Scotland's Rural College

Quantifying and mitigating greenhouse gas emissions from global aquaculture

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Preparation of this document

Preparation of this technical paper was coordinated by Dr Mohammad R. Hasan of the Aquaculture Branch, FAO Fisheries and Aquaculture Department as a part of FAO's Strategic Objective (SO2): Increase and improve provision of goods and services from Agriculture, Forestry and Fisheries. This publication will contribute to the organizational outcome 20101: producers and natural resource managers adopt practices that increase and improve the provision of goods and services in agricultural sector production systems in a sustainable manner. Globally, aquaculture is a key sector, which makes an important contribution to food security directly (by increasing food availability and accessibility) and indirectly (as a driver of economic development). In order to enable sustainable expansion of aquaculture, we need to understand aquaculture's contribution to global greenhouse gas (GHG) emissions and how it can be mitigated. The rationale of this study is to synthesize the existing evidence to provide an overview of the current contribution of global aquaculture to GHG emission, and an explanation of how the emissions might be mitigated.

The authors would like to express their sincere thanks to the numerous feed mill owners, carp, tilapia and catfish farmers and all other stakeholders involved in the broader aquaculture sub-sector who were interviewed, consulted or otherwise took part in the study, for their contribution to the qualitative and quantitative data and information. The authors acknowledge the technical support from the Scottish Government's Rural and Environment Science and Analytical Services Division (RESAS) Environmental Change Programme (2016-2021).

For consistency and conformity, the use of scientific and English common names of fish species in this technical paper were used according to FishBase (www.fishbase.org/search.php).

Ms Marianne Guyonnet and Ms Lisa Falcone are acknowledged for their assistance in quality control and FAO house style. Mr Koen H. Ivens prepared the layout design for printing. The publishing and distribution of the document were undertaken by FAO, Rome.

Abstract

Global aquaculture makes an important contribution to food security directly (by increasing food availability and accessibility) and indirectly (as a driver of economic development). In order to enable sustainable expansion of aquaculture, we need to understand aquaculture's contribution to global greenhouse gas (GHG) emissions and how it can be mitigated. This study quantifies the global GHG emissions from aquaculture[1] (excluding farming of aquatic plants) and explains how cost-effectiveness analysis (CEA) could be used to appraise GHG mitigation measures. Cost-effective mitigation of GHG from aquaculture can make a direct contribution to United Nations Sustainable Development Goals 13 (Climate Action), while supporting food security (Goal 2: Zero Hunger), and economic development (Goal 8: Decent Work and Economic Growth).

Aquaculture accounted for approximately 0.45 percent of global anthropogenic GHG emissions in 2013, which is similar in magnitude to the emissions from sheep production. The modest emissions reflect the low emissions intensity of aquaculture, compared to terrestrial livestock (in particular cattle, sheep and goats), which is due largely to the absence of enteric CH_4 in aquaculture, combined with the high fertility and low feed conversion ratios of finfish and shellfish. However, the low emissions from aquaculture should not be grounds for complacency. Aquaculture production is increasing rapidly, and emissions arising from post-farm activities, which are not included in the 0.45 percent, could increase the emissions intensity of some supply chains significantly. Furthermore, aquaculture can have important non-GHG impacts on, for example, water quality and marine biodiversity. It is therefore important to continue to improve the efficiency of global aquaculture to offset increases in production so that it can continue to make an important contribution to food security. Fortunately, the relatively immature nature of the sector (compared to agriculture) means that there is great scope to improve resource efficiency through technical innovation. CEA can be used to help identify the most cost-effective efficiency improvements. In this technical paper we explain CEA and provide an example illustrating how it could be applied to tilapia production, and provide some guidance on how to interpret the results of CEA.

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[1] Throughout this document, aquaculture is defined as the culture of aquatic animals only and excludes farming of aquatic plants.

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Abbreviations and acronyms

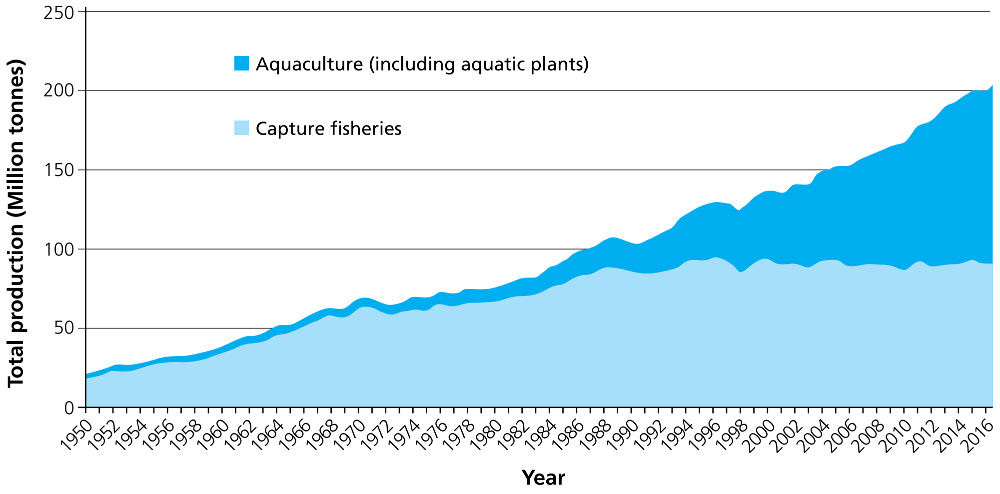
AFFRIS	Aquaculture Feed and Fertilizer Resources Information System
AP	abatement potential
BEIS	Department for Business Energy & Industrial Strategy, United Kingdom
bFCR	biological feed conversion ratio
CE	cost-effectiveness
CEA	cost-effectiveness analysis
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent: the amount of CO_2 equivalent to the quantity of GHG gases associated with a process
CW	carcass weight
eFCR	economic feed conversion ratio
EF	emission factor
EI	emissions intensity, i.e. the emissions per unit of output, e.g. $kgCO_2e/kgLW$
FAO	Food and Agriculture Organization of the United Nations
FCR	feed conversion ratio
F-gases	fluorinated gases
GHG	greenhouse gas
GLEAM	global livestock environmental assessment model
Gt	giga tonnes (1 000 mega/million tonnes)
kg	kilogramme
$kgCO_2e$	kg carbon dioxide equivalent
kt	kilotonnes/thousand tonnes
kgLW	kg live weight
$ktCO_2e$	kt carbon dioxide equivalent
kWh	kilowatt hour
l	litre
LUC	land use change
LW	live weight
MACCs	marginal abatement cost curves
MJ	mega joules
Mt	mega tonnes/million tonnes
N	nitrogen
N_2O	nitrous oxide
SG	species-group
SCC	social cost of carbon
SEAT	Sustaining Ethical Aquaculture Trade
tLW	tonne live weight
TSP	triple super phosphate
USEPA	United States Environmental Protection Agency
USD	United States dollar

1. Introduction

Globally, aquaculture is a key sector, which makes an important contribution to food security directly (by increasing food availability and accessibility) and indirectly (as a driver of economic development). Importantly, fish, produced by this rapidly growing sector, are rich in protein; contain essential micronutrients and essential fatty acids, which cannot easily be substituted by other food commodities (FAO, 2017a).

FIGURE 1

World capture fisheries and aquaculture production from 1950 – 2017



Source: FAO (2019).

The sector has expanded rapidly since the 1980s (Figure 1) and Gentry *et al.* (2017) have argued that the capacity for further expansion of marine aquaculture are theoretically huge and may be underestimated. In light of this, FAO (2017a) concluded that as the sector further expands, intensifies and diversifies, it should recognize the relevant environmental and social concerns and make conscious efforts to address them in a transparent manner, backed with scientific evidence.

One of the key environmental (and social) concerns is climate change, more specifically the greenhouse gas emissions that arise along food supply chains. In order to enable sustainable expansion of aquaculture, we need to understand aquaculture's contribution to global GHG emissions and how they can be mitigated. The aims of this paper are to (a) quantify the total GHG emissions from global aquaculture and (b) explain how cost-effectiveness analysis may be used to identify the economically efficient ways of reducing GHG emissions from aquaculture.

2. Quantifying the greenhouse gas emissions from global aquaculture

2.1 SCOPE

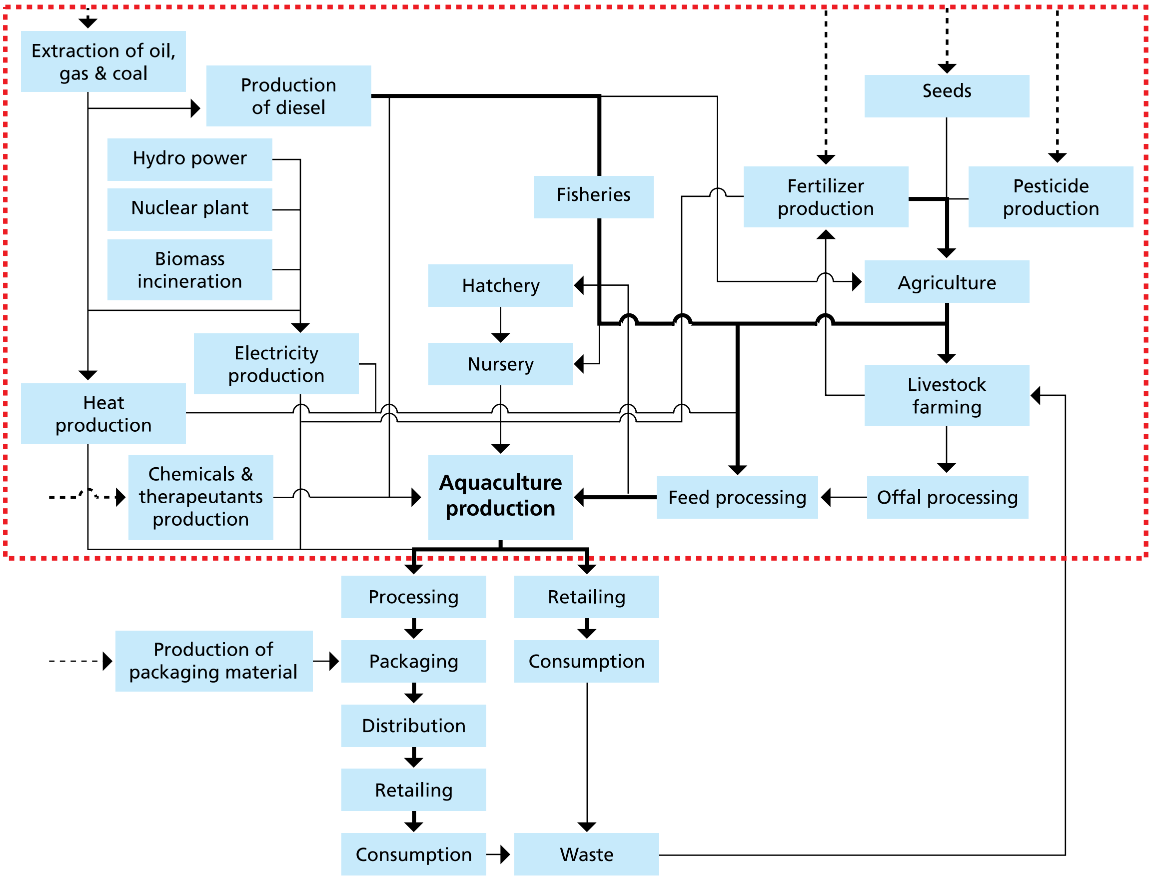
The system boundary of the analysis is shown in Figure 2. It was defined based on a review of previous studies, which indicated that the emissions intensity (EI) was likely to be primarily a function of processes occurring during the following stages:

- Production of feed raw materials;
- Processing and transport of feed materials;
- Production of compound feed in feed mills and transport to the fish farm;
- Rearing of fish in water.

