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Exploratory analysis of resource demand and the environmental footprint of future aquaculture development using Life Cycle Assessment

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Authors

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ABSTRACT

Increases in fish demand in the coming decades are projected to be largely met by growth of aquaculture. However, increased aquaculture production is linked to higher demand for natural resources and energy as well as emissions to the environment. This paper explores the use of Life Cycle Assessment to improve knowledge of potential environmental impacts of future aquaculture growth. Different scenarios of future aquaculture development are taken into account in calculating the life cycle environmental impacts. The environmental impact assessments were built on Food and Agriculture Organization statistics in terms of production volume of different species, whereas the inputs and outputs associated with aquaculture production systems were sourced from the literature. The matrix of input-output databases was established through the Blue Frontiers study (available online: www.worldfishcenter.org/sites/default/files/report.pdf).

Keywords: aquaculture, scenarios, life cycle analysis, environmental impacts.

This is a discussion draft. The final version will be published online at www.worldfishcenter.org

Introduction

Increases in fish demand in the coming decades are projected to be met by growth of supply from aquaculture. Driven by population growth, and increasing wealth as well as urbanization (Hall et al., 2011), fish consumption is expected to rise, and aquaculture production will grow substantially in the future to meet demand (World Bank, 2013). This growth has the potential to provide important food security and employment benefits, particularly in developing countries, but also risks increasing demand for ecosystem services and causing increased environmental impacts. Such issues raise questions about identifying and implementing policies and practices that minimize impacts on the environment and enhance environmental sustainability.

Life Cycle Assessment (LCA) has been increasingly applied to determine the potential environmental impacts of aquaculture systems (Henriksson et al., 2012). Rooted in the life cycle approach, LCA is regarded by scientists and industry as a useful tool for assessing the maximum potential environmental impacts that could occur along the whole life cycle of product. WorldFish has used LCA for determining the environmental footprint of aquaculture at a sectoral level (Hall et al., 2011). Foreground and background data were gathered to establish a dataset of aquaculture technologies and associated inputs and outputs to aquaculture systems globally that could be used to assess environmental impacts. This paper builds on the Blue Frontiers database of aquaculture to explore the use of LCA to determine the future global environmental impacts of aquatic production systems under different scenarios of growth.

The intention is not to define absolute impacts of future aquaculture growth; rather the purpose of the paper is twofold: (i) to explore the application of LCA methodology for assessing potential environmental impacts over the life cycle of aquaculture production in the future, at a global level; and (ii) to better understand the influence of technology and management choices on environmental impacts and resource demands. This work also provides supporting data and analysis for the aquaculture installments of the 2013-14 World Resources Report: "Creating a Sustainable Food Future" (Waite et al., 2014).

Methods

Goal and scope definition

The study aimed to evaluate the potential environmental impacts of different scenarios of future aquaculture growth in 2050. Aquaculture production in 2010 was used as the baseline, with a projection of 140 million metric tons (Mt) of aquaculture production in 2050. Hall et al. (2011) summarize earlier projections of future aquaculture production based on models that use various assumptions and approaches to forecast wild fisheries and aquaculture production as far into the future as 2030, using estimates of fish supply and demand, fish prices, population growth, and per capita fish consumption. Hall et al. (2011) estimate that aquaculture production will grow from 60 Mt in 2010 to between 65 Mt and 85 Mt by 2020, and between 79 Mt and 110 Mt by 2030. Similar estimates are made in World Bank (2013). Growth from 60 Mt in 2010 to roughly 100 Mt in 2030 implies a linear path rising at 2 Mt per year. Extending this same 2-Mt-per-year growth rate between 2030 and 2050 for the purpose of this paper, we arrive at an estimated production of 140 Mt in 2050. The baseline in 2010 of 60 Mt was derived from FAO aquaculture statistics for 2010 (FAO, 2013). Seaweeds are excluded from both the 2010 baseline and projections of aquaculture production to 2050.

The scope of analysis was from cradle to farm gate, by covering crop production (i.e., feed ingredients), feed production and farming practices. The product unit was set as per metric ton of aquatic animals (wet weight at the farm gate). The impact categories of interest were: climate change, terrestrial acidification, freshwater eutrophication, marine eutrophication, agricultural land occupation, water use, biotic depletion (e.g. the depletion of wild fish stocks used for feed) and cumulative energy demand. It should be noted here that water use, biotic depletion, and cumulative energy demand were the outcome from an inventory data analysis which is a phase of life cycle assessment involving the compilation and quantification of inputs and outputs.

Characterization of aquaculture technologies and inventory analysis

Aquaculture technologies were characterized based on six characteristics (Table 1), following the farming system and feeding regime descriptions in Blue Frontiers (Hall et al., 2011: 17-18). The characterizations involve 75 production elements (Hall et al., 2011: 78-79) that describe aquaculture technologies or farming systems that together accounted for 82 percent of total world aquaculture production in 2008.

Country	Habitat	Species Group	Production System	Intensity	Feed Regime
Country of production	Coastal or inland (FAO brackish water and marine categories are combined into one coastal category)	12 animal species groups, plus seaweed; seaweed is excluded from the analysis	(4 categories) Ponds, cages and pens, bottom culture, and off-bottom culture	(3 categories) Intensive, semi-intensive and extensive	(5 categories) Natural feeds, trash fish, mash feeds, pellet feeds, extracted foods

Table 1. Aquaculture technology characterization.

For each production element, inventory data of crop production (i.e., feed ingredients), feed production and farming practices were included, and the following inputs and outputs associated with the aquaculture production systems were evaluated:

- Activity data at farm level.
- Land, water, chemicals and energy.
- Emissions to water, soil and air.

The following activities were excluded from the analysis, as their impacts were negligible or sufficient data were not available to warrant their inclusion:

- Capital goods.
- Seed production.
- Packaging production.
- Transport of feed to farm.
- Waste disposal.

Further explanation can be found in Hall et al. (2011).

Inventory data were derived from the Blue Frontiers report database (Hall et al., 2011) with the following revision:

- Feed ingredient data were partially updated with additional new information, where available, for the main species cultured.

Foreground (on-farm) data - i.e., inputs and outputs at the farm level - were gathered from literature review, and the collected data were validated based on WorldFish experiences and through expert consultation.

Background data on crop production, feeds production and electricity production were gathered from the site-specific data and supplemented by international databases (i.e., FAO) for aquaculture production volume, land use and the yield of crops used in the production of feeds.

Impact assessment methods

ReCiPe is a life cycle impact assessment methodology combining mid-point and endpoint (18 midpoint indicators and three endpoint indicators), which is the methodology recently developed in the Netherlands (Goedkoop et al., 2009). It builds on the Eco-indicator 99 and the Institute of Environmental Sciences (CML) Handbook on LCA. We focused on the following impact categories in the present study:

- **Climate change:** the characterization factor of climate change is the global warming potential. The unit is kilograms (kg) per year carbon dioxide (CO_2) equivalents.
- **Terrestrial acidification:** the characterization factor of terrestrial acidification potentials is expressed in sulfur dioxide (SO_2^-) equivalents, and is therefore area-independent.
- **Freshwater eutrophication:** the methodology to calculate eutrophication has been updated since Hall et al. (2011) was published. Hall et al. (2011) used software from the CML, which calculates freshwater and marine eutrophication collectively; ReCiPe calculates freshwater and marine eutrophication separately, and we've adopted this approach for the current report. The characterization factor of freshwater eutrophication accounts for the environmental persistence (fate) of the emission of nutrients containing phosphorus (P). The unit is kg per year P to freshwater equivalents.
- **Marine eutrophication:** the characterization factor of marine eutrophication accounts for the environmental persistence (fate) of the emission nutrients containing nitrogen (N). The unit is kg year per N to marine equivalents.
- **Agricultural land occupation:** this is the amount of agricultural land occupied for a certain time, which includes the pond-based or sea-based farm areas (i.e., direct land and water use), as well as the agricultural areas required for crop-based feed production (indirect land use). The unit is square meters (m^2) multiplied by the time of occupation in years. Direct and indirect land uses are calculated together, but the results are presented as direct and indirect land use and the units are converted from m^2 to million hectares for presentation in the figures.
- **Water use:** this is the total amount of water used for aquaculture production (both direct use in farming systems and indirect use such as water use for electricity production and crop production). This measure doesn't consider how much water is returned to natural systems after it has been used i.e., we are not quantifying "water consumption". The unit is cubic meters (m^3) but is converted to thousand GL for presentation in the figures.

