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The Consequential Benefits of Algal Biofuels

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Abstract

Ocean resources have been exploited at unprecedented rates, leading to marine biodiversity loss, food web changes, and other alterations of ocean ecosystem functions and structures. The capture of wild fish for human consumption and fishmeal are the primary drivers. Microalgae oil has long been investigated for biofuel production. Its co-product, defatted microalgal biomass, has potential to replace fishmeal from wild fish catch and thus mitigate ocean resource depletion.

This study develops a new indicator for assessing consequential impacts on ocean resources in life cycle assessment. The indicator is based on primary production required, a concept previously used in ecological assessments and life cycle assessments to evaluate ecological impacts of fisheries and aquaculture. We estimate the primary production required for fishmeal production from the ocean (166 kg carbon/kg fishmeal), and the potential of defatted microalgae biomass displacing fishmeal. Results show that defatted microalgae biomass can lead to highly variable, but potentially significant, reductions in ocean resource demand. The variability is a function of the potential for replacement, which depends on the cultured fish species considered. As an example of this significance, based on available data for estimating the potential for defatted microalgal biomass to displace fishmeal for cultured tilapia, salmon, shrimp, carp, flounder, yellowtail and cod, by 2020 net primary production demand from the ocean could be reduced by approximately one billion tons of carbon.

1. Introduction

Human population growth and changing diets across the world have led to increasing demand for food, and particularly for nutrient and protein rich animal products, including fish and shellfish. As a result, ocean resources have been exploited at unprecedented rates (Foley et al., 2011), leading to marine biodiversity loss, food web changes, and other alternations of ocean structure (Avadí & Fréon, 2013). According to the Food and Agriculture Organization (FAO) review of world fish stocks, 17% of fisheries are over-exploited and over 52% are with risk of population decline (Tacon, 2009). Fishery and aquaculture activities are primary drivers of ocean resource depletion, because wild fish are captured for both direct human consumption and as feed for cultured fish (Hasan, 2012). Historically, fishmeal from low-value pelagic fish was an inexpensive primary protein source for cultured fish. However rapid growth of the aquaculture industry has resulted in an increased demand for, and increased price of, these fish, and a decreased availability of fishmeal.

Total fish[1] supply from ocean catch fisheries is projected to slow down as a result of more strict controls in many countries that are intended to prevent fishery depletion and collapse (Metian, 2009; Tacon et al., 2011), this in turn leads to reductions in the catch for high-value fish intended for human consumption, as well as the low value fish used in aquaculture systems to produce fish for human consumption. Concurrently, increasing demand for fish along with concern for the sustainability of marine fish, has led to investigation of substitutions for low-value fish as a protein source (Olsen & Hasan, 2012). In particular, researchers have been seeking less expensive plant-based meals as fishmeal replacement, but unfortunately, they often result in reduced fish growth performance or require large amounts of other dietary supplements to achieve high growth rates (Shurson, 2012).

Algae is a natural food source for many aquatic animals, and may provide an alternative to terrestrially-sourced plant-based feeds (e.g. soy meal) that better meets the requirements of aquatic organisms. If

[1] Definitions apply for catch fish categories from FAO. (2011), p. 79.
Fish (= all aquatic animal species): Literally, a cold-blooded lower vertebrate that has fins, gills and scales (usually) and lives in water. Used as a collective term and includes molluscs, crustaceans and any aquatic animal that is harvested (FAO Glossary of Aquaculture, available at: www.fao.org/fi/glossary/aquaculture/default.asp). **Fishmeal**: Protein-rich meal derived from processing whole fish (usually small pelagic fish and bycatch) as well as residues and by-products from fish processing plants (fish offal) (FAO Glossary of Aquaculture, available at: www.fao.org/fi/glossary/aquaculture/default.asp).

essential nutrients can be provided by algae-based fish feed, algae-based fishmeal could substitute for feeds from wild capture fisheries in proportion with their nutrient content or market value, and could potentially reduce withdrawals of wild fish and the related impacts on ocean ecosystems (Miara et al., 2014).

Algae avert some of the most challenging problems of terrestrial crops, such as direct and indirect land use change, and in some cases can be grown on low-quality water sources that are unfit for terrestrial crops. Because of these characteristics, along with the potential high productivity, algae has long been investigated as a potential source of biofuel. The typical pathway for algal biofuels assumes that accumulated algal oil is extracted and converted into biodiesel or renewable diesel. This process results in a co-product, defatted algae[2] biomass (DAB), which is a potential aquaculture feed.

The potential of using DAB as a replacement for fishmeal for farmed fish species has been studied for various fish species and microalgae strains, and many of these studies show great potential to effectively provide protein, lipids, vitamins and energy to cultured fish (Shah et al., 2017). In some cases, microalgae-based feeds were shown to improve the weight, growth, health and immune system of both fish and animals when used as livestock feed (Brennan & Owende, 2010; Muller-Feuga, 2000; Pulz & Gross, 2004; Spolaore et al., 2006). This may be due in part to the fact that microalgae can be a source of fatty acids that are essential to fish growth (Qiao et al., 2014).