The system boundary is therefore "cradle to farm-gate". It is recognised that significant emissions (and losses of product) can occur post-farm during transport, processing and distribution. However, aquaculture products have many routes to market and including post-farm processes would therefore require a more complex analysis.

FIGURE 2

Inputs to the aquaculture chains that may impact GHG emissions. The system boundary of the study is indicated by the dashed red line



Source: Henriksson *et al.* (2014a).

Species/system included

Global aquaculture is a complex sector consisting of many different species reared in a variety of systems and environments. In order to manage this complexity, the analysis focuses on the main cultured aquatic animal species-groups (aquatic plants are excluded). These were identified by extracting production data from FAO (2016a), listing the species-groups within each geographical region (according to FAO definitions) in order of production amount, then selecting the groups until they accounted for >90 percent of the production within the region. This approach captured an estimated 92 percent of global production (Table 1).

TABLE 1
Total production and production included in the analysis, by species-group and region

	Production (thousand tonnes, 2013)		% of total in analysis	% of included production
	Total	Included in analysis		
Breakdown by region				
East Asia	54 787	50 320	92	79
South Asia	6 952	6 404	92	10
Sub-Saharan Africa	502	487	97	1
West Asia and North Africa	1 418	1 271	90	2
Latin America and Caribbean	2 467	2 392	97	4
New Zealand and Australia	177	168	95	0
Eastern Europe	140	127	91	0
Western Europe	2 250	2 031	90	3
North America	592	571	97	1
Russian Federation	155	145	94	0
WORLD	69 440	63 916	92	100
Breakdown by species-group				
Bivalves	14 739	14 717	100	23
Catfishes (freshwater)	4 202	4 155	99	7
Cyprinids	20 795	20 734	100	32
Freshwater fishes, general	4 765	4 735	99	7
Indian major carps	4 866	4 143	85	6
Marine fishes, general	2 863	2 510	88	4
Salmonids	2 928	2 746	94	4
Shrimps and prawns*	5 542	5 525	100	9
Tilapias	4 883	4 650	95	7

Source: Data from FAO (2016a) to ensure that at least 90 percent of the aquatic animal production in each region was represented.

*Marine shrimps and freshwater prawns.

2.1.1 GHG categories

The major GHGs associated with aquaculture production are:

- **N_2O** (nitrous oxide) arising from the microbial transformation of N (nitrogen) (mainly from applied fertilizers) in soils during the cultivation of feed crops. Significant amounts of N_2O may also be emitted from ponds as a result of the microbial transformation of nitrogenous compounds in ponds (e.g. synthetic fertilizers, manures, composts, uneaten feed and excreted N), although the magnitudes of these emissions are less readily quantified.
- **CO_2** (carbon dioxide) arising from *pre-farm* energy use (primarily associated with feed and fertilizer production), *on-farm* energy use (e.g. pumping of water, use of electricity, other fuel consumption) and during *post-farm* distribution and processing. CO_2 emissions also arise from changes in above and below ground carbon stocks induced by land use and land use change (LUC) (primarily driven by increased demand for feed crops, which can lead to the conversion of forest and grassland to arable land).
- **CH_4** (methane) arising mainly from the anaerobic decomposition of organic matter during flooded rice cultivation. May also arise during fish farm waste management.
- **F-gases** (fluorinated gases) - small amounts of these potent greenhouse gases are leaked from cooling systems on-farm and post-farm.

The sub-categories of GHG included in the analysis are summarised in Table 2. GHG sources falling within the cradle to farm-gate system boundary, but not included in the analysis, are summarised in Table 3.

TABLE 2

Summary of the GHG categories included in the calculations

Name	Description
Feed: fertilizer production	Emissions arising from the production of synthetic fertilizers applied to crops
Feed: crop N_2O	Direct and indirect nitrous oxide from the application of N (synthetic and organic) to crops and crop residue management
Feed: crop energy use	CO_2 from energy use in field operations, feed transport and processing
Feed: crop LUC	CO_2 from land use change arising from soybean cultivation
Feed: rice CH_4	Methane arising from flooded rice cultivation
Feed: fishmeal	CO_2 from energy use in the production of fishmeal
Feed: other materials	Emissions from the production of a small number of "other" feeds (including animal by-products, lime and synthetic amino acids)
Feed: blending & transport	CO_2 from energy use in the production and distribution of compound feed
Pond fertilizer production	Emissions arising from the production of synthetic fertilizers applied to increase aquatic primary productivity
On-farm energy use	Emissions arising from the use of electricity and fuels on fish farm
Pond N_2O	N_2O from the microbial transformation of nitrogenous materials (fertilizers, excreted N and uneaten feed) in the fish farm water body

TABLE 3

GHG sources falling within the cradle to farm-gate system boundary, but not included in the analysis

Process	Gas	Comment
Energy in the manufacture of on-farm buildings and equipment (including packaging)	CO_2	Difficult to quantify, unlikely to be a major source of emissions
Production of cleaning agents, antibiotics and pharmaceuticals	CO_2	Unlikely to be a major source of emissions
Anaerobic decomposition of organic matter in ponds	CH_4	Difficult to quantify, unlikely to be a major source of emissions
N_2O from the animal	N_2O	Possibly significant for invertebrates, but difficult to quantify
LUC arising from pond construction	CO_2	Difficult to quantify, unlikely to be a major source of emissions
Pond cleaning maintenance	CO_2	Difficult to quantify, unlikely to be a major source of emissions
CO_2 sequestered in carbonates	CO_2	Possibly significant for invertebrates?
CO_2 sequestered in pond sediments	CO_2	Difficult to quantify, potentially significant
Leakage of coolants	F-gases	Difficult to quantify, potentially significant (particularly post-farm)

Carbon sequestration in pond sediments

Pond carbon sequestration was excluded from the present study. It has been suggested [see Verdegem and Bosma (2009) and Boyd *et al.* (2010)] that ponds could act as net carbon sinks if primary productivity is stimulated. However other studies (such as the Sustaining Ethical Aquaculture Trade (SEAT) project, see Henriksson *et al.*, 2014a,b) exclude these sinks due to uncertainties over the sequestration rates and permanence of the C storage. For example, most ponds get excavated, and much of the sequestered C could be oxidised, depending on how the sludge is managed. In addition, stimulating the growth requires relatively large inputs of nitrogen and phosphorus to the water, which could lead to problems such as eutrophication. There is also a concern about the fish welfare in such conditions, as the nutrient additions significantly change the water quality, which may not suit some species of fish.

2.2 METHODOLOGY

The methodology is summarised in Figure 3 and further details are provided below.

2.2.1 Emission factors for feed raw materials

The emission factors (EFs) for crop feed materials were based on the values derived using GLEAM (FAO, 2017b). Regional average values were used for each feed, meaning that the EFs at least partially capture variation in crop production efficiency between regions. EFs for additional feeds (e.g. fishmeal, poultry meal, feather meal, meat & bone meal, blood meal, groundnut meal) were derived from Feedprint (2017) and EFs for fish oil from Pelletier and Tyedmers (2010). Non-commercial feed materials were assumed to be produced locally, and have different emission profiles to their commercial equivalents (e.g. no emissions from transport).

2.2.2 Emission factors for fertilizers

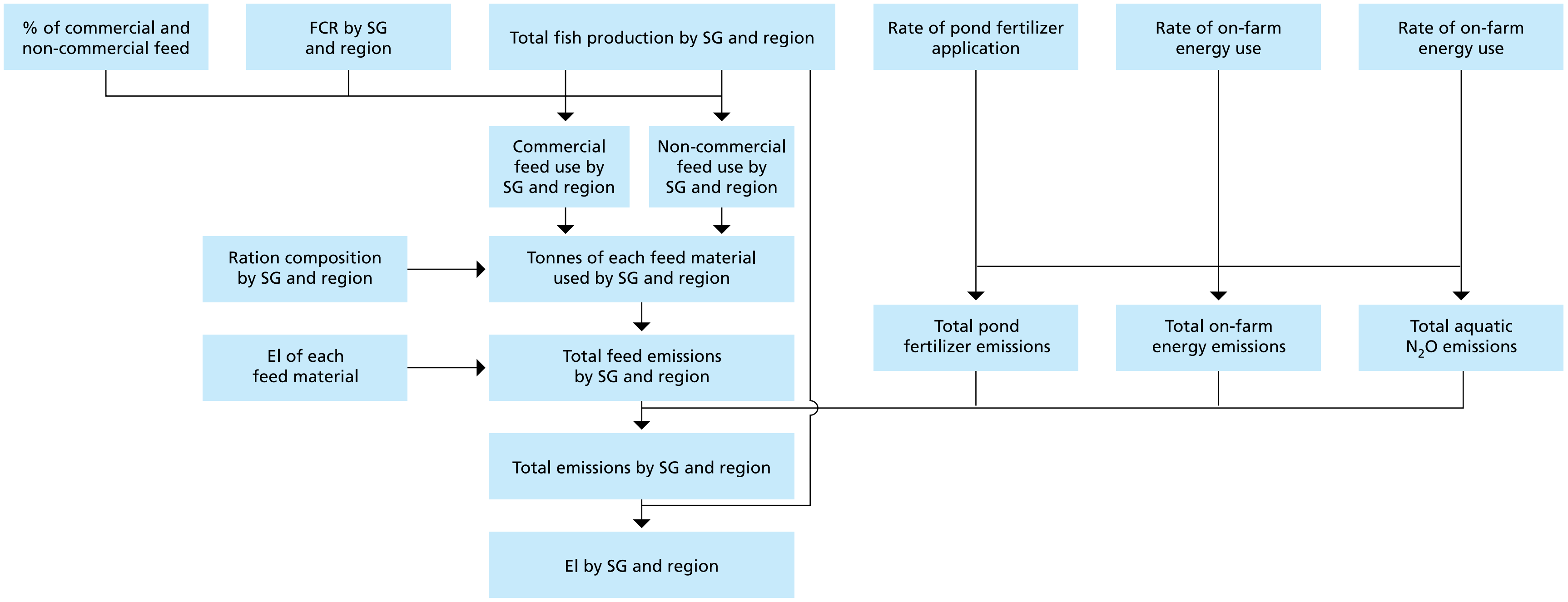
EFs for fertilizers such as urea and potash were derived from Kool *et al.* (2012), which provides EFs for each fertilizer for five geographic regions: western Europe; Russian Federation and central Europe; North America; China and India; and rest of the world.

2.2.3 Feed conversion ratios and ration composition

A distinction was made between two types of aquafeed as follows: (a) commercial aquafeed, which are compound feeds purchased from specialised feed manufacturers and/or feed wholesalers/retailers. The feed is comprised of materials sourced nationally and internationally, which are formulated and blended into high quality compounded pellet feeds and (b) farm-made/semi-commercial aquafeeds (which often include mashes or wet pellets) made on the farm or produced by small-scale feed manufacturers from locally sourced feed materials. The proportions of production reared on commercial and non-commercial rations were estimated based on Tacon and Metian (2015).