- **Cumulative energy demand:** characterization factors are given for the energy resources divided into five impact categories: nonrenewable, fossil; nonrenewable, nuclear; renewable, biomass; renewable, wind, solar, geothermal; and renewable, water. The unit is gigajoules (GJ) and presented in million GJ in the results.
- **Biotic depletion:** the amount of wild fish required to support the aquaculture system. The unit is metric tons of wild fish.

Future aquaculture technology scenarios

Future scenarios were developed by a small group of experts and were later partly modified to reflect the practical realities of data availability and manipulation to ensure adequate input data for analysis. Environmental impacts and resource demand were calculated for each of the 75 aquaculture production elements and were modeled in six different scenarios out to 2050 based on several assumptions associated with each scenario.

Each scenario delivered new combinations of the 75 production elements and the environmental impact was modeled using LCA. Two baseline scenarios, and six future scenarios were modeled according to the following approach and assumptions.

The two baseline scenarios are as follows:

Baseline scenario – 2010 (current situation). This scenario involves the 75 combinations of aquaculture systems in 2010 using FAO 2010 production data. Seaweeds are excluded, and total aquaculture (aquatic animal) production is 60 Mt.

Baseline scenario – 2050 (business as usual). This scenario assumes no change in species, system or country mix of production in 2050. Seaweeds are excluded, and aquaculture production in 2050 is 140 Mt. We did not adjust for systems that were previously projected (in Blue Frontiers – Hall et al., 2011) to grow faster or slower than their current rate, because we have tried to keep the calculations and analysis as simple and transparent as possible. With five scenarios and 75 production combinations, there were too many dimensions to adjust the rate of growth in different sectors.

The six future scenarios for 2050 aquaculture are as follows:
Scenario 1: improved efficiency in input use. This scenario assumes an increase in efficiency of production technologies and farming practices. The assumptions are as follows:

- the same mix of 75 combinations of aquaculture technologies as in 2010, excluding seaweeds.
- Aquaculture (aquatic animal) production is 140 Mt.
- Advances in technology and management due to market forces and farmers improving efficiency lead to the same amount of fish produced with 10% less inputs. The inputs and outputs that were reduced by 10% were water, organic and inorganic fertilizers, electricity, feed, and nitrogen and phosphorus emissions to water. Direct land use was not adjusted based on the premise that farms won't reduce in size once established.

Scenario 2: significant intensification. This scenario assumes a significant intensification of pond farming. The proportion of production from intensive pond farms increases and the proportion from extensive and semi-intensive pond systems decreases in a proportional manner. This scenario focuses on pond systems because there is a substantial opportunity to intensify pond systems, especially in developing countries; e.g., in Bangladesh (Belton and Azad, 2012). The assumptions are as follows:

- estimated production volumes for 2050 (business as usual) for pond systems are modified whenever Blue Frontiers combinations contain semi-intensive/intensive or extensive/semi-intensive ponds (e.g., tilapia, China, inland, ponds).
- For pond systems, production volumes are calculated by halving the production volume coming from a less intensive system and the equivalent volume added to the next category of pond intensification.

- The proportion (volume of production) of intensive pond farms increases; that is 50 percent of extensive farms shift to semi-intensive and 50 percent of semi-intensive farms shift to intensive. This calculation was based on the baseline production volumes for 2010 (from FAOSTAT) and then we shifted 50 percent of the production volume from extensive to semi-intensive and 50 percent from semi-intensive to intensive. We recognize that this sharp shift in production is not realistic. However, it was not possible to model a gradual shift in production as we are only looking at one time point.

Scenario 3: shifting energy supply. This scenario explores the influence of changes in energy supply. The assumptions are as follows:

- Potential energy resources in 2050 are forecasted using the data on direction of energy policy in each country (Annex A).
- The 2050 energy mix is used to recalculate the environmental impacts.
- Species, system and country contribution to production follows 2008 Blue Frontiers categories.
- Total aquaculture production in 2050 is 140 Mt.

Scenario 4: adoption of best practice. This scenario explores how adoption of best practices might influence the future environmental impact of aquaculture. Best performers in terms of feed conversion ratio (FCR) were identified from Tacon and Metian (2008) and applied across the systems (country and system intensity) for the same species. FCR is seen as one of the key indicators of operational performance at farm level, as it plays an important role in contributing to the potential impacts due to the linkage between aquaculture feeding practices and demand on agricultural products, fishmeal and fish oil. High FCRs are also an indication of feed wastage or insufficient feed formulations and result in more pressure on land required to grow feed ingredients and biotic depletion due to the process of sourcing fishmeal and fish oil. The assumptions in this scenario are as follows:

- Analysis is based on the best performers (lowest FCR) in each intensification category for each species or commodity group, and then applied across all production systems for that species. The analysis is based on the assumption that all producers will apply the best practices and achieve FCRs as low as the best performers.
- Species, system and country contribution to production follows 2008 Blue Frontiers categories.
- Total aquaculture production in 2050 is 140 Mt.

Scenario 5: freshwater species. This scenario explores the impacts of shifting to a higher proportion of global production from freshwater finfish farming (e.g., tilapia, catfish) relative to farming of marine finfish and shrimp species. A shift toward freshwater species and not toward marine species was chosen because there has been a gradual shift toward freshwater aquaculture in Asia, where 66 percent of production was from freshwater species in 2010 (FAO, 2012). The World Bank (2013) make similar predictions, demonstrating that although there will be growth for some of high-value marine species – i.e., shrimp and salmon in recirculating aquaculture systems and cages – the fastest growth is expected for tilapia, carp and Pangasius (catfish). The assumptions are as follows:

- 20 percent increase in the share of production resulting from all freshwater finfish systems, accompanied by a proportional decreased share of marine species produced.
- System and country contribution to production follows 2008 Blue Frontiers categories.
- Total aquaculture production in 2050 is 140 Mt.

Scenario 6: combined effect of all scenarios. This scenario investigates the environmental impact of improving efficiency (S1), intensifying (S2), shifting the energy supply (S3), adopting best practice in terms of FCR (S4), and replacing fish oil with fishmeal for salmon and trout production (case study). This means that scenario 1 (10% improvement in efficiency) was used as the base scenario in SimaPro. Electricity sources were modified to come from renewable sources and FCR were reduced to the best performer in each species category. The feed for salmonids was subsequently changed to exclude fish oil and fish meal. The characterization factors were calculated and these were multiplied with the production data from the intensification scenario. The parameters from scenario 5 (production shifting to freshwater) were not included in this scenario because we could not shift production to intensification and to freshwater farming.

Disruptive technology case study – replacing fish oil and meal with crop ingredients. This case study looks only at the influence of replacing fish oil and fishmeal in salmonid diets with a nutritionally complete mix of crop-based ingredients, based on evidence and technical feasibility studies from the published literature (Boissy et al. 2011). Salmon and trout were used in the case study as examples to understand the influence on impacts if fish oil and fish meal were replaced with crop-based ingredients. Moreover, salmon and trout are among the key species requiring a high feed protein content. The assumptions are as follows:

- Salmon and trout production of 790.719 Mt in 2010 and 2,057.026 Mt in 2050. (Pelletier, 2006; Ellingsen and Aanondsen, 2006).
- Species, system and country contributions to production of salmon and trout follow 2008 Blue Frontiers categories.

Results

The outputs from the LCA are provided below in graphs and tabular form showing total aquaculture sector impacts under the different scenarios outlined in the previous section.