Consequential impacts of biofuels have been a topic of concern and research at least since Searchinger et al.'s 2008 paper illustrating the potential net increase in GHG emissions for first generation biofuels derived from purpose-grown terrestrial crops relative to fossil fuels when consequential land use change emissions are accounted for (Searchinger et al., 2008). Additional exploration and thought on the consequential effects of terrestrial biofuels (both first and second generation fuels) has continued (Mohr & Raman, 2013), but to date an exploration of the potential consequential effects of algal-based fuels has not been undertaken. When algae-based meal is used as fish feed to avoid fish catching for substitute

2 The term algae is used in this study instead of microalgae. Note all strains discussed in later sections are microalgae strains.

species, there is a potential consequential environmental effect on ocean fisheries, which is described in Figure 1. Figure 1 also includes the potential effect on terrestrial resources if algae-based meals displace crop-based feeds (either for aquaculture or livestock).

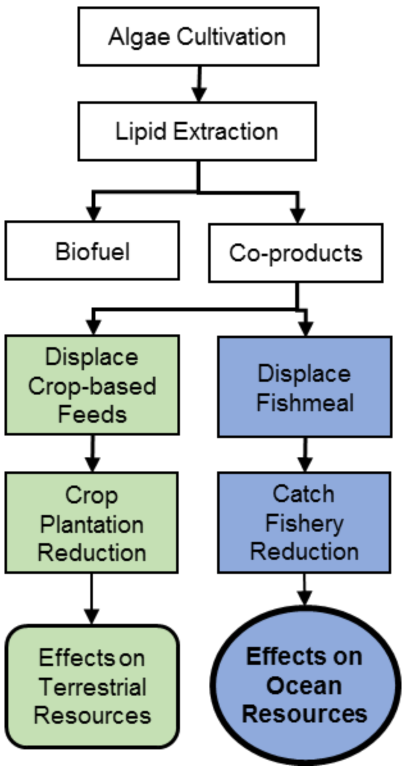

Figure 1 Direct and indirect impacts on land and ocean resources

This study evaluates consequential impacts on ocean resources induced by co-products from algal oil production systems using available models and applicable impact factors. The productivity of marine fisheries, environmental impacts from marine fish capturing, quality and quantity of fishmeal produced from microalgae, substitution potentials and ecological consequences are investigated.

2. Methods

2.1 Review of Methods: Consequential analysis in Life Cycle Assessment

There are two different approaches for performing LCA: attributional and consequential. Attributional LCA (ALCA) describes information on energy and material flows for a chosen system including a product's production, use phase and disposal or recycling (Plevin et al., 2014; Thomassen et al., 2008). ALCA generally provides information on the average unit of a product and is commonly used to identify direct life cycle impacts of products (Brander et al., 2009). The indirect effects induced from changes in the output of a product are not considered in an ALCA. Consequential LCA (CLCA) investigates the consequences of changes to a product output, including effects both inside and outside the life cycle of the product (Brander et al., 2009). Causal relationships are modeled between the change of the product output (sometimes framed as a *decision*, e.g. to produce more or less of a product) in CLCAs to estimate environmental impacts of potential decisions (Plevin et al., 2014). These two approaches aim to answer different questions. ALCA may reasonably be used to identify opportunities for reducing environmental impacts in different processes of the life cycle (e.g. hotspot analysis) or inform comparisons between products (Brander et al., 2009), while CLCA is designed to capture marginal environmental consequences of production systems and indirect effects on affected systems and inform decision makers on the broader impacts of policies that are intended to change levels of production (Earles & Halog, 2011; Plevin et al., 2014). In CLCA, co-products are handled with the displacement approach. This study takes a CLCA perspective, and application of the displacement approach is the primary mechanism whereby indirect effects are captured.

The principal consequential effect of terrestrial crops used as biofuel feedstocks, such as corn, soybean and sugarcane, is indirect land use change (iLUC), which has been extensively studied and modeled (Edwards et al., 2010; Gnansounou et al., 2008; Hertel et al., 2009; Lapola et al., 2010). However, the indirect effects from microalgae cultivation and co-products produced from microalgae biofuel production system have rarely been discussed. While many researchers have pointed out the benefits of algae cultivation with respect to avoiding iLUC, consequential effects from microalgae-based fuels have not been studied or discussed, and may be more relevant for ocean resources than terrestrial ones. While the indirect effects of microalgae biofuel production may be positive or negative, and may be relevant for ocean resources, the basic economic mechanisms at work that drive iLUC are similar for those that drive indirect effects on ocean resources. Therefore, it is necessary to review existing methods for evaluating consequential changes from crop biofuels and apply the method to current approach.

2.2 Methods Used for Assessing Consequential Impacts for Terrestrial Biofuels

The iLUC hypothesis assumes biofuel production competes for agriculture resources resulting in higher prices of agricultural products. The increased prices cause alternate lands such as forest and grassland to shift into farmlands, and in the end cause carbon losses from converted ecosystems. The modeling process usually starts with an assumed biofuel production increase and a cropland increase for the biofuel feedstock crop cultivation. Sanchez et al. categorized the methodology for modeling iLUC as economic (market-based) methods (economic equilibrium models) and cause-effect methods (Sanchez et al., 2012).