Changes in commercial conditions make it difficult to keep up to date through academic papers, as the feed compositions are improved/changed frequently and farming conditions fluctuate with improvements and emerging disease challenges. To account for this, feed composition (protein and energy), raw material rations and economic feed conversion ratios (eFCRs, which take into account average mortalities) were derived from a range of sources including : AFFRIS (AFFRIS, 2017), FAO publications (e.g. Tacon, Metian and Hasan, 2009; Hasan and Soto, 2017; Robb *et al.*, 2017), journal articles (e.g. Tacon and Metian, 2008, 2015), grey literature (e.g. White, 2013) and expert opinion to reflect the most recent updates. Feed conversion ratios used and their sources are given in Table 4.

FIGURE 3
Schematic diagram of the method used to quantify the total emissions and emissions intensity



Notes: SG - species-group; FCR - feed conversion ratio; EI- emissions intensity.

TABLE 4

Feed conversion ratios used in the model as representative of the species-group in each region

Region	East and Southeast Asia		South Asia		Sub-Saharan Africa		West Asia & North Africa		Latin America and Caribbean		New Zealand and Australia		Eastern Europe		Western Europe		North America		Russian Federation	
Species-group	FCR	*Sources*	FCR	*Sources*	FCR	*Sources*	FCR	*Sources*	FCR	*Sources*	FCR	*Sources*	FCR	*Sources*	FCR	*Sources*	FCR	*Sources*	FCR	*Sources*
Catfishes (freshwater)	1.69	8	1.69	8	1.20	4,13	-		-		-		-		-		2.50	18	-	
Cyprinids	1.70	4, 9, 10, 11, 12	1.80	4, 8, 9,10, 11, 12	1.80	4	1.70	10,11, 12	-		-		1.70	a	-		-		1.80	4,10, 11,12
Freshwater fishes, general	1.80	8	1.80	8	1.80	-	-		1.80	-	-		-		-		-		-	
Indian major carps	-		1.80	8	-		-		-		-		-		-		-		-	
Marine fishes, general	1.70	a	-		-		2.75	4	-		1.52	3	-		2.06	14,15,16,17	-		-	
Salmonids	-		-		-		0.92	4,5	1.30	4,6	1.41	1,2,3	1.20	a	1.13	6,7	1.30	6	1.25	a
Shrimps and prawns	1.91	a	1.83	a	-		-		1.50	a	-		-		-		2.48	a	-	
Tilapias	1.70	8	1.59	8	1.70	4	1.70	4	1.70	4	-		-		-		-		-	

Notes: FCR is calculated from the kg of dry feed that is used to produce 1 kg of live fish; (-) indicates species-group x location combination not included in the study.

Source(s) of information: [a] personal observation; [1] Walker *et al.* (2014); [2] White (2013); [3] Skretting Australia (2013); [4] Tacon and Metian (2008); [5] Pyc (2012); [6] EWOS (2013); [7] Marine Harvest (2015); [8] Robb *et al.* (2017); [9] FAO (2016b); [10] FAO (2016c); [11] FAO (2016d); [12] FAO (2016e); [13] FAO (2016f); [14] Myrseth (2014); [15] Bjorndal and Fernandez-Polanco (2014); [16] Ottolenghi (2008); [17] Myolonas *et al.* (2010); [18] Robinson and Li (2015).

2.2.4 Total production by species-group and region

Production data for 2013 was extracted from FAO (2016a).

2.2.5 On-farm energy use

Energy is used on fish farms for a variety of purposes, primarily for pumping water, lighting and powering vehicles. The average amount of energy required to produce one tonne of live weight of fishes and shellfishes, and the proportions of electricity, diesel and petrol used, were calculated based on values presented in the literature (Table 5). The rates of electricity, diesel and petrol used per tonne of live weight (LW) were then multiplied by emission factors (Table 6) to determine the emission intensity (Table 7). Global EFs were used for petrol and diesel, and regional EFs were used for grid electricity (BEIS, 2016) (Table 6).

TABLE 5

Average amount of on-farm energy use to produce one tonne of live fish and shellfish and the percentage contribution of each energy source to the total

Species-group	Average amount of on-farm energy (MJ/tLW) use				
	Electricity	Diesel	Petrol	Total	Sources
Bivalves	1 067 (37.4)	1 790 (62.7)	0 (0.0)	2 857	5, 7
Catfishes (freshwater)	206 (90.0)	23 (10.0)	0 (0.0)	229	6, 9
Cyprinids	258 (32.2)	424 (52.9)	119 (14.9)	801	9
Freshwater fishes, general	2 653 (77.0)	586 (17.0)	207 (6.0)	3 446	6, 9
Indian major carps	258 (32.2)	424 (52.9)	119 (14.9)	801	9
Marine fishes, general	0 (0.0)	551 (47.2)	617 (52.8)	1 168	1, 2
Salmonids	0 (0.0)	551 (47.2)	617 (52.8)	1 168	1, 2
Shrimps and prawns	14 068 (75.7)	4 511 (24.3)	2 (0.0)	18 581	3, 4, 6, 8
Tilapias	2 653 (77.0)	586 (17.0)	207 (6.0)	3 446	6, 9

Notes: Values in the parenthesis indicates the percentage total of different energy sources

Sources: 1. Ayer and Tyedmers (2008); 2. Pelletier *et al.* (2009); 3. Sun (2009); 4. Cao (2012); 5. Fry (2012); 6. Hendrikson *et al.* (2014a,b); 7. Hornborg and Zeigler (2014); 8. Paterson and Miller (2014); 9. Robb *et al.* (2017).

TABLE 6

Energy emission factors by power type and region

Power type	Region	Emission factors (kgCO_2e/MJ)
Diesel	Global	0.074
Petrol	Global	0.070
Electricity	North America	0.145
	Russian Federation	0.107
	Western Europe	0.096
	Eastern Europe	0.109
	West Asia & northern Africa	0.177
	East Asia	0.213
	New Zealand and Australia	0.138
	South Asia	0.186
	Latin America and Caribbean	0.055
	Sub-Saharan Africa	0.177

Source: BEIS (2016).

TABLE 7

Emission factor for on-farm energy use (kgCO_2e/tLW)

	Bivalves	Catfishes	Cyprinids	Freshwater fishes, general	Indian major carps	Marine fishes, general	Salmonids	Shrimps and prawns	Tilapias
East Asia	360	46	267	623	267	84	84	3 331	623
South Asia	331	40	238	551	238	84	84	2 948	551
Sub-Saharan Africa	322	38	229	528	229	84	84	2 826	528
West Asia & North Africa	322	38	229	528	229	84	84	2 826	528
Latin America and Caribbean	191	13	98	203	98	84	84	1 103	203
New Zealand and Australia	280	30	187	423	187	84	84	2 272	423
Eastern Europe	249	24	156	347	156	84	84	1 866	347
Western Europe	236	22	143	314	143	84	84	1 692	314
North America	288	32	195	443	195	84	84	2 376	443
Russian Federation	247	24	154	341	154	84	84	1 834	341

Source: calculated in this study.

Aquatic N_2O emissions

According to Hu *et al.* (2012) N_2O emissions from the water body on the fish farm arise "from the microbial nitrification and denitrification, the same as in terrestrial or other aquatic ecosystems". However, quantifying the emissions from the pond surface to the air is challenging, because they depend on the pH and dissolved oxygen content of the pond, and both fluctuate greatly (Bosma *et al.*, 2011). Despite these difficulties, pond N_2O emissions were included in the present study, to illustrate their likely contribution to the total emissions, and to allow the comparison of the GHG associated with aquaculture products to be compared with the GHG associated with terrestrial livestock products (for which N_2O from excreted N is routinely quantified).

The amount of N_2O per species-group was determined by multiplying the production by the N_2O emission factor per kg of production (Hu *et al.*, 2012), i.e. 1.69 gN_2O-N per kg of production, or 0.791 $kgCO_2e$/kgLW production. This equates to a conversion rate of N to N_2O-N of 1.8 percent, which is higher that the 0.71 percent used in Henriksson *et al.* (2014a).

2.3 RESULTS AND DISCUSSION

2.3.1 Total emissions from global aquaculture

Production and GHG emissions are reported in Tables 8 and 9. The total GHG emissions for the 9 species-groups are 201 $MtCO_2e$ (Table 9). These are for the year 2013 and represent 63 915 thousand tonnes of live weight or 92 percent of total shellfish and finfish production in that year.

TABLE 8

Production of different species-group by region, 2013

	Bivalves	Catfishes	Cyprinids	Freshwater fishes, general	Indian major carps	Marine fishes, general	Salmonids	Shrimps and prawns	Tilapias	TOTAL
	Production (thousand tonnes)									
East Asia	13 526	3 400	19 189	4 010	0	2 338	0	4 379	3 480	50 320
South Asia	0	363	990	453	4 143	0	0	455	0	6 404
Sub-Saharan Africa	0	239	28	50	0	0	0	0	169	487
West Asia & North Africa	0	0	321	0	0	161	137	0	652	1 271
Latin America and Caribbean	345	0	0	223	0	0	834	641	349	2 392
New Zealand and Australia	101	0	0	0	0	12	55	0	0	168
Eastern Europe	0	0	107	0	0	0	20	0	0	127
Western Europe	546	0	0	0	0	0	1 485	0	0	2 031
North America	199	153	0	0	0	0	169	50	0	571
Russian Federation	0	0	98	0	0	0	47	0	0	145
WORLD	14 717	4 155	20 734	4 735	4 143	2 510	2 746	5 525	4 650	63 915

Source: FAO (2016a).

TABLE 9

GHG emissions by species-group and region, 2013

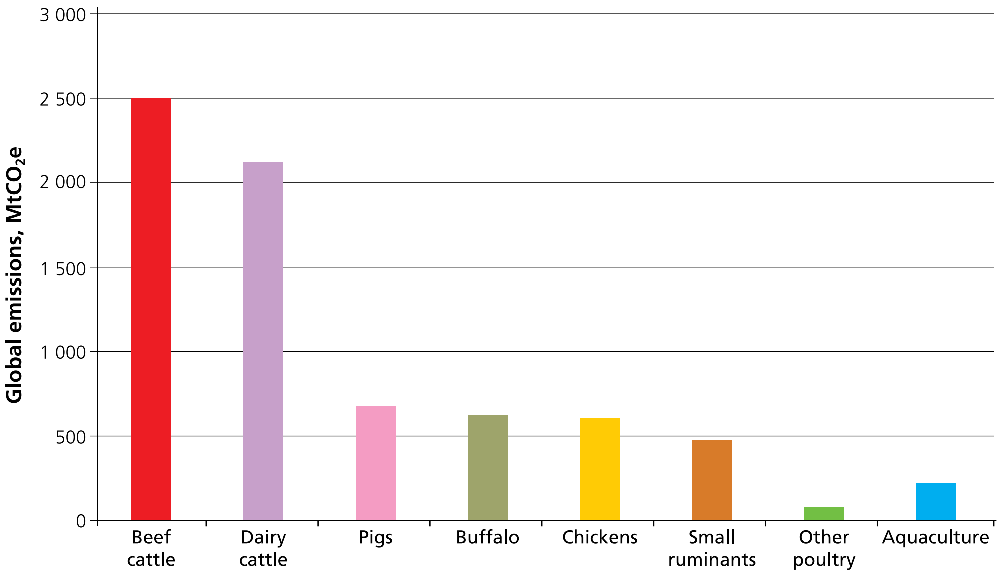
	Bivalves	Catfishes	Cyprinids	Freshwater fishes, general	Indian major carps	Marine fishes, general	Salmonids	Shrimps and prawns	Tilapias	TOTAL
	Global GHG emissions ($ktCO_2e$)									
East Asia	15 575	11 035	62 921	14 426	0	12 286	0	31 060	14 126	161 429
South Asia	0	949	3 107	1505	12 105	0	0	2 895	0	20 561
Sub-Saharan Africa	0	526	71	137	0	0	0	0	554	1 288
West Asia & North Africa	0	0	881	0	0	696	293	0	2 168	4 037
Latin America and Caribbean	339	0	0	508	0	0	3 746	1 958	697	7 248
New Zealand and Australia	108	0	0	0	0	139	108	0	0	355
Eastern Europe	0	0	170	0	0	0	43	0	0	213
Western Europe	561	0	0	0	0	0	4 037	0	0	4 598
North America	215	363	0	0	0	0	384	226	0	1 188
Russian Federation	0	0	156	0	0	0	108	0	0	264
WORLD	16 799	12 873	67 305	16 576	12 105	13 120	8 719	36 139	17 544	201 181

Source: calculated in this study.