Climate change

Greenhouse gas (GHG) emissions will increase from about 332 Mt to 776 Mt CO_2 eq. as a result of higher demand for fish in 2050 when compared to 2010 (Figure 1). Among the different scenarios in 2050, the scenario for increased intensification (S2) increased climate change impacts above that of the business-as-usual baseline scenario (Figure 1). This can be explained by higher energy and feed demands in intensive systems compared to semi-intensive or extensive systems, which both lead to increased GHG emissions. Samuel-Fitwi et al. (2013) also demonstrated that the global warming potential of intensive trout systems is 3 561 kg CO_2 eq. per 1 metric ton of live rainbow trout, compared to extensive systems, which produce 2 239 kg CO_2 eq. for the same volume of fish. Ziegler et al. (2012) also demonstrated that fuel use in both fishing and feed production are two of the key aspects of GHG emissions, both of which may increase in intensive aquaculture production.

Combining the attributes of scenarios 1, 3, 4 and the case study in scenario 6, had the most significant impact in terms of mitigating GHG emissions. The majority of this mitigation is likely due to shifting the energy supply to more renewable sources in each country, as seen by the low GHG emissions projected in scenario 3. Scenario 6 demonstrates that a combination of shifting energy supply (S3), increasing efficiency (S1) and applying best management practices for feeding (S4) has potential to actually decrease GHG emissions from aquaculture production in 2050 to below the emissions from aquaculture in 2010.

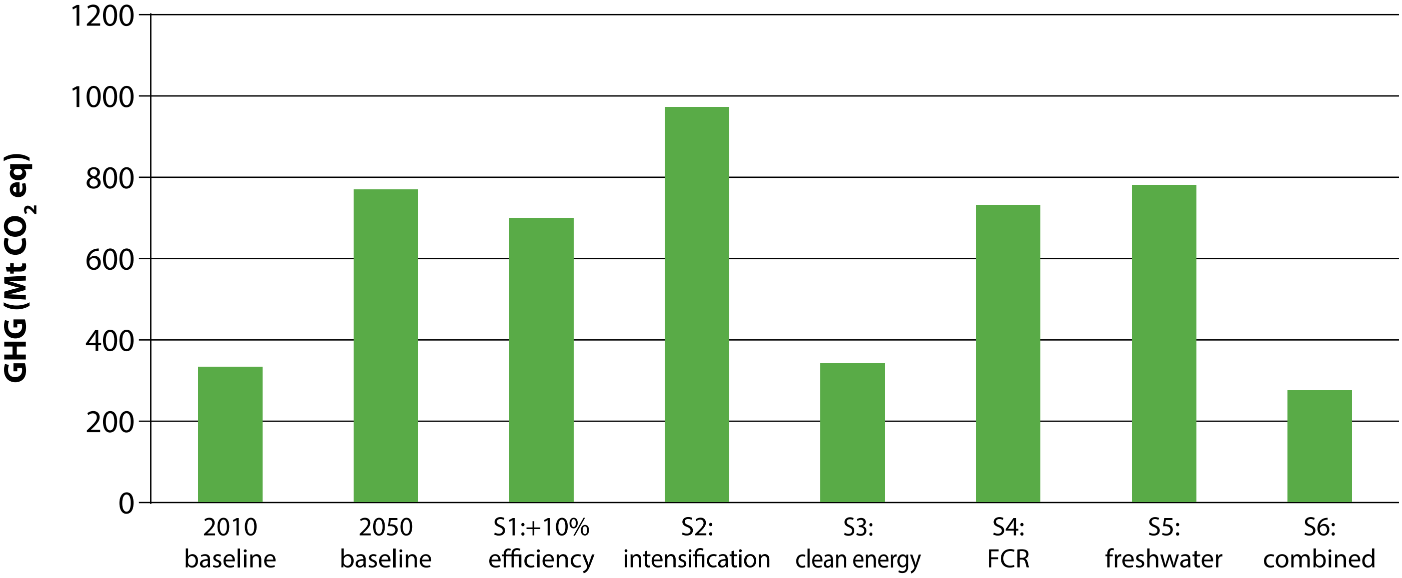

Figure 1. Climate change impacts under six potential production scenarios for global aquaculture in 2050 of global aquaculture.

Freshwater eutrophication
Freshwater eutrophication will increase from about 0.4 Mt to 0.9 Mt P eq. as a result of higher demand for fish in 2050 when compared to 2010 (Figure 2). Even under the combined scenario (S6), freshwater eutrophication increases substantially despite improving a range of production parameters.

Scenario 3, shifting energy supply to renewable resources, appears to be the best performer out of scenarios 1-5. Comparing different scenarios in 2050, shifting away from burning fossil fuels reduces the production of gaseous nutrients and in turn reduces atmospheric deposition of nutrients (Selman and Greenhalgh, 2009). The shifting of species mix to 20 percent more production from freshwater finfish species would potentially lead to the highest impacts on freshwater eutrophication because the release of wastewater containing particulate and dissolved nutrients would increase. It is likely that had we modeled a scenario in which there was a shift toward marine species instead of freshwater species, some of the freshwater eutrophication impact would be mitigated, although release of fertilizers during growing and processing feeds would mean that not all impact is mitigated (Troell et al., in review). Increasing intensification potentially has a significant effect on eutrophication, which is likely driven by the production of more feeds from agricultural lands, increasing fertilizer use and land conversion. Land conversion reduces the nutrient-trapping ability of landscapes and enhances nutrient leaching to adjacent waterways (Selman and Greenhalgh, 2009).

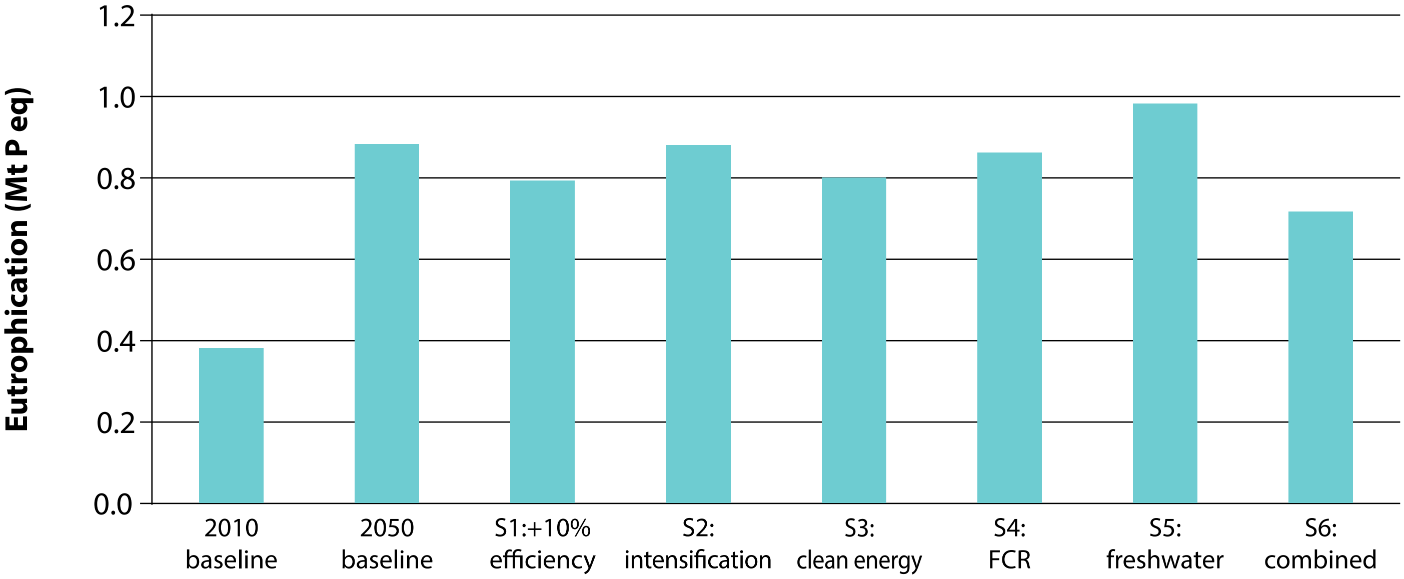

Figure 2. Freshwater eutrophication impacts under six potential production scenarios for global aquaculture in 2050 of global aquaculture.

