on development planning for aquaculture production and consumption in the Mekong Delta up to

2015 and strategic planning up to 2020. Department of Aquaculture, Ministry of Agriculture and Rural Development, Ho Chi Minh City Vietnam.

Vik J, Borgstrom R, and Skaala O. 2001. Cannibalism governing mortality of juvenile brown trout, *Salmo trutta* in a Regulated Stream, Regulated Rivers: Research and Management, vol. 17, pp. 583-594.

Vogel A, 2010. Global Seafood Sustainability Initiative and its Benchmarking Concept and Architecture. Presentation given at the Workshop on Ecolabelling and Fisheries Sustainability, Morocco, 1st-3rd December 2010. Global Seafood Sustainability Initiative, Bonn, Germany. 10 slides. Available at: http://www.infosamak.org/english/presentations/GSSI%20Benchmarking%20Concept%20_A%20Vogel.pdf

Wang S, Wu D, Mathan M, Lamon-Fava S, Lecker J, and Lichtenstein A. 2009. Reduction in dietary omega-6 polyunsaturated fatty acids: eicosapentaenoic acid plus docosahexaenoic acid ratio minimizes atherosclerotic lesion formation and inflammatory response in the LDL receptor null mouse, Atherosclerosis, vol. 204, pp. 147-155.

Wang M, Hanjie L. and Molberg J, 2004. Allocation of energy use in petroleum refineries to petroleum products. Implications for life-cycle energy use and emission inventory of petroleum transportation fuels. International Journal of Life Cycle Assessment, vol. 9, 1, pp 34-44.

Wang, K., 2010. Analysis on the hog raising scale and their benefit -the analysis based on the case of Yingpan Village in jiangdong town of Fuling District Regional (In Chinese). Southwest University. Available at: http://d.wanfangdata.com.cn/Thesis_Y1671317.aspx.

Ward C and Slater B. 2002. Anaerobic digestion of fish processing by-products, Nutrition and Food Science, vol. 32, no. 2, pp. 51-53.

Weidema B, 2001. Avoiding co-product allocation in Life-Cycle Assessment. Journal of Industrial Ecology, vol. 4, 1, pp 11-33.

Weidema B, Lindeijer E, 2001 Physical impacts of land use in product life cycle assessment. Report IPL-033-01, prepared as part of the EUREKA project EUROENVIRON 1296 LCAGAPS. Department of Manufacturing Engineering and Management, Technical University of Denmark, Lyngby. 52pp.

Werner F and Richter K, 2000. Economic allocation in LCA: a case study about aluminium window frames. International Journal of Life Cycle Assessment, vol. 5, 2, pp 79-83.

WFLO. 2008, Fish, Comminuted, Deboned, and Minced , WFLO Commodity Storage Manual. WFLO, Virginia, USA.

Whiteman K and Gatlin D. 2005. Evaluation of fisheries by-catch and by-product meals in diets for red drum *Sciaenops ocellatus* L, Aquaculture Research, vol. 36, pp. 1572-1580.

WHO and FAO. 2003, Code of Good Practice for Fish and Fishery Products, CAC/RCP 52-2003.WHO, FAO Food Standards Programme, Rome. 125pp.

WHO and FAO. 2004, Code of Practice on Good Animal Feeding, CAC/RCP 54-2004.FAO/WHO Food Standards Programme, Rome. 8pp.

WHO and FAO, 2010a. Codex Alimentarius Commission Procedural Manual, 19th Edition edn, FAO/WHO Food Standards Programme, Rome. 184pp.

WHO and FAO, 2010b. Codex General Standard for Contaminants and Toxins in Food and Feed, Codex Stan 193-1995.FAO/WHO Food Standards Programme, Rome. 41pp

Wiggers V R, Wisniewski Jr, Madureira L A S, Chivanga Barros A, and Meier H F. 2009. Biofuels from waste fish oil pyrolysis: continuous production in a pilot plant, Fuel, vol. 88, pp 2135-2141.

Wilkinson K G, 2007. The Biosecurity of on-farm mortality composting. Journal of applied Microbiology, vol. 102, pp609-618.

Wisniewski Jr, Wiggers V R, Simionatto E L, Meier H F, Barros A A C, and Madureira L A S. 2009. Biofuels from waste fish oil pyrolysis: chemical composition. Fuel, vol.89, 3, pp 563-568.

World Business Council for Sustainable Development and World Resources Institute. 2012. The Greenhouse Gas Protocol - A Corporate Accounting and Reporting Standard. Revised Edition. WBCSD, Geneva Switzerland. WSI Washington, USA. 32pp.

WWF. 2008. Aquaculture Dialogues Process Guidance Document. http://www.worldwildlife.org/what/globalmarkets/aquaculture/WWFBinaryitem9674.pdf. World Wildlife Fund. 11pp.

WWF. 2011. Draft standards for responsible for responsible shrimp aquaculture. http://www.worldwildlife.org/what/globalmarkets/aquaculture/dialogues-shrimp.html . World Wildlife Fund. 104pp.

Yamada H, Daigo I, Matsuno Y, Adachi Y and Kondo Y, 2006. Application of Markov Chain Model to calculate the average number of times of use of a material in society. International Journal of Life Cycle Assessment, vol. 11, 5, pp 354-360.

Yi J B, Kim Y T, Bae H J, Whiteside W S, and Park H J, 2006. Influence of transglutaminase-induced coss-linking on properties of fish gelatin films, Journal of Food Science, vol. 71, 9, pp 376-383.

Yunoki S, Nagai N, Suzuki T, and Munekata M, 2004. Novel biomaterial from reinforced salmon collagen gel prepared by fibril formation and cross-linking, Journal of Bioscience and Bioengineering, vol. 98, 1, pp 40-47.

Yunoki S, Suzuki T, and Takai M, 2003. Stabilization of low denaturation temperature collagen from fish by physical cross-linking methods, Journal of Bioscience and Bioengineering, vol. 96, 6, pp 575-577.

Zampogna F, 2009. Aquaculture Statistics - 2007, 83/2009.Eurostat Statistics in Focus, 83/2009, European Communities, Luxemburg. 8pp.

Zhong Y, Madhujith T, Mahfouz N, and Shahidi F, 2007. Compositional characteristics of muscle and visceral oil from steelhead trout and their oxidative stability. Food Chemistry, vol. 104, pp 602-608.

Zhou P and Regenstein J M, 2007. Comparison of water gel desserts from fish skin and pork gelatins using instrumental measurements. Food Chemistry and Toxicology, vol. 72, 4, pp 196-201.

Ziegler F and Valentinsson D, 2006. Environmental Life Cycle Assessment of Norway lobster (*Nephrops norvegicus*) caught along the Swedish west coast by creels, conventional trawls and species-selective trawls. A data report. SIK report 746. Swedish Institute for Food and Biotechnology. Gothenburg, Sweden. 19pp.

Ziegler F, Nilsson P, Mattsson B and Walther Y, 2003. Life Cycle Assessment of frozen cod fillets including fishery-specific environmental impacts. International Journal of Life Cycle Assessment, vol. 8, 1, pp 39-47.