Assuming that the remaining 8 percent of production has the same emissions intensity (EI), the total emissions in 2013 for all shellfish and finfish aquaculture would be 219 $MtCO_2e$. The IPCC Fifth Assessment Report estimated total anthropogenic emissions to be 49 (±4.5) $GtCO_2eq$/year in 2010 (IPCC, 2014), so culture of aquatic animals represented approximately 0.45 percent of total anthropogenic emissions in 2013. This is considerably lower than livestock emissions (Figure 4), which were estimated to account for 14.5 percent of global emissions in 2006 (Gerber *et al.* 2013), although note that this figure also includes some post-farm emissions. The global emissions from aquaculture (excluding culture of aquatic plants) are lower than livestock because (a) there is a greater amount of livestock production (in 2013 aquatic animals accounted for 7 percent of global protein intake, approximately half of which was from aquaculture, compared to 33 percent of protein from livestock products (FAO 2017c), and (b) overall livestock has a higher emissions intensity than aquaculture.

FIGURE 4

Total global emissions from aquaculture of aquatic animals in 2013, compared to the livestock emissions estimates in 2006



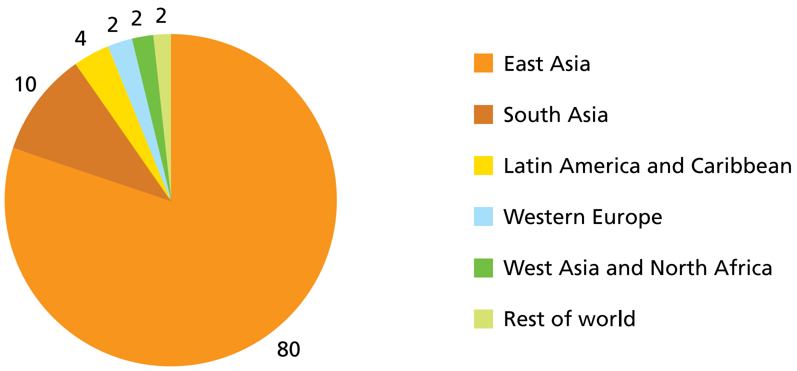
Notes: Livestock emissions estimates in 2006 are obtained from Gerber et al. (2013); the livestock estimates include a small amount of post-farm emissions.

Figures 5 to 7 and Table 10 show the total emissions disaggregated by species-group, geographical region and emission category. The geographical pattern of emissions closely mirrors production, i.e. most of the emissions arise in the regions with the greatest production: East Asia and South Asia. Emissions also correlate closely with production for most species-groups, e.g. cyprinids account for 34 percent of emissions and 32 percent of production. However, there are exceptions to this: shrimp account for 18 percent of emissions but only 9 percent of production, while bivalves produce 9 percent of emissions but represent 23 percent of production.

Production of crop feed materials (the green segments of Figure 7) accounts for 40 percent of total aquaculture emissions. When the emissions arising from fishmeal production, feed blending and transport are added, feed production accounts for 57 percent of emissions. The bulk of the non-feed emissions arise from the emission of N_2O and energy use on the fish farm.

FIGURE 5

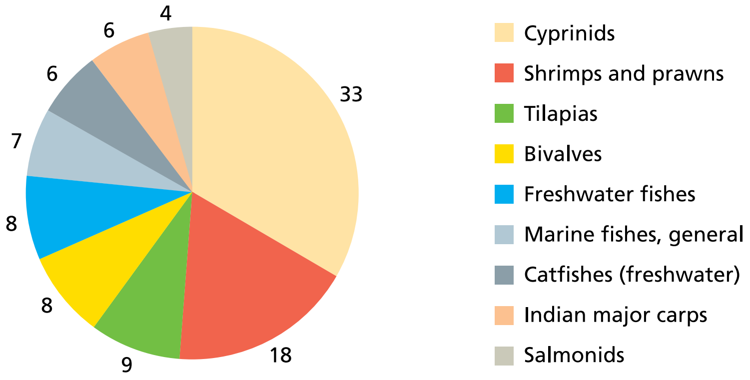
Percentage share of total GHG emissions by region



Source: calculated in this study.

FIGURE 6

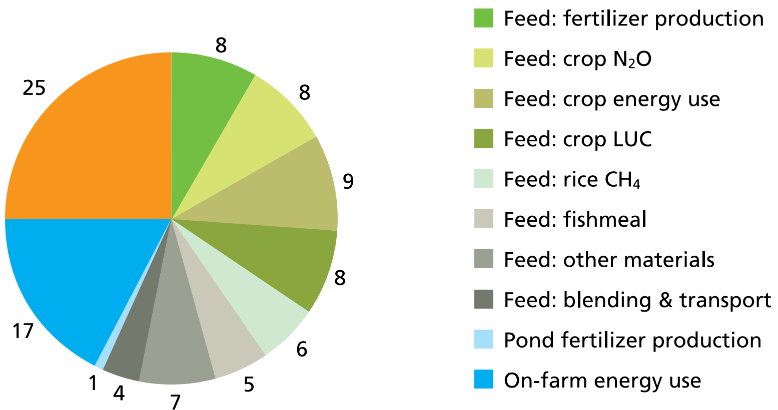
Percentage share of total GHG emissions by species-group



Source: calculated in this study.

FIGURE 7

Percentage share of GHG emissions by source category



Source: calculated in this study.

TABLE 10

Global GHG emissions by species-group and emission category, 2013

	Global GHG emissions ($ktCO_2e$)										
	Crop fertilizer production	Crop N_2O	Crop energy use	Crop LUC	Rice CH_4	Fishmeal	Other materials	Blending/ transport	Pond fertilizer production	On-farm energy use	Aquatic N_2O	TOTAL
Bivalves	0	0	0	0	0	0	0	0	0	5152	11647	16 799
Catfishes (freshwater)	1 698	1 644	1 668	1 780	903	393	699	616	0	183	3288	12 873
Cyprinids	6 295	5 642	9 723	5 396	7 409	3 424	2 938	3 442	1 156	5 471	16 409	67 305
Freshwater fishes, general	1 510	1 394	2 220	887	1 712	809	595	758	124	2 819	3 748	16 576
Indian major carps	2 345	2 679	891	0	832	281	49	528	236	986	3 279	12 105
Marine fishes, general	385	387	265	680	10	791	7 838	566	0	212	1 987	13 120
Salmonids	345	613	708	2 661	0	1 326	431	231	0	232	2 173	8 719
Shrimps and prawns	2 336	2 328	1 717	2 781	585	3 205	1 302	740	21	16 751	4 372	36 139
Tilapias	2 049	2 033	1 818	2 345	613	537	1 089	589	118	2 672	3 680	17 544
TOTAL	16 962	16 721	19 010	16 530	12 065	10 764	14 942	7 470	1 656	34 478	50 583	201 181

Source: calculated in this study.

2.3.2 Emissions intensity of aquaculture

The global average EI of each species-group is shown in Figure 8. For most of the finfish, the EI lies between 2.9 and 3.8 kgCO_2e/kg LW (i.e. per kg of whole, unprocessed fish) at the farm gate. The exception is the category "marine fishes, general", which has a significantly higher EI, due to the assumption that the ration in East Asia (and New Zealand and Australia) is 100 percent trash fish (which has a higher EI than most crop feed materials) and the higher FCR of this species-group. Shrimps and prawns have the highest EI, due to the higher amounts of energy used primarily for water aeration and pumping in these systems (Table 5). In contrast, bivalves have the lowest EI as they have no feed emissions, relying on natural food from their environment. Within the finfish, there are some differences in the sources of GHG emissions. Species predominantly reared in Asia (i.e. Indian major carps, freshwater catfishes and cyprinids) have higher rice methane emissions, while the carnivorous salmonids have more emissions associated with fishmeal and higher crop LUC emissions (arising from soybean production), reflecting their higher protein rations.

Comparing global averages, aquaculture has a much lower EI than ruminant meat and is similar to the main monogastric commodities (pig meat and broiler meat) (Figure 9). It should be noted that there can be significant variation in the EI of commodities, depending on factors such as genetics, feeding and farm management (for a discussion of the factors influencing the EI of ruminants and monogastrics, see Opio *et al.*, 2013 and MacLeod *et al.*, 2013). Fish (both finfish and shellfish) have lower EI than ruminants for three main reasons: they do not produce CH_4 via enteric fermentation, they have much higher fertility (so the "breeding overhead" is therefore much lower) and they have lower feed conversion ratios (which are a key determinant of fish EI, given the predominance of feed related emissions). Fish generally have lower FCRs than terrestrial mammals, due to the latter's higher maintenance and respiratory costs (Gjedrem *et al.*, 2012). Being buoyant and streamlined, fish require less energy for locomotion, they are cold-blooded, and they excrete ammonia directly.

Aquaculture is also more complicated than terrestrial livestock production, in the sense that it has many more species being farmed. Each species in theory has different nutritional requirements, although the information to provide this accurately is often lacking. This drives relatively poor use of nutrients and instead a focus on providing certain raw materials that could mimic what is consumed in the wild – for example feeding high inclusions of fishmeal to some carnivorous species; in particular marine fishes. The opportunity to optimise nutrition is probably greater in aquaculture than in terrestrial species, since much greater research effort has been focussed on terrestrial species to date.