Marine eutrophication

Under a business-as-usual scenario (baseline), impacts on marine eutrophication will rise from 1.4 Mt in 2010 to 3.2 Mt in 2050 (Figure 3). Adopting best practice by reducing FCRs (S4) was the best performer in terms of the impact on marine eutrophication. Reducing FCRs is usually achieved by reducing feed waste and improving dietary composition to optimize assimilation of nutrients; together these will reduce runoff of nitrogen with wastewater. As with freshwater eutrophication above, intensification (S2) and a shift toward production from freshwater species (S5) performed poorly. Intensification drives up agricultural production to meet feed demands, and this in turn enhances runoff from fertilizers. Direct nutrient release from aquaculture systems will potentially also increase under intensification and given that direct release of nutrients from aquaculture can account for up to half of the nutrient emissions throughout the life cycle of a seafood product, this could have significant impacts unless wastewaters are sufficiently managed (Henriksson et al., 2014). Shifting energy supply (S3) is among the worst performers even though burning less fossil fuel lowers atmospheric deposition of N into waterways (Selman and Greenhalgh, 2009).

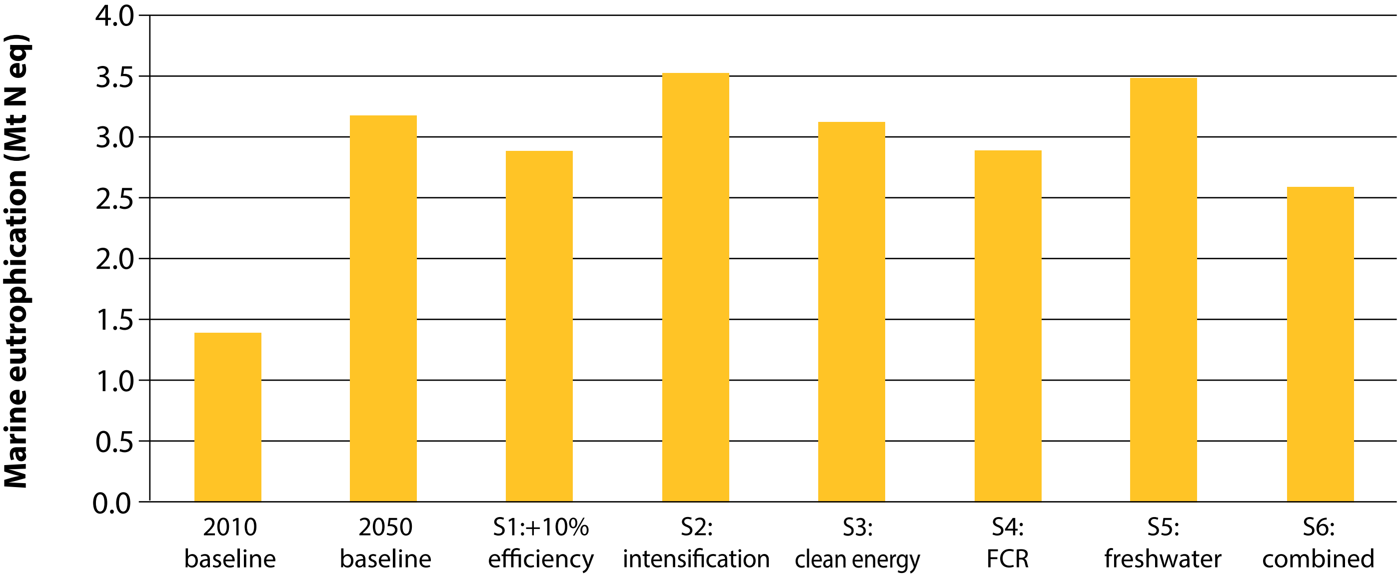

Figure 3. Marine eutrophication impacts under six potential production scenarios for global aquaculture in 2050.

Terrestrial acidification

Terrestrial acidification will increase from about 2.8 to 6.4 Mt SO_2 eq. as a result of higher demand for fish in 2050 when compared to 2010 (Figure 4). Increased intensification (S2) could potentially lead to the highest impact on terrestrial acidification (8.2 Mt), increasing impacts above the 2050 baseline impacts (Figure 4). Henriksson et al. (2014) demonstrated that across catfish, shrimp, tilapia and prawn systems in four Asian countries, the burning of diesel on capture fishing boats for fishmeal production dominated acidifying emissions, which could partly explain impact due to increased intensification (which leads to increased fishmeal and fish oil requirements). Likewise, the shifting of species mix to more freshwater species is associated with higher sulfur dioxide emissions from electricity production particularly from coal and ammonia emissions released during crop production; e.g., rapeseed and wheat grain. The volume of changing species mix from seawater to freshwater species increases the species from freshwater that use high energy and feed and are produced in large volumes (e.g., carp), so impacts are enhanced. Shifting of energy sources to renewable sources, lowering FCR and increasing production efficiency could potentially significantly reduce the impacts on terrestrial acidification potential, and the combined effect of all scenarios (S6) demonstrates that impacts on terrestrial acidification could actually be reduced below 2010 levels despite the increase in production from 60 Mt to 140 Mt (Figure 4).

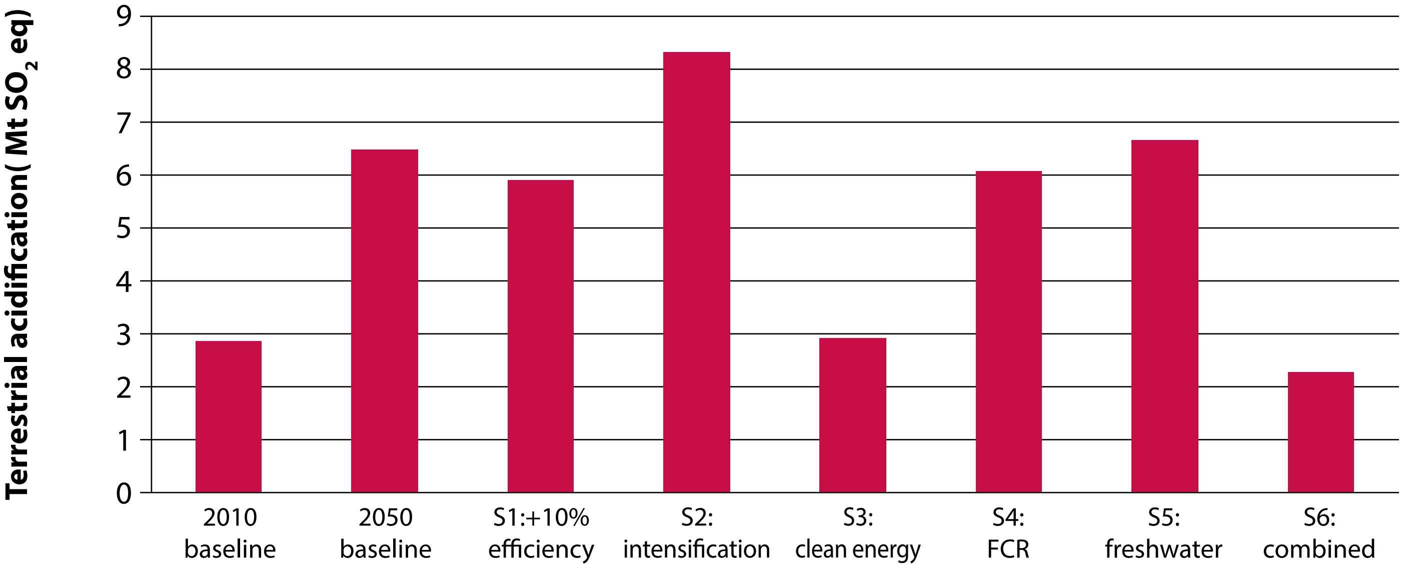

Figure 4. Terrestrial acidification potential under six potential production scenarios for global aquaculture in 2050 of global aquaculture.

Direct land occupation

Direct land occupation - i.e., that used for the area of the farm - will increase from about 28 to 66 million hectares (Mha) per year eq. as a result of higher demand for fish in 2050 (Figure 5). Comparing different scenarios in 2050, increasing intensification (S2) of aquaculture systems is the only technique that significantly reduces the direct land use. As the parameters of S2 (intensification) are excluded from S6 (combined) even this combined scenario does not demonstrate improvements in direct land occupation.