2.3.3 Limitations of the analysis

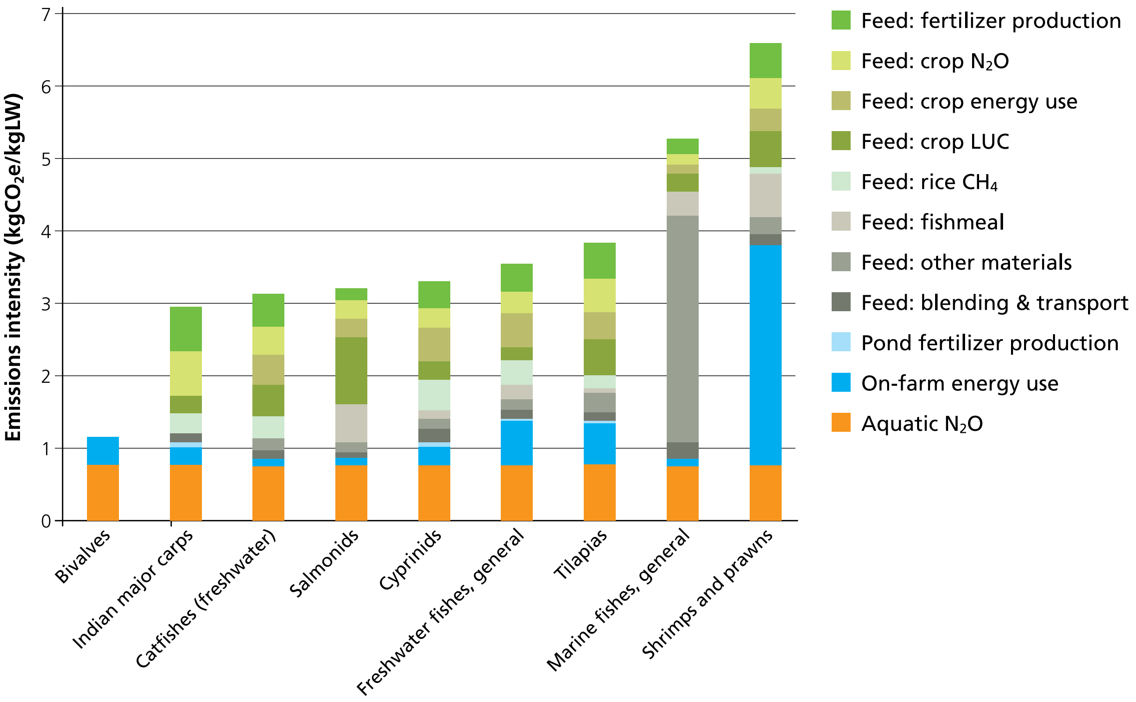
The emissions are calculated for aquaculture of aquatic animal only, and therefore do not include the emissions arising from the production of aquatic plants, which constitute a significant proportion of global aquaculture production.

The analyses do not include losses and emissions occurring post farm. Depending on the specifics of the post-farm supply chain (e.g. mode of transport, distance transported, mode of processing, storage conditions), significant emissions can arise from energy use in transportation or from refrigerant leakage in cold chains (Winther *et al.*, 2009). However, it should be noted that all GHG emissions are attributed to the aquaculture in this study, whereas, in practice, aquaculture produces processing by-products that are often used in other sectors and the associated emissions should be allocated to these sectors.

The estimates of aquatic N_2O should be treated with caution, as the rate at which N is converted to N_2O in aquatic systems can vary greatly, depending on the environmental conditions. Hu *et al.* (2012) noted that nitrification and denitrification processes are influenced by many parameters (e.g. dissolved oxygen concentration, pH, temperature).

FIGURE 8

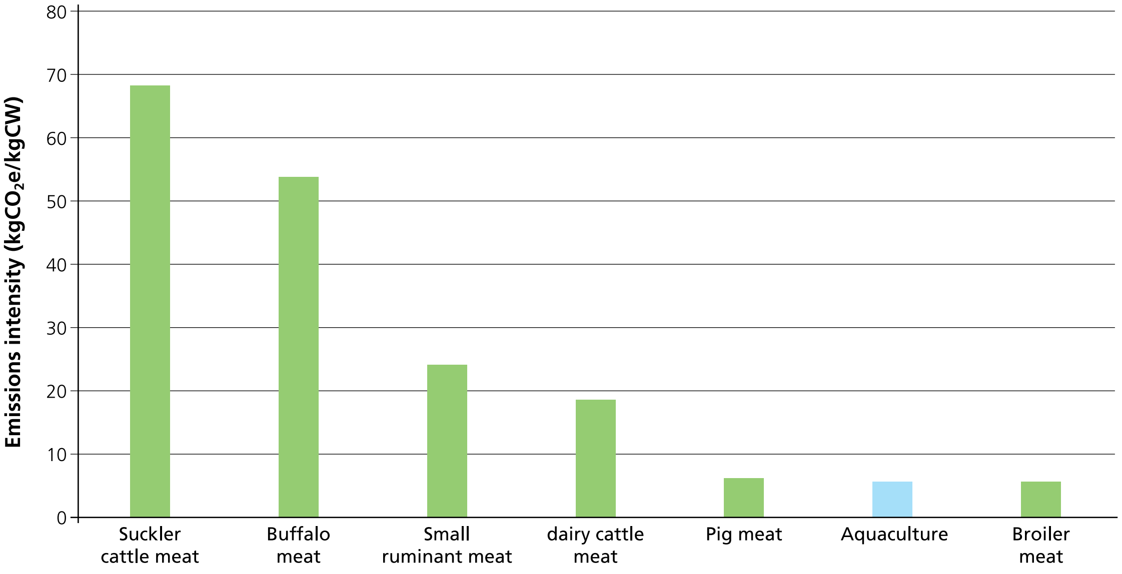
Global average emissions intensity (EI) of each species-group



Source: calculated in this study.

FIGURE 9

Comparison of the emissions intensity (EI) of livestock commodities with animal aquaculture



Sources: cattle, buffalo and small ruminants (Opio *et al.*, 2013); pig meat (MacLeod *et al.*, 2013); broiler meat (MacLeod *et al.*, 2013); aquaculture (calculated in this study).

3. Mitigating greenhouse gas emissions in aquaculture

3.1 BACKGROUND

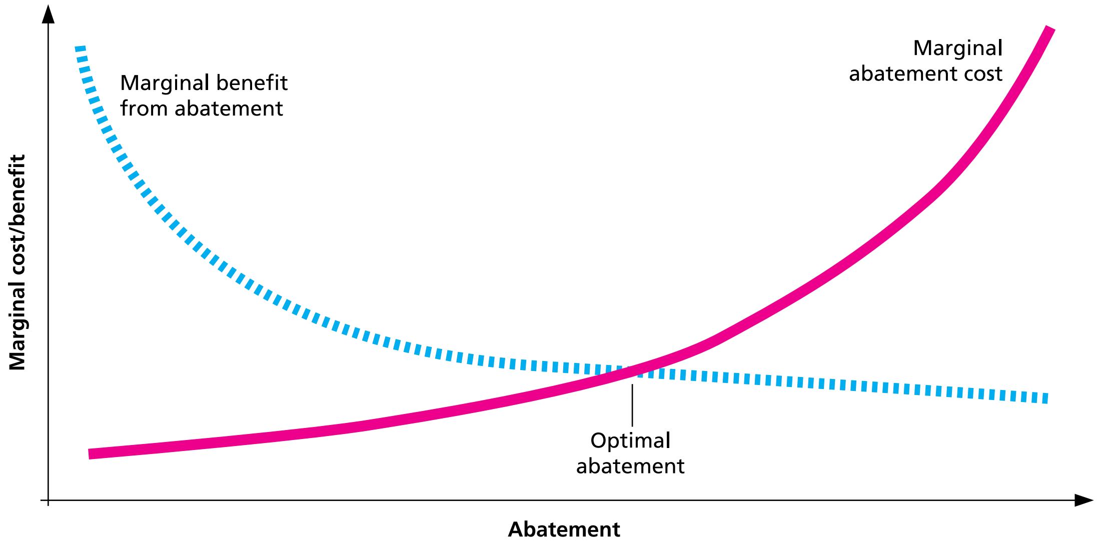
Waite *et al.*, (2014) have argued that because the aquaculture sector is relatively young compared with terrestrial livestock sectors, it offers great scope for technical innovation to further increase resource efficiency. They go on to identify four broad technological approaches to reducing the environmental impact of aquaculture: (1) breeding and genetics, (2) disease control, (3) nutrition and feeding, and (4) low-impact production systems. Within each of these approaches are many individual measures that could be used to reduce (or mitigate) GHG emissions. Some of these measures may be quite expensive while others are relatively cheap or may even reduce cost. In order to achieve the twin goals of reducing emissions, while increasing the supply of affordable protein, we need to analyse the effects that introducing measures may have on farm profits and emissions. Cost-effectiveness analysis (CEA) can help us to understand these effects.

3.2 COST-EFFECTIVENESS ANALYSIS

Reducing GHG emissions should be achieved in ways that are cost effective (i.e. focusing on measures that achieve the desired reduction at least cost) and socially efficient (i.e. reducing emissions up to the point at which the costs of mitigation are equal to the social benefits of reducing the emissions). Marginal abatement cost curves, or “MACCs”, provide a way of analysing the cost-effectiveness of potential mitigation measures, and have been widely used in the development of mitigation policy for agriculture (MacLeod *et al.*, 2015). A MACC shows the cost of reducing pollution by one additional unit (expressed in CO_2 equivalent) and can be plotted against a curve showing the marginal benefit of reducing pollution to enable the identification the optimal level of pollution abatement (Figure 10). In GHG mitigation studies, the MACCs derived from modelling are often smooth curves, while those based on bottom-up cost engineering approaches are more often represented as a series of discrete bars, each of which represents a mitigation measure (Figure 11). The width of each bar represents the reduction in GHG emissions, while the height of the bar shows the cost-effectiveness of the measure. The area under each bar is equal to the total cost of the measure.

The marginal cost of abatement can be calculated in various ways. Vermont and De Cara (2010) divide MACCs into three main types based on the methodology used to derive the curves: (i) bottom up cost-engineering; (ii) micro-economic modelling, with exogenous prices; (iii) regional/sectoral supply-side equilibrium models. An example of the bottom-up approach to cost effectiveness analysis is provided below.

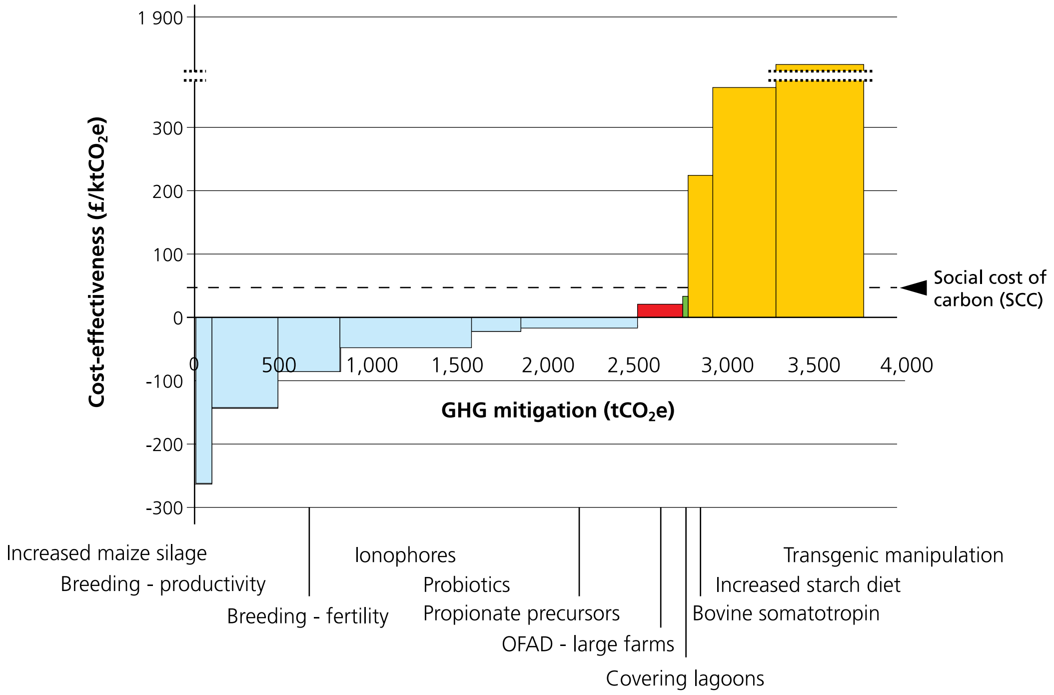
FIGURE 10
Marginal abatement costs and benefits



Notes: For a given measure, optimal pollution abatement occurs where the marginal cost of abatement equals the marginal benefit, i.e. where the two curves cross.