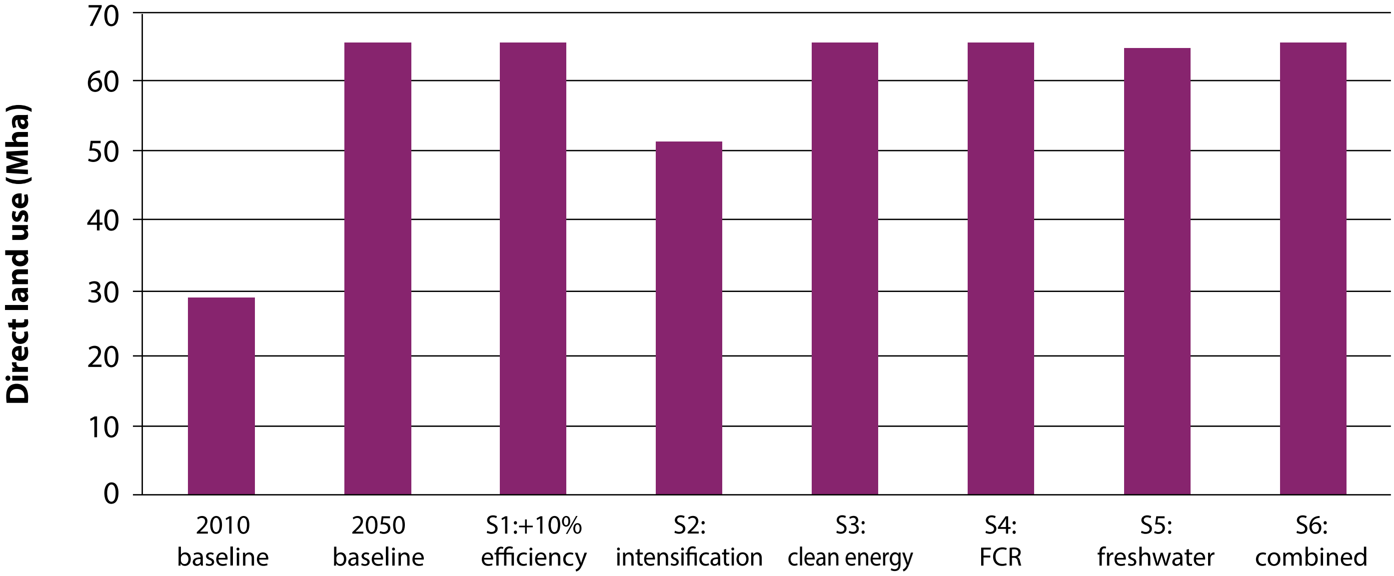

Figure 5. Direct land occupation under six potential production scenarios for global aquaculture in 2050 of global aquaculture.

Land occupation (indirect for feeds)

Indirect land occupation (for feeds) will increase from about 26 to 62 Mha per year eq. as a result of higher demand for fish in 2050. Comparing different scenarios in 2050, the shift of species mix to more freshwater species would lead to an increase in cropland used relative to the baseline scenario, due to the higher share of crop-based ingredients in their feeds as well as a large volume of freshwater production. The other scenarios lead to a decrease in area of indirect land occupation relative to the 2050 baseline scenario. In particular, lower FCR scenario at the same intensification level could potentially reduce the pressure on land occupation. Lower FCRs will help reduce the pressure on crop production (i.e., crop-based feed ingredients) that is required for feed production.

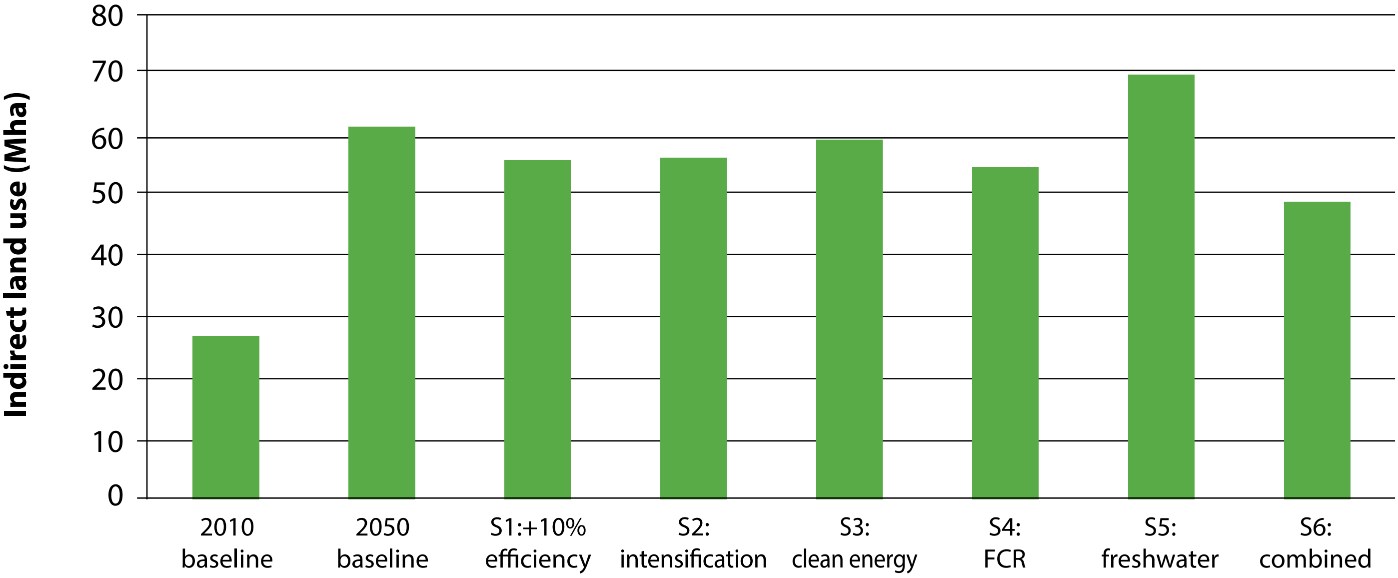

Figure 5. Indirect land occupation under six potential production scenarios for global aquaculture in 2050 of global aquaculture.

Water use

Water use will increase from about 201 thousand gigaliters (GL) to 469 thousand GL as a result of higher demand for fish in 2050 (Figure 6). Comparing different scenarios in 2050, the shifting of species mix to more freshwater finfish species could potentially lead to a higher impact on water use. One would expect that had we modeled the opposite - i.e., a shift toward more production coming from marine species - then the majority of this impact would be mitigated (Gephart et al., 2014). However, a large proportion (71 percent in carp and tilapia farming) of the water used in aquaculture production is consumed during crop production for feeds, which applies to both freshwater and marine aquaculture systems (Mungkung et al., 2013). The application of lowest FCR among the same intensification level could potentially reduce the impact, followed by the shifting of energy from predominantly fossil fuels to renewable sources, the increased intensification level of farming systems, and increased production efficiency. The higher impact from shifting to more freshwater species was associated with the water demand for pond-based freshwater aquaculture systems, while the increased intensification and production efficiency would potentially improve the water-use efficiency.