Source: Pearce and Turner (1990).

FIGURE 11
Example of a marginal abatement cost curve (MACC) for United Kingdom dairy mitigation measures and the marginal benefit of mitigation, the social cost of carbon[2]



Sources: MacLeod *et al.* (2015).

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[2] The social cost of carbon, "a measure, in dollars, of the long-term damage done by a tonne of carbon dioxide (CO_2) emissions in a given year. This dollar figure also represents the value of damages avoided for a small emission reduction" (USEPA, 2017).

Example: A bottom-up approach analysing the cost-effectiveness of three mitigation measures on tilapia farms in Bangladesh

Analysing the cost-effectiveness of mitigation measures can be broken down into five main steps:

1. Identification and selection of mitigation measures;
2. Review the potential effects of the measures;
3. Calculation of the emissions and farm profit for a farm (or farms) under baseline conditions;
4. Calculation of the emissions and farm profit for a farm (or farms) with each measure; and
5. Based on 3 and 4, calculation of the change in emissions and profits arising from each measure and calculation of the cost-effectiveness (CE) of each measure.

Step 1. Identification and selection of mitigation measures

The selection of measures is an important and often time-consuming process. It involves reviewing the evidence to generate a long list of measures then applying selection criteria to identify a short list of measures for quantitative analysis. Depending on the specific situation selection criteria may include:

Does the measure work in theory?

- What effect does the measure have on emissions and production?
- How does its effect vary (e.g. between countries, water conditions, farm types)?
- What is the certainty of the effect?
- What might the unintended consequences be?

How much could the measure reduce emissions in practice?

- What are the measures of applicability, e.g. what percent of production could it be implemented on?
- What are the barriers to uptake?
- How amenable is it to different policies approaches? (i.e. could incentives be provided and compliance monitored?)

In this example, we have picked one measure from three different approaches to illustrate the method: (1) breeding for improved FCR, (2) vaccination for streptococcosis and (3) adding phytase to the ration.

Step 2. Review the potential effects of the measures

Measure 1. Breeding for improved FCR

Breeding programmes can be used to improve the physical performance of fish, but it has been argued that "aquaculture generally lags far behind plant and terrestrial farm animals with respect to uptake of this technology". Gjedrem *et al.* (2012). Ponzoni *et al.* (2007) and Omasaki *et al.* (2017) found that breeding tilapia for improved FCR leads to increases in gross margin. When selecting for one trait (in this case lower FCR), one has to avoid negative impacts on other desirable traits. Thoa *et al.* (2016) found that it was possible to reduce FCR while selecting for increase body size in tilapia and Gjedrem *et al.* (2012) noted favourable correlations between growth rate and FCR in finfish in general. The assumptions used to estimate the change in emissions and profit are summarised in Table 11.

TABLE 11

Assumed change in parameters from moving from wild to improved varieties

Parameter	Change	Source of information
FCR	-15%	Gjedrem *et al.* (2012) report a -20% change in FCR in Atlantic salmon over five generations of selection
Cost of purchasing fingerlings	+80%	Ansah *et al.* (2014) report an 150% increase in the price of improved tilapia fingerlings in the Philippines

Source: this study.

Measure 2. Vaccination for streptococcosis

Streptococcosis is one of the major bacterial diseases of tilapia, resulting in high mortality and huge economic losses (Liu et al 2016). Vaccines exist for the disease and Aguirre (2007) reported the reduction in mortality resulting from a two-step vaccination protocol using AQUAVAC™ GARVETIL™ vaccine. The assumptions used to estimate the change in emissions and profit are summarised in Table 12.

TABLE 12

Assumed change in parameters from moving from a two-step vaccination

Parameter	Change	Source of information and assumption
Mortality rate	-50%	Based on Aguirre (2007)
Treatment cost	Large farm: USD450 Small farm: USD150	Assumption Assumption

Source: this study.

Measure 3. Adding phytase to the ration

Phytate is an indigestible form of phosphorus that has a low bioavailability for tilapia (NRC, 2011) due to absence of an intestinal phytase. In addition, phytate is capable of binding to positively charged proteins, amino acids and minerals in plants (Afinah *et al.*, 2010) thus reducing the bioavailability of nutrients (Adeoye *et al.*, 2016). It is common in plant raw materials, particularly soybean and rice bran. In theory supplementing tilapia rations with phytase should therefore improve nutrient utilisation and reduce FCR. The assumptions used to estimate the change in emissions and profit are summarised in Table 13.

TABLE 13

Assumed change in parameters from supplementing the ration with phytase

Parameter	Change	Assumption
Effect on FCR	-10%	Based on Adeoye et al. (2016), who reported a 19% reduction in FCR
Increase in feed unit price	Large farm: USD14.6/tonne Small farm: USD9.8/tonne	Assuming a 2% increase in feed price

Source: this study.

Steps 3 and 4. Calculation of the emissions and farm profit for a farm under baseline conditions and with each measure implemented

Two farm types typical of those in Bangladesh were modelled: (a) a large commercial farm producing 13.5 tonnes live weight of tilapia each year (Table 14, scenario 1) and (b) a smaller farm producing 2.6 tonnes of live weight (Table 14, scenario 2), with only one crop per year from both systems. The smaller farms are household ponds distributed widely across Bangladesh and account for a large proportion of national tilapia production. The large farm is a more commercially oriented and based on semi-intensive culture method with higher stocking density and regular use of extruded feed.

In order to quantify the farm profit, a financial model was developed and data on rates of input use, farm performance (i.e. fish FCR and mortality) and prices of inputs and outputs gathered via a survey of tilapia produces in Bangladesh (2017 Field Survey). This was used to calculate the gross margin (revenue minus variable costs) for the farms in the baseline scenario (no mitigation measures) and with each of the mitigation measures implemented. Table 14 shows the results for each scenario; parameters changed to reflect the effect of each measure are shown in white on a blue background, secondary changes are shown as blue on a white background. Table 14 also reports the total GHG emissions arising each year. These are calculated using the approach outlined in Part 1 of this report. The results of the model are highly dependent on the assumptions made, but give an indication of the strength of the leverage various factors have on overall EI.

TABLE 14

Income, variable costs, gross margin and total GHG emissions each year for the large and small tilapia farm under baseline conditions (scenario 1 and 2) and with each mitigation measure (scenario 3-8)

Scenario number:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Large farm	**Small farm**	**Large: phytase**	**Small: phytase**	**Large: vaccine**	**Small: vaccine**	**Large: breeding**	**Small: breeding**
Production								
Fingerlings mass at input (kg)	600	6	600	6	600	6	600	6
No of fingerlings	60 000	19 200	60 000	19 200	60 000	19 200	60 000	19 200
Fingerling mass at input (kg)	0.01	0.0003	0.01	0.0003	0.01	0.0003	0.01	0.0003
Grow out period (days)	110	120	110	120	110	120	110	120
FCR: individual (bFCR)	1.32	1.42	1.19	1.28	1.32	1.42	1.12	1.21
Average survival (%)	90	80	90	80	95	90	90	80
Average LW of mortalities (kg)	0.14	0.09	0.14	0.09	0.14	0.09	0.14	0.09
LW of mortalities (kg)	810	328	810	328	405	164	810	328
% of LWG harvested	94	89	94	89	97	95	94	89
FCR: farm (eFCR)	1.40	1.60	1.26	1.44	1.36	1.50	1.19	1.36
Individual fish mass at harvest (kg)	0.25	0.17	0.25	0.17	0.25	0.17	0.25	0.17
No of fish harvested	54 000	15 360	54 000	15 360	57 000	17 280	54 000	15 360
Mass of fish harvested (kg)	13 500	2 611	135 00	2 611	14 250	2 938	13 500	2 611
Annual fish production (kgLW)	13 500	2 611	13 500	2 611	14 250	2 938	13 500	2 611
Revenue								
Unit price (USD/kg tilapia LW)	1.33	1.02	1.33	1.02	1.33	1.02	1.33	1.02
Income (USD/year)	17 955	2 663	17 955	2 663	18 953	2 996	17 955	2 663

TABLE 14 *(continued)*

Scenario number:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Large farm	**Small farm**	**Large: phytase**	**Small: phytase**	**Large: vaccine**	**Small: vaccine**	**Large: breeding**	**Small: breeding**
Variable costs								
Feed amount (kg/year)	18 900	4 178	17 010	3 760	19 356	4 409	16 065	3 551
Unit cost (USD/kg)	0.73	0.49	0.74	0.50	0.73	0.49	0.73	0.49
Annual cost (USD)	13 797	2 047	12 666	1 879	14 130	2 160	11 727	1 740
Fingerling input (kg/year)	600	6	600	6	600	6	600	6
Fingerling unit cost (USD/kg)	3.6	18.1	3.6	18.1	3.6	18.1	6.5	32.5
Annual cost (USD)	2 172	115	2 172	115	2 172	115	3 910	206
Diesel (l)	0	60	0	60	0	60	0	60
Unit cost (USD)	0	0.78	0	0.78	0	0.78	0	0.78
Annual cost (USD)	0	47	0	47	0	47	0	47
Electricity (kWh)	500	0	500	0	500	0	500	0
Unit cost (USD)	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00
Annual cost (USD)	48	0	48	0	48	0	48	0
Urea (kg)	55	33	55	33	55	33	55	33
Unit cost (USD)	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Annual cost (USD)	13	8	13	8	13	8	13	8
TSP (kg)	27	15	27	15	27	15	27	15
Unit cost (USD)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Annual cost (USD)	11.34	6.3	11.34	6.3	11.34	6.3	11.34	6.3
Other chemicals (USD)	60	28	60	28	60	28	60	28
Other chemicals (USD)	0	0	0	0	450	150	0	0
Total variable costs (USD)	**16 102**	**2 251**	**14 970**	**2 083**	**16 884**	**2 514**	**15 770**	**2 035**
Gross margin (USD)	**1 853**	**413**	**2 985**	**581**	**2 068**	**482**	**2 185**	**628**
Total GHG (kgCO$_2$e)	**44 885**	**8 735**	**41 862**	**8 132**	**45 886**	**9 196**	**40 350**	**7 831**

Source: 2017 Field Survey.

Step 5. Calculation of the change in emission and profit arising from each measure and calculation of the cost-effectiveness (CE) of each measure

The gross margin and emissions for each "with measure" scenario (3 – 8) were adjusted so that they were the gross margin and emissions that would arise if the "with measure" scenario was producing the same output as the baseline scenario. The change in gross margin and emissions were then calculated by subtracting the results for the baseline scenario from the with emissions scenario. The cost-effectiveness was then calculated by dividing the change in gross margin by the abatement potential (the change in emissions, Table 15). The abatement potential and cost-effectiveness were then used to derive a simple MACC for each system (Figures 12–13).