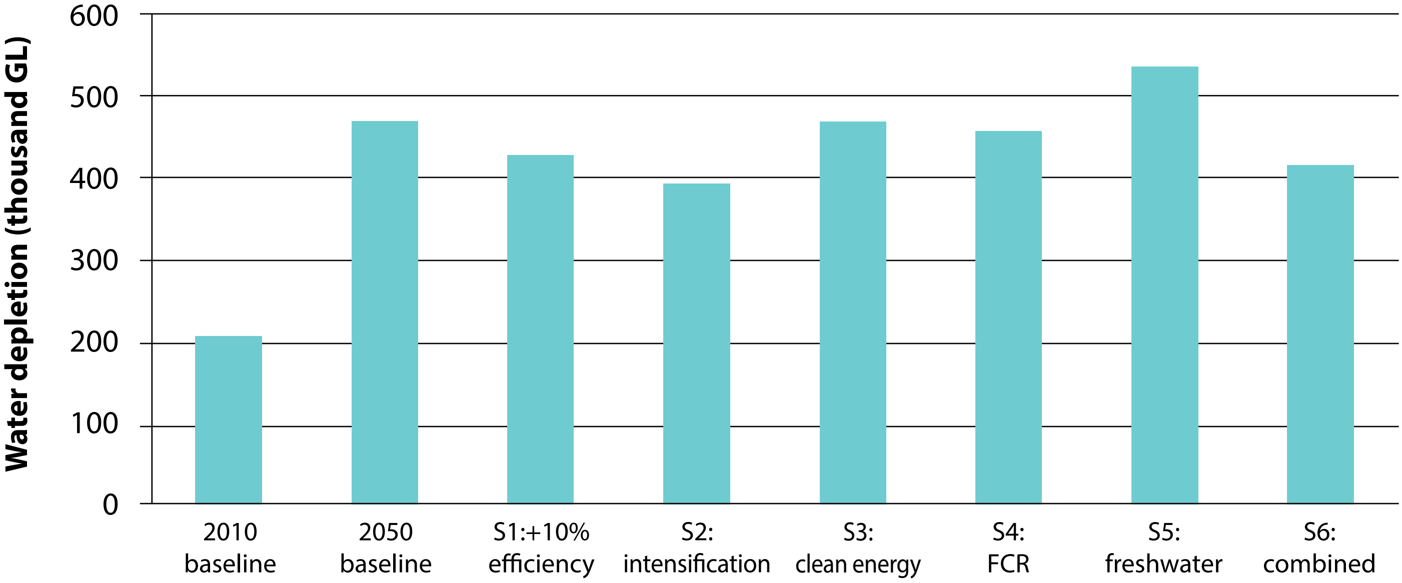

Figure 6. Water use under six potential production scenarios for global aquaculture in 2050.

Cumulative energy demand

Cumulative energy demand (CED) is the sum of all the energy that is spent on producing a final product and includes energy from fossil fuels, nuclear power, biomass fuels and renewable energies (Henriksson, 2009). CED will increase from about 4 583 million GJ to 10 700 million GJ as a result of higher demand for fish in 2050 (Figure 7). Comparing different scenarios in 2050, the increased intensification level of farming systems could potentially increase the CED. These estimates are in line with Henriksson (2009), who found that extensive milkfish farms were more energy-efficient than semi-intensive or intensive farms per metric ton of produce. However, the impact could potentially be reduced by the shifting of energy from non-renewables to renewable sources in line with country energy policies, and increasing production efficiency and lowering FCR. The latter is because feed is typically the most significant contributor to total CED (Henriksson, 2009).

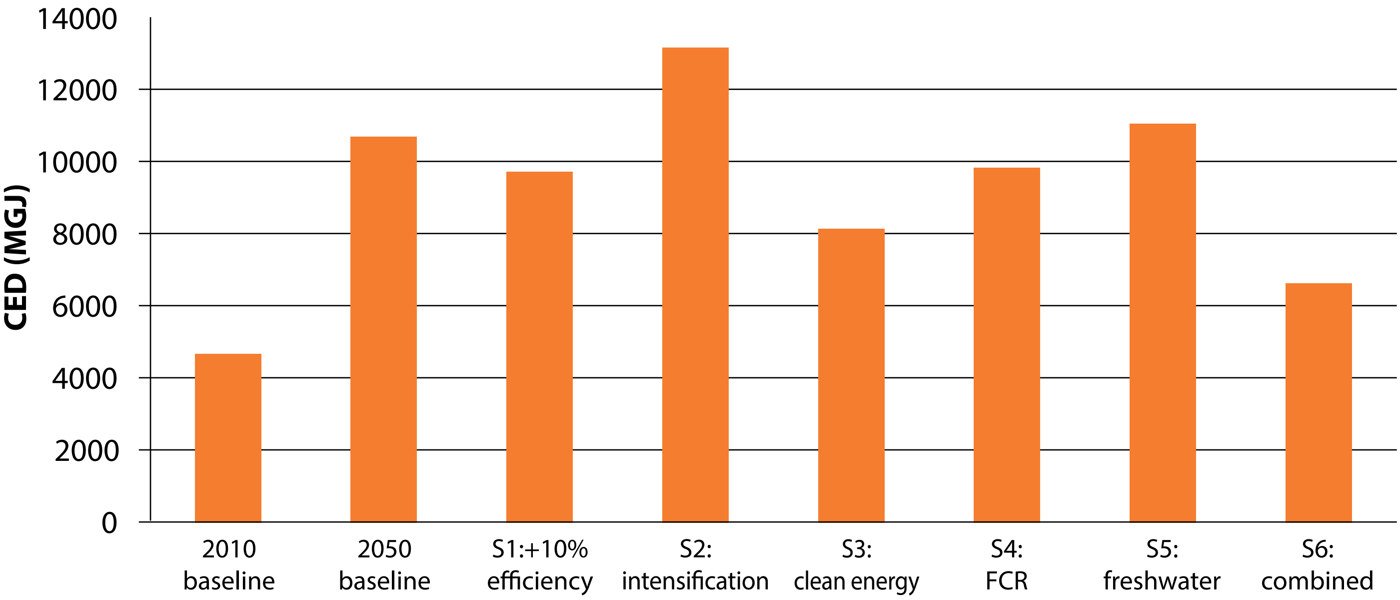

Figure 7. Cumulative energy demand under six potential production scenarios for global aquaculture in 2050 of global aquaculture.

Biotic depletion

Biotic depletion is the amount of wild fish required to produce fishmeal and fish oil for the aquaculture system. Biotic depletion will increase from about 20 Mt to 47 Mt as a result of higher demand for fish in 2050 (Figure 8). Combining all scenarios into scenario 6 has the largest positive effect on biotic depletion and would result in a relatively smaller increase in biotic depletion above the 2010 baseline levels of 20 Mt to 29 Mt in 2050 (Figure 8). Lower FCRs (S4) will potentially reduce the impact on biotic depletion through a direct reduction of pressure on fishmeal and fish oil to produce feeds; this is also demonstrated in our case study, given below. Increased production efficiency (S1) and the shifting of species mix to more freshwater species (S5) will also reduce biotic depletion below the 2050 business-as-usual scenario (2050 baseline; Figure 8). Hall et al. (2011) demonstrated that although inland pond culture dominated impacts in most impact categories (due to the positive relationship between production and absolute levels of impact), marine cage culture dominated biotic depletion, so it follows that a shift toward production from freshwater species, which are largely herbivorous or omnivorous, would reduce biotic depletion. Conversely, increased intensification has the largest effect on biotic depletion.

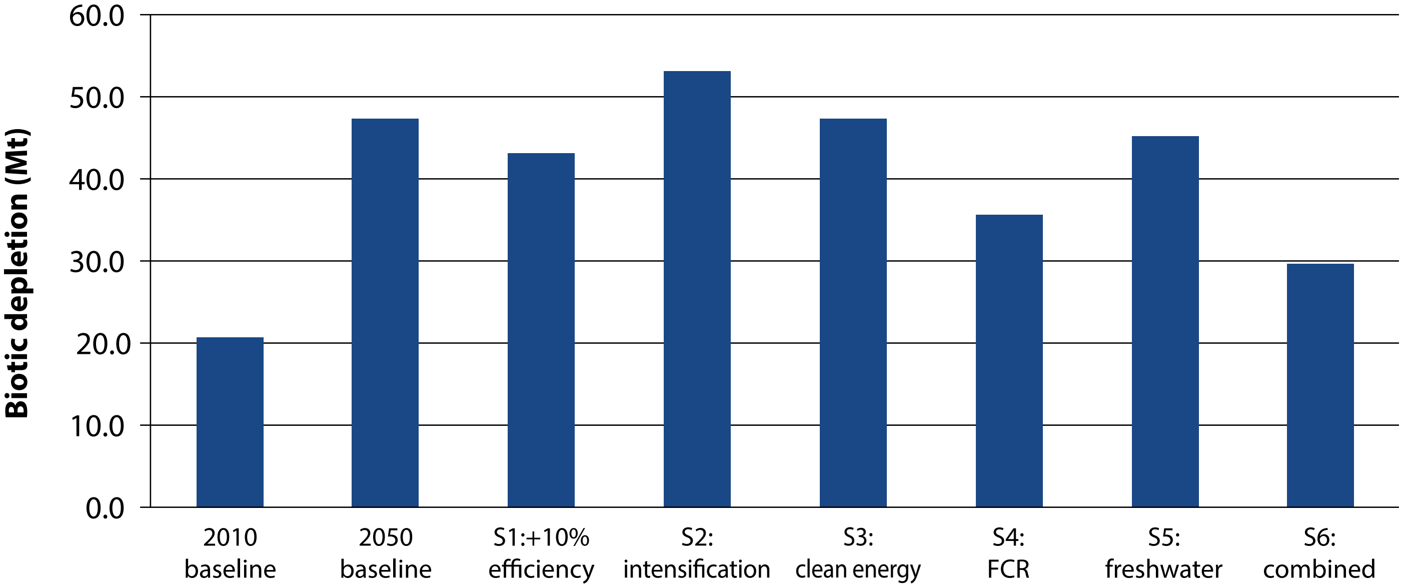

Figure 8. Biotic depletion under six potential production scenarios for global aquaculture in 2050 of global aquaculture.

Disruptive technology in the salmon sector

This case study of a disruptive technology assumes that salmonid, inclusive of salmon and trout, feeds will eventually be comprised of a nutritionally balanced diet of a variety of crop-based ingredients, including but not limited to soybean meal, so that no fishmeal or fish oil would be required. The analysis followed the scenario in Boissy et al. (2011). The results show that the impacts on biotic depletion will be almost entirely mitigated and that climate change and water depletion will be slightly reduced, while shifting the impacts to terrestrial acidification, freshwater eutrophication, marine eutrophication and land occupation (Figure 9). Although biotic depletion will be largely resolved, the impacts will be shifted to the higher demand for land occupation in line with the production of crop-based feed ingredients; e.g., sunflower, soybean meal, wheat grain and rapeseed.

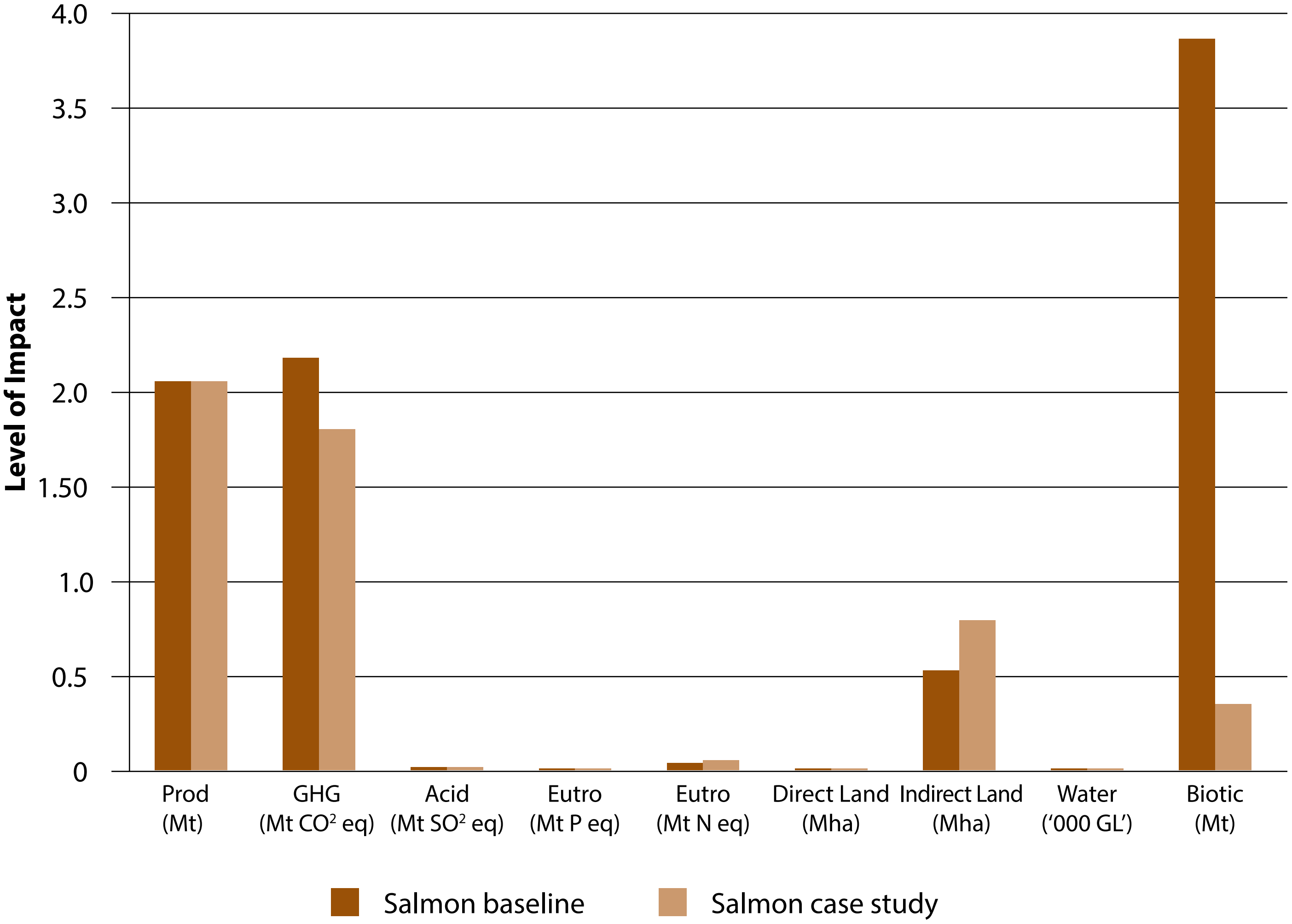

Figure 9. Effects of replacement of fishmeal and fish oil with soy-based ingredients in salmonid diets on environmental impacts. Cumulative energy demand was omitted; the impact under both the baseline scenario and the case study were 56 M GJ.

Summary and conclusions

Table 2 summarizes a subset of "possible" potential impacts associated with increasing production from 60 Mt in 2010 to 140 Mt in 2050 under various scenarios based on the development of best practices, shifting of energy resources or cultured species, and disruptive technologies. For each scenario, it also shows how much higher each impact is in 2050 relative to 2010. In the 2050 baseline (business-as-usual), all impacts are 2.3 times higher than in 2010, reflecting the fact that productivity remains unchanged. For Scenarios 1-6 and the case study, increases in productivity (resource use efficiency) are shown in green, decreases are shown in red, and places where productivity remains relatively unchanged are shown in yellow.

Scenario	**Production (Mt)**	**Direct land occupation for farms (Mha)**	**Indirect land occupation for feeds (Mha)**	**Wild fish used for feeds — biotic depletion (Mt)**	**Freshwater consumption ('000 GL)**	**Freshwater eutrophication potential (Mt P eq)**	**Marine eutrophication potential (Mt N eq)**	**Climate change — GHG emissions (Mt CO_2 eq)**
2010								
Baseline	60	28.1	26.4	20.2	201	0.4	1.4	332.3
2050								
Baseline (business as usual)	140	65.6	61.6	47.2	469.0	0.9	3.2	775.8
x higher	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
1. Improved efficiency in input use	140	65.6	55.6	42.9	426.3	0.8	2.9	705.6
x higher	2.3	2.3	2.1	2.1	2.1	2.1	2.1	2.1
2. Significant intensification	140	51.2	56.3	53.0	391.7	0.9	3.5	979.1
x higher	2.3	1.8	2.1	2.6	2.0	2.3	2.6	3.0
3. Shifting energy supply	140	65.6	59.4	47.2	468.1	0.8	3.1	343.6
x higher	2.3	2.3	2.3	2.3	2.3	2.1	2.3	1.0
4. Adoption of current best practice	140	65.6	54.8	35.3	456.3	0.9	2.9	737.4
x higher	2.3	2.3	2.1	1.8	2.3	2.3	2.1	2.2
5. Shifting species mix	140	64.7	70.3	45.0	535.7	1.0	3.5	786.3
x higher	2.3	2.3	2.7	2.2	2.7	2.5	2.6	2.4
6. All scenarios	140	65.6	49.0	29.4	414.1	0.7	2.6	276.7
x higher	2.3	2.3	1.9	1.5	2.1	1.9	1.9	0.8
Case study: Replacing fish-based ingredients with crop-based (note: explores only salmonid production, not all aquaculture)	2.1	0.0	0.1	0.0	5.5	0.01	0.06	1.8
x higher	2.6	N/A	3.9	0.0	2.3	2.7	3.6	2.2

Notes: 2010 baseline includes total estimated impacts from the 75 production systems that represented 90 percent of world aquaculture production in 2010, divided by 90 percent to estimate complete global impacts. "x higher" refers to the level of production in a given 2050 scenario versus the 2010 baseline of total aquaculture production. For instance, production in 2050 (business as usual) was 2.3 times higher than in 2010.