TABLE 15

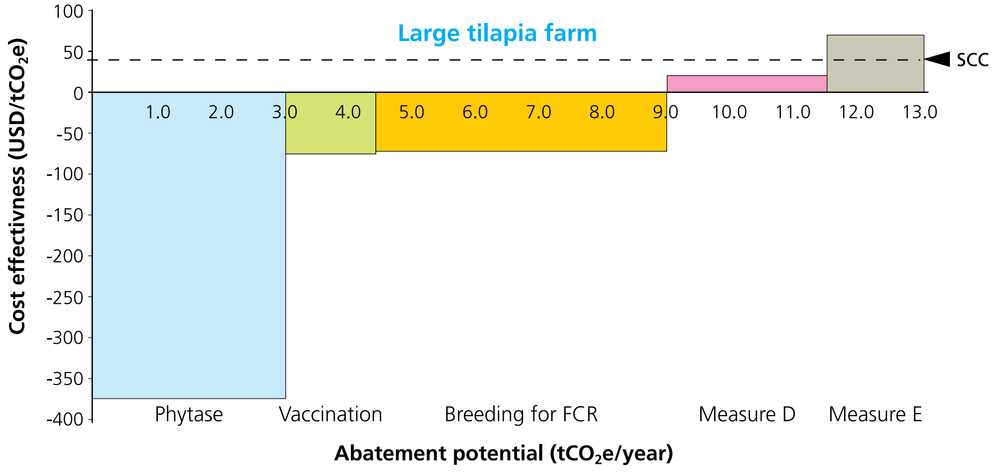
Abatement potential and cost-effectiveness of the mitigation measures

	Emissions intensity ($kgCO_2e/kgLW$)	Abatement potential (AP) (tCO_2e)	Change in gross margin (USD)	Cost-effectiveness (USD/tCO_2e)
Large farm, baseline	3.32			
Large farm, phytase	3.10	-3.0	1131	-374
Large farm, vaccine	3.22	-1.4	106	-75
Large farm, breeding	2.99	-4.5	332	-73
Small farm, baseline	3.35			
Small farm, phytase	3.11	-0.6	168	-279
Small farm, vaccine	3.13	-0.6	16	-29
Small farm, breeding	3.00	-0.9	215	-238

Source: calculated in this study.

FIGURE 12

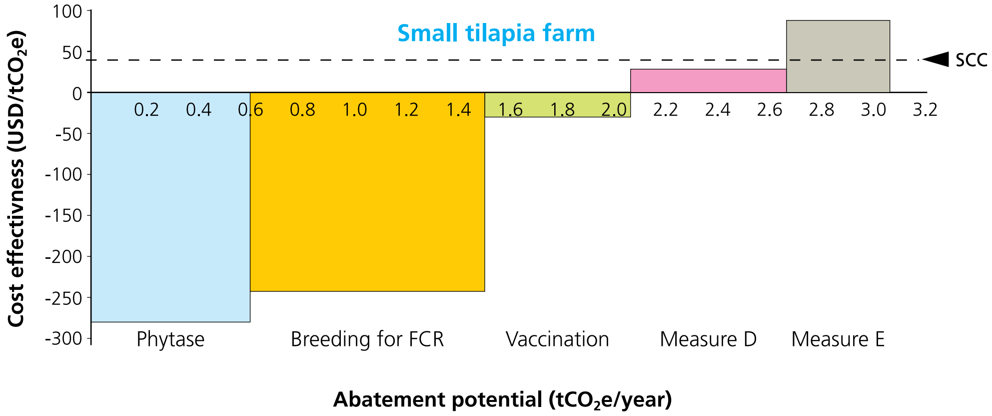
Simplified marginal abatement cost curve for five mitigation measures implemented in a large tilapia farm in Asia



Notes: Measures D and E are generic measures inserted to illustrate the typical MACC structure; SCC: social cost of carbon (USEPA, 2017).

Source: calculated in this study.

FIGURE 13
Simplified marginal abatement cost curve for five mitigation measures implemented in a small tilapia farm in Asia



Notes: Measures D and E are generic measures inserted to illustrate the typical MACC structure. SCC: social cost of carbon (USEPA, 2017).

Source: calculated in this study.

3.3 INTERPRETING THE MACCS

Figures 12 and 13 indicate that significant reductions in emissions could be achieved for each of the measures. Implementing the “win-win” measures (i.e. those with negative costs) could lead to a reduction of 9.0 tCO$_2$e on the large farm (a reduction of 20 percent) and 2.1 tCO$_2$e on the small farm (24 percent). However, this assumes that the AP from each measure is additive. In practice, implementing one measure may reduce the AP (and increase the CE) of another measure. In extreme cases, measures may be mutually exclusive. In our example, there are two measures that reduce FCR (phytase and breeding) and it is unlikely that the reductions in FCR are additive.

Measures can be divided into three categories, based on their CE.

CE < 0$/tCO$_2$e

Measures with negative CE, which lie below the x-axis and reduce emissions while increasing profitability (“win-win” measures). In theory these should be adopted readily by farmers, but in practice these may be more expensive in practice than the studies suggest. Some significant costs, such as the transaction and learning costs of adopting measures, are difficult to quantify and therefore frequently omitted from the calculations of cost-effectiveness. Farmers’ risk aversion may also discourage them from adopting specific practices. Alternatively, it has been suggested that farmers do not necessarily adopt win-win measures because they do not act in rational profit maximising ways. Instead, their decision-making is influenced by internal factors (e.g. cognition, habit and attitudes to risk), social factors (e.g. norms and roles), the policy environment, and other farm business constraints (Pike, 2008). Moran *et al.* (2013) have gone so far as to suggest that approaches “informed by psychological and evolutionary insights, should supersede a generic win–win narrative that is a politically convenient, yet overly simplistic and potentially counterproductive, basis for mitigation policy.”

$SCC < CE > 0\$/tCO_2e$

Measures such as D, whose CE is positive but lower than the SCC, i.e. measures that cost money to implement, but which provides benefits to society that are greater than the costs. Uptake of these measures should provide a net benefit to society, but in an unregulated market, there will be chronic under-investment in them. It may be possible to develop policies to correct these market failures by, for example, providing incentives to adopt measures, although verifying adoption can be challenging for some types of measures.

$CE > SCC$

Measures such as E, whose CE is greater than the SCC. These are unlikely to provide a net benefit to society and should not be adopted.

When interpreting the MACCs, it is important to remember they have limitations. Firstly, they present the AP and CE on a typical or average farm. In reality, the AP and CE can vary both spatially and temporally for a particular farm type, depending on factors such as feed and fish prices. Secondly, they tend not to indicate the accuracy of the results, which is important given the potentially large error margins. The results can be highly sensitive to variation in certain parameters (such as FCR or feed costs), and therefore to the assumptions made about how mitigation measures will impact on these parameters. Because of this, CEA results should be seen as guidelines rather than prescriptions applicable to individual farms or individual years. Finally, our example (and in fact most CEA) only examines one dimension of the measures, in this case GHG emissions. However, some of the measures to reduce GHG emissions could have significant (positive or negative) ancillary effects (e.g. on the environment, animal welfare or human health) that should be factored into decision-making. For example, vaccination for streptococcosis is likely to improve animal welfare and lead to reductions in antibiotic use.

4. Conclusions

Aquaculture is a biologically efficient way of producing animal protein compared to terrestrial livestock (particularly cattle, sheep and goats) due largely to the high fertility and low feed conversion ratios of fish. The biological efficiency is reflected in the relatively low prices and emissions intensities of many aquaculture commodities. However, the low GHG emissions from aquaculture should not be grounds for complacency. Aquaculture production is increasing rapidly, and emissions arising post-farm, which are not included in this study, could increase the emissions intensity of some supply chains significantly. Furthermore, aquaculture can have important non-GHG impacts on, for example, water quality and marine biodiversity. It is therefore important to continue to improve the efficiency of global aquaculture to offset increases in production so that it can continue to make an important contribution to food security. Fortunately, the relatively immature nature of the sector (compared to agriculture) means that there is great scope to improve resource efficiency through technical innovation, often in ways that reduce emissions while improving profitability. CEA can be used to help identify the most cost-effective efficiency improvements, thereby supporting the sustainable development of aquaculture.

References

Adeoye, A.A., Jaramillo-Torres, A., Fox, S.W., Merrifield, D.L. & Davies, S.J. 2016. Supplementation of formulated diets for tilapia (*Oreochromis niloticus*) with selected exogenous enzymes: Overall performance and effects on intestinal histology and microbiota. *Animal Feed Science and Technology*, 215: 133–143.

AFFRIS. 2017. *Aquaculture Feed and Fertilizer Resources Information System*. Rome, FAO. (available at www.fao.org/fishery/affris/en/).

Afinah, S., Yazid, A.M., Anis Shobirin, M.H. and Shuhaimi, M. 2010. Phytase: application in food industry. *International Food Research Journal,* 17: 13–21.

Aguirre, M. 2007. AQUAVAC™ GARVETIL™ vaccine safely reduces streptococcosis mortality in tilapia. In *New Advances for Warmwater Aquaculture*. San Antonio, Texas (available at http://www.prworks.net/Clients/SAP/aquavac_garvetil.html).

Ansah, Y.B., Frimpong, E.A. & Hallerman, E.M. 2014. Review: Genetically-improved tilapia strains in Africa: Potential benefits and negative impacts. *Sustainability,* 6: 3697–3721; doi:10.3390/su6063697 (available at www.mdpi.com/journal/sustainability)

Ayer, N.W. & Tyedmers, P.H. 2008. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner Production,* 17(3): 362–373.

BEIS (Department for Business Energy & Industrial Strategy). 2016. *Government GHG conversion factors for company reporting: Methodology paper for emission factors*. London, UK Department of Business, Energy & Industrial Strategy. 112 pp. (available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/553488/2016_methodology_paper_Final_V01-00.pdf).

Bjorndal, T & Fernandez-Polanco, J. 2014. *Turbot aquaculture: production and markets.* http://www.aquacultuurvlaanderen.be/sites/aquacultuurvlaanderen.be/files/public/attachments/article/871/Turbot%20aquaculture%20production%20and%20market.pdf.

Bosma, R., Thi Anh, P. & 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: 903–915.

Boyd, C.E., Wood, C.W., Chaney, P.L. & Queiroz, J.F. 2010. Role of aquaculture pond sediments in sequestration of annual global carbon emissions. *Environmental Pollution*, 158 (8): 2537–2540.

Cao, L. 2012. *Farming shrimp for the future: A sustainability analysis of shrimp farming in China*. PhD Thesis, University of Michigan. 160 pp.

EWOS. 2013. *Annual sustainability report*. http://www.reporting.ewos.com/sustainability-reports/gri-report-2013/performance/?id=ew-i09

FAO. 2016a. *FishStatJ - software for fishery statistical time series* (available at www.fao.org/fishery/statistics/software/fishstatj/en).

FAO. 2016b. *Cultured aquatic species information program. Hypophthalmichthys nobilis (Richardson, 1845).* (available at www.fao.org/fishery/culturedspecies/Hypophthalmichthys_nobilis/en).

FAO. 2016c. *Aquaculture feed and fertilizer resources information system. Common carp feed formulation.* (available at www.fao.org/fishery/affris/species-profiles/common-carp/feed-formulation/en/.

FAO. 2016d. *Cultured aquatic species information programme. Ctenopharyngodon idellus.* (available at www.fao.org/fishery/culturedspecies/Ctenopharyngodon_idellus/en).

FAO. 2016e. *Aquaculture feed and fertilizer resources information system. Silver carp feed formulation.* (available at www.fao.org/fishery/affris/species-profiles/silver-carp/feed-formulation/en/).

FAO. 2016f. *Aquaculture feed and fertilizer resources information system. North African catfish feed formulation and manufacture.* (available at www.fao.org/fishery/affris/species-profiles/north-african-catfish/feed-formulation-and-manufacture/en/.

FAO. 2017a. *World aquaculture 2015: a brief overview*. FAO Fisheries and Aquaculture Circular No. 1140. Rome. 34 pp.

FAO. 2017b. *Global Livestock Environmental Assessment Model (GLEAM).* Rome, FAO. 109 pp. (available at www.fao.org/gleam/en/).