Table 2. Summary of environmental impacts of aquaculture associated with the different scenarios.

The results essentially confirm that impacts from aquaculture are likely to grow as production increases to 140 Mt in 2050. There are many sources of uncertainty in predicting aquaculture growth pathways nearly 40 years into the future, but these results provide a first broad comparison of possible impacts under possible scenarios. They are not an absolute prediction of impacts, but suggest that significant transformation is required if the sector's future impacts are to be mitigated. Making more accurate predictions - and analysis of impacts at a regional or national level - would require much deeper analysis. Still, this analysis serves as an important first step to examine the possible consequences and tradeoffs of plausible aquaculture growth pathways.

These results indicate that a mix of internal factors (e.g., intensity of production systems) and external factors (e.g., electricity energy sources) will influence the future environmental footprint of aquaculture.

It is worth noting that the potential impacts were estimated from the possible consequences of environmental impacts associated with the inputs and outputs required throughout the life cycle production activities at the farm level. As a result, the environmental impact indicators are not absolute values, but should be used for comparative purposes. Even so, the figures are still useful to reach a broad perspective in terms of potential impacts and possible mitigation measures.

Key points emerging from this analysis:

- Holding aquaculture's environmental impacts to 2010 levels – let alone reducing them - will be a challenge given the sector's projected rapid growth to 2050. Looking back at aquaculture's rapid growth and intensification since the 1980s and the sector's use of land, water, feed, and energy, it is clear that the use of these resources is a key constraint to future production growth. Furthermore, issues of water pollution, farmed fish disease and escapes continue to compromise the sustainability of the sector. For a detailed discussion, see Waite et al. (2014).
- Under most scenarios, many of the impacts come close to doubling between 2010 and 2050, although impacts range from staying almost constant (e.g., greenhouse gas emissions as energy sources shift towards renewables) to nearly tripling (e.g., greenhouse gas emissions under significant intensification).
- The increasing cost of inputs will likely drive changes in management practices and some increase in efficiency (Scenario 1), but policies will likely be necessary to further mitigate environmental impacts.
- Shifting energy supplies (Scenario 3) greatly reduces energy use and greenhouse gas emissions relative to "business as usual," while holding most other impacts constant to the baseline scenario.
- No one "easy solution" reduces impacts, and in many cases, the effects on impacts relative to "business as usual" are mixed. Encouraging intensification of pond systems (Scenario 2), shifting the species mix toward freshwater species (Scenario 5), and replacing fish-based feed ingredients with plant-based ones (Scenario 6) offer mixed results and tradeoffs across the impact categories. For instance, increased intensification would reduce land and water use relative to business as usual, but lead to increased biotic depletion (demand for wild fish as feed) and greenhouse gas emissions. There is therefore a need for deeper analysis of the tradeoffs under different scenarios, with more detailed data in order to provide insights at finer scales (e.g., national level).
- Lowering FCR (Scenario 4) provides positive results and current certification schemes which work on the theory of "pulling" worst performers up to a standard performance level should be encouraged across the board but must also be accompanied by context specific solutions.
- Some analysts believe that due to land and water scarcity, the proportion of marine fish species cultured will actually increase relative to freshwater species between now and 2050. Such a scenario would essentially entail a reversal of the assumptions and impacts in Scenario 5. Therefore, relative to "business as usual," an increase in the proportion of marine species would thus likely raise demand for fish-based feeds, but reduce land and water use, water pollution, and greenhouse gas emissions.
- Combining approaches represented by these scenarios, as seen in Scenario 6 (e.g., shifting the energy mix, facilitating adoption of best practices, and increasing efficiency), has the potential to reduce impacts and in some cases hold impacts at 2010 levels. This substantial reduction of impacts will require transformative change, including:

- Low-carbon energy sources and better energy efficiency
- Low-carbon feed ingredients with sufficient nutrient levels required which ensures FCRs are not inadvertently increased
- Development and widespread adoption of genetically improved strains of fish for improved yields
- Investment in technical support, research, training and extension - especially in developing countries
- Significant improvements in feeding management (as reflected in feed conversion ratios)
- Improved composition of production mix (habitat, farming systems and species)
- Deeper analysis of the tradeoffs (at local- or national-level scales, incorporating socioeconomic data to better understand costs and benefits)

Although holding aquaculture's environmental impacts to 2010 levels will be difficult given the high expected rate of growth of the sector, the results show that there are important options for mitigating impact. To achieve sustainability, socio-economic aspects must also be considered, perhaps by incorporating social and economic variables along with environmental variables. More in depth analysis of the inputs and management factors influencing environmental impacts would also be necessary for design of potentially lower impact growth options.

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Annex A: References for energy production mix in 2010 and 2050

Country	Source (2050)
Canada	http://www.greenpeace.org/canada/Global/canada/report/2010/9/E%5BR%5Dcanada.pdf
India	http://www.greenpeace.org/international/en/publications/Campaign-reports/Climate-Reports/Energy-Revolution-2012/
China	http://www.greenpeace.org/international/en/publications/Campaign-reports/Climate-Reports/Energy-Revolution-2012/
Vietnam	http://aperc.ieej.or.jp/publications/reports/outlook.php
Japan	http://www.iea.org/publications/freepublications/publication/WEO2011_WEB.pdf
Chile	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2_individual.html
Indonesia	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2_individual.html
Mexico	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2/EDSO5_V2_Mexico.pdf
Philippines	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2/EDSO5_V2_Philippines.pdf
Thailand	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2/EDSO5_V2_Thailand.pdf
USA	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2/EDSO5_V2_United_States.pdf
Bangladesh	http://www.iaea.org/INPRO/4th_Dialogue_Forum/DAY_3_01_August-ready/5._-_INPRO_BGD.pdf
Egypt	http://www.isn.ethz.ch/Digital-Library/Publications/Detail/?lng=en&id=153488
UK	http://www.optimalpowersystems.com/stuff/electricity_generation_in_UK_in_2050.pdf

Baseline (2010)	
Bangladesh	http://www.iaea.org/INPRO/4th_Dialogue_Forum/DAY_3_01_August-ready/5._-_INPRO_BGD.pdf
Canada	http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf
Chile	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2_individual.html
China	http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf
Ecuador	http://www.lumes.lu.se/database/alumni/10.12/Thesis/Eguez_Alejandro_2012002.pdf
Egypt	www.ceps.be/ceps/dld/7356/pdf
India	http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf
Indonesia	http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf
Japan	http://www.fepc.or.jp/english/library/electricity_eview_japan/__icsFiles/afieldfile/2011/01/28/ERJ2011_full.pdf
Korea (South)	http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf
Korea (North)	**Data not avaliable**
Mexico	http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf
Norway	http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf
Philippines	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2/EDSO5_V2_Philippines.pdf
Thailand	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2/EDSO5_V2_Thailand.pdf
UK	http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf
USA	http://aperc.ieej.or.jp/publications/reports/outlook/5th/volume2/EDSO5_V2_United_States.pdf
Vietnam	http://aperc.ieej.or.jp/publications/reports/outlook.php