FAO. 2017c. FAOSTAT Food Balance Sheets. (available at www.fao.org/faostat/en/#data/FBS).

FAO. 2019. *FishStatJ, Vers. 3.01.0*. Rome, FAO. (available at www.fao.org/fishery/statistics/software/fishstatj/en).

Feedprint. 2017. *Feedprint Carbon Footprint of Animal Nutrition.* (available at http://webapplicaties.wur.nl/software/feedprint/ Wageningen).

Fry, J.M. 2012. *Carbon footprint of Scottish suspended mussels and intertidal oysters*. Pitlochry, Scotland: Scottish Aquaculture Research Forum (SARF). 56 pp.

Gentry, R.R., Froehlich, H.E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S.D. & Halpern, B.S. 2017. Mapping the global potential for marine aquaculture. *Nature Ecology & Evolution,* 1 (9): 1317–1324. doi:10.1038/s41559-017-0257-9.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Rome, FAO. 115 pp.

Gjedrem, T., Robinson, N. & Rye, M. 2012. The importance of selective breeding in aquaculture to meet future demands for animal protein: A review. *Aquaculture*, 350: 117–129.

Hasan, M.R. & Soto, S. 2017. *Improving feed conversion ratio and its impact on reducing greenhouse gas emissions in aquaculture.* FAO Non-Serial Publication. Rome, FAO. 33 pp. (available at http://www.fao.org/3/a-i7688e.pdf).

Henriksson, P.J.G., Zhang, W., Nahid, S.A.A., Newton, R., Phan, L.T., Dao, H.M., Zhang, Z., Jaithiang, J., Andong, R., Chaimanuskul, K., Vo, N.S., Hua, H.V., Haque, M.M., Das, R., Kruijssen, F., Satapornvanit, K., Nguyen, P.T., Liu, Q., Liu, L., Wahab, M.A., Murray, F.J., Little, D.C. & Guinée, J.B. 2014a. *Final LCA case study report—results of LCA studies of Asian aquaculture systems for tilapia, catfish, shrimp, and freshwater prawn.* SEAT Deliverable Ref: D 3.5.

Henriksson, P.J.G., Zhang, W., Nahid, S.A.A., Newton, R., Phan, L.T., Dao, H.M., Zhang, Z., Jaithiang, J., Andong, R., Chaimanuskul, K., Vo, N.S., Hua, H.V., Haque, M.M., Das, R., Kruijssen, F., Satapornvanit, K., Nguyen, P.T., Liu, Q., Liu, L., Wahab, M.A., Murray, F.J., Little, D.C. & Guinée, J.B. 2014b. *Final LCA case study report. Primary data and literature sources adopted in the SEAT LCA studies*. SEAT Deliverable Ref: D 3.5. Annex report. Stirling, United Kingdom, SEAT Project. 121 pp. (available at http://media.leidenuniv.nl/legacy/d35-annexreport.pdf).

Hornborg, S. & Ziegler, F. 2014. *Aquaculture and energy use: a desk-top study*. Gothenburg, University of Gothenburg. 19 pp. https://swemarc.gu.se/digitalAssets/1536/1536133_publication---energy-use-in-aquaculture.pdf

Hu, Z., Lee, J.W., Chandran, K., Kim, S. & Khanal, S.K. 2012. Nitrous oxide (N_2O) emission from aquaculture: A Review. *Environmental Science and Technology*, 46 (12): 6470–6480. DOI: 10.1021/es300110x

IPCC. 2014. Summary for Policymakers, *In Climate Change 2014, Mitigation of Climate Change.* Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge, Cambridge University Press. 30 pp.

Kool, A., Marinussen, M. & Blonk, H. 2012. *LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: GHG Emissions of N, P and K fertilizer production.* Gouda, the Netherlands, Blonk Consultants. 15 pp.

Liu, G., Zhu, J., Chen, K., Yao, H., Liu, Y., Zhang, W. and Lu, C. (2016). Development of Streptococcus agalactiae vaccines for tilapia. Diseases of Aquatic Organisms. 122. 10.3354/dao03084

MacLeod, M., Gerber, P., Mottet, A., Tempio, G., Falcucci, A., Opio, C., Vellinga, C., Henderson, B. & Steinfeld, H. 2013 Greenhouse gas emissions from pig and chicken supply chains – A global life cycle assessment. Rome, FAO.

MacLeod, M., Eory, V., Gruere, G. and Lankoski, J. 2015. *Cost-Effectiveness of Greenhouse gas mitigation measures for agriculture: A literature review*. OECD Food, Agriculture and Fisheries Papers, No. 89. Paris, OECD Publishing. 73 pp.

Marine Harvest. 2015. *Salmon industry handbook*. (available at http://marineharvest.com/about/news-and-media/news/marine-harvest-asa-osemhg-nysemhg--2015-salmon-industry-handbook/).

Moran, D., Lucas, A. & Barnes, A. 2013. Mitigation win–win. *Nature Climate Change*, 3 (7): 611–13.

Myolonas, C.C., de la Gandara, F., Corriero, A., and Rios, A.B. 2010. Atlantic bluefin tuna (Thunnus thynnus) farming and fattening in the Mediterranean Sea. *Reviews in Fisheries Science*, 18(3): 266 –281

Myrseth, B. 2014. Strategy for the production and marketing of salmon and a comparison with the seabass and seabream industry. *In* Performance of the sea bass and sea bream sector in the Mediterranean. Minutes of a workshop held within Aquaculture Europe 2014. Kursaal, Spain. 24 pp.

Omasaki, S.K., Janssen, K., Besson, M. & Komen, H. 2017. Economic values of growth rate, feed intake, feed conversion ratio, mortality and uniformity for Nile tilapia. *Aquaculture*, 481: 124–132

Opio, C., Gerber, P., Vellinga, T., MacLeod, M., Falcucci, A., Henderson, B., Mottet, A., Tempio, G. & Steinfeld, H. 2013. Greenhouse Gas Emissions from Ruminant Supply Chains – A Global Life Cycle Assessment. Rome, FAO. 191 pp.

Ottolenghi, F. 2008. Capture-based aquaculture of bluefin tuna. *In* A. Lovatelli & P.F. Holthus, eds. *Capture-based aquaculture. Global overview,* pp. 169–182. FAO Fisheries Technical Paper. No. 508. Rome, FAO. 298 pp.

Paterson, B. & Miller, S. 2014. Examining energy use in shrimp farming. *Global Aquaculture Advocate*, November 2014: 30–32.

Pearce, D.W. & Turner, R.K. 1990. *Economics of natural resources and the environment*. London, Harvester Wheatsheaf. 378 pp.

Pelletier, N. & Tyedmers, P. 2010. A life cycle assessment of frozen Indonesian tilapia fillets from lake and pond-based production systems. *Journal of Industrial Ecology,* 14(3): 467–481

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B. & Silverman, H. 2009. Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems. *Environmental Science & Technology,* 43 (23): 8730–8736

Pike, T. 2008. Understanding Behaviours in a Farming Context: Bringing theoretical and applied evidence together from across Defra and highlighting policy relevance and implications for future research. London, Defra Agricultural Change and Environment Observatory Discussion Paper, Defra. 29 pp. (available at https://statistics.defra.gov.uk/esg/ace/research/).

Ponzoni, R.W., Nguyen, N.H. & Khaw, H.L. 2007. Investment appraisal of genetic improvement programs in Nile tilapia (*Oreochromis niloticus*). *Aquaculture*, 269: 187–199.

Pyc, A. 2012. Expert topic - trout. *International Aquafeed*, May 16, 2012. (available at https://iaffeatures.wordpress.com/2012/05/16/expert-topic-trout/)

Robb, D.H.F, MacLeod, M., Hasan, M.R. & Soto, D. 2017. *Greenhouse gas emissions from aquaculture: a life cycle assessment of three Asian systems.* FAO Fisheries and Aquaculture Technical Paper No. 609. Rome, FAO. 110 pp.

Robinson, E.H. & Li, M.H. 2015. Feed conversion ratio for pond-raised catfish. Information sheet 1364, Mississippi Agricultural and Forestry Experiment Station, Mississippi State University, USA. 5 p.

Skretting Australia. 2013. Annual Sustainability Report. (available at https://www.skretting.com/siteassets/au-temp-files/nexus-and-reports-and-brochures/2013-austsust-report_web.pdf).

Sun, W. 2009. *Life cycle assessment of indoor recirculating shrimp aquaculture system.* MSc Thesis University of Michigan. 52 pp.

Tacon, A.G.J., & Metian, M. 2008. Global overview on the use of fishmeal and fish oil in industrially compounded aquafeeds: trends and future prospects. *Aquaculture*, 285: 146–158.

Tacon, A.G.J., Metian, M. & Hasan, M.R. 2009. *Feed ingredients and fertilizers for farmed aquatic animals: sources and composition.* FAO Fisheries and Aquaculture Technical Paper. No. 540. Rome, FAO. 209 pp. (also available at www.fao.org/docrep/012/i1142e/i1142e.pdf).

Tacon, A.J.G. & Metian, M. 2015. Feed matters: satisfying the feed demand of aquaculture. *Reviews in Fisheries Science & Aquaculture*, 23 (1): 1–10, DOI: 10.1080/23308249.2014.987209

Thoa N.P., Ninh N.H., Knibb W. & Nguyen N.H. 2016. Does selection in a challenging environment produce Nile tilapia genotypes that can thrive in a range of production systems? *Sci. Rep.* 6: 21486. doi: 10.1038/srep21486.

USEPA (United States Environmental Protection Agency). 2017. The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions (available at https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html).

Verdegem, M.C.J. & Bosma, R.H. 2009. Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. Water Policy, 11(S1): 52–68.

Waite, R., Beveridge, M., Brummett, R., Castine, S., Chaiyawannakarn, N., Kaushik, S., Mungkung, R. Nawapakpilai, S. & Phillips, M. 2014. Improving Productivity and Environmental Performance of Aquaculture. Working Paper, Instalment 5 of "Creating a Sustainable Food Future". Washington, DC, World Resources Institute. 59 pp.

Walker, S.P., Symonds, J.E., Bailey, J., Dodds, K.G., Hely, F., & Amer, P. 2014. Measurement and genetics of feed conversion efficiency in three fish species. World Aquaculture 2014 Meeting Abstract. (available at https://www.was.org/meetings/ShowAbstract.aspx?Id=33217).

White, A. 2013. A comprehensive analysis of efficiency in the Tasmanian Salmon industry. PhD thesis, Bond University, Australia. 301 pp.

Winther, U., Ziegler, F., Hognes, E.S., Emanuelsson, A., Sund, V. & Ellingsen, H. 2009. Carbon footprint and energy use of Norwegian seafood products. Trondheim, SINTEF Fisheries and Aquaculture. Report No. SFH80 A096068. 89 pp.

Aquaculture of aquatic animals accounted for approximately 0.45 percent of global anthropogenic GHG emissions in 2013, which is similar in magnitude to the emissions from global sheep production. The low emissions reflect the high productivity of aquaculture compared to terrestrial livestock, in particular the higher fertility and lower feed conversion ratios. It also reflects the absence of enteric methane, which is an important source of emissions from ruminants. However, aquaculture is growing rapidly and improving the efficiency of aquaculture production remains an important way of offsetting the additional emissions that would otherwise arise from this growth. Fortunately, the relatively immature nature of the sector means that there is great scope to improve resource efficiency through technical innovation. Cost-effectiveness analysis (CEA) can be used to help identify the most cost-effective efficiency improvements. This report explains CEA and provides an example illustrating how it could be applied to tilapia production.

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