2.2.1 Economic Methods

Many economic equilibrium models have been developed, including FAPRI-CARD, GTAP, IMPACT, and LEI-TAP (Edwards et al., 2010; Lapola et al., 2010; Sanchez et al., 2012; Schmidt et al., 2015), that have been used for iLUC modeling. These economic models can be distinguished into two groups, partial equilibrium (PE) models, and computable general equilibrium (CGE) models. PE modeling determines substitutable and complementary goods based on the price elasticity of supply and demand and maximize net social payoff, CGE models (such as GTAP) include all sectors of the economic system and are usually more comprehensive than PE models (Earles & Halog, 2011). The economic models, which either include only agricultural markets (PE models) or the global economy (CGE models), generally establish relationships between demand for land and crops by biofuel production and the effects on crop area, deforestation, and consumption reduction based on historical price data of crops, land types and fuels. Uncertainties and significant variation among iLUC estimates for ethanol production were generated from economic modeling due to different assumptions on the structures of causal relationships between crop and land conversion, yield change of crops, geographical boundaries and temporal scenarios (Sanchez et al., 2012).

2.2.2 Cause-effects Models

Compared to economic models, a cause-effect model usually establishes the link between the demand of crop and land, and land conversion based on statistical data on land use changes and physical data on crop yields (Sanchez et al., 2012). Cederberg et al. (2011) applied a simple method to evaluate indirect carbon emissions from deforestation resulting from beef production. The modeling process included estimation of land productivity of cows, estimation of GHG emissions from deforestation and the distribution of emissions over time and products (Cederberg et al., 2011). Bird et al. (2013) created a deterministic model to identify the amount of indirect land use change when agricultural crops were used for energy production. The model used the demand and supply for worldwide food and estimated that every additional 1 TJ bioenergy could result in 18 hectares of deforestation. The model can be used to determine deforestation rates for different crops based on the yield and energy productivity. Audsley et al. (2010) assigned a single emission factor for agricultural land used by evenly distributed global annual GHG emissions from land use change on all agricultural lands, assuming commercial agriculture was one driving factor of land use change.

2.3 Indirect resource change modeling for ocean resources

Both CGE and PE models require historical market and price elasticity data for production sectors. Existing models have not previously included ocean resources in their assessments, and in fact historical market and price elasticity data are not available for relevant ocean products (e.g. high and low value pelagic fish). Thus, rather than adopting an economic modeling approach, this project adopts a cause-effect method to assess the indirect effects of generating co-products that affect ocean resources.

2.3.1 Choice of impact assessment - Ocean Biotic Resource Depletion

Like land use impacts, human activities such as fishing, aquaculture, shading, and seafloor destruction lead to significant impacts on marine ecosystems. Although impacts on marine ecosystems have been poorly addressed by the scope of life cycle impact assessment (LCIA) (Langlois et al., 2015), various characterization factors have been investigated and discussed to represent “sea use” impacts for LCIA. For wild fish catching activities, the environmental impact of biomass removal can be quantified through the amount of primary organic carbon required to sustain the production of one unit of harvested fish (Luong et al., 2015). Among different characterization factors, biotic primary carbon requirement, referred to as net primary production (NPP, in units of kg carbon) has been used as an ecological impact measure in fishery and aquaculture LCAs (Avadí & Fréon, 2013; Cashion et al., 2016; Efole Ewoukem et al., 2012). NPP stands for the mass of carbon originally derived from photosynthesis that is required to meet the specific production of a product of biological origin. The NPP method estimates the primary production required to yield marine biomass consumption at a trophic level (TL) of the catch through estimating the carbon content in the target species and the energy loss based on understanding of the transfer efficiency (TE) between two adjacent TLs (Cashion et al., 2016). To implement this as an indicator of impact in LCA, the effects of human interventions on the stock of marine biomass present within the ecosystem is quantified at the midpoint level with primary production required (PPR), a common unit of kg of primary carbon equivalent per kg removed biomass (kg carbon/kg biomass) (Pauly & Christensen, 1995).

2.3.2 The displacement of fishmeal by algae biomass

The performance of DAB as a substitute for fishmeal has been studied with different fish species. Table 1 summarizes previous research on the effects of displacing fishmeal with DAB. Because the effect of DAB differs based on the algal strain and the fish species being fed, results are reported for each unique combination of the algal strain used to generate the DAB and the fish species consuming it.

Table 1 Empirical data for DAB effects on fishmeal reduction in fish feeds

Reference	**Algae strain**	**Location**	**Fed species**	**Feed conversion ratio (FCR)**	**Fishmeal reduction (kg/kg fed fish)**	**DAB inclusion (kg)**
(Rahimnejad et al., 2017)	Chlorella vulgaris	Korea	Olive flounder	0.97	0.1	0.15
(García-Ortega et al., 2015)	Desmochloris sp.	Hawaii	Juvenile Nile tilapia	1.16	0.88	0.67
(Ju et al., 2017)	Haematococcus	Hawaii	Juvenile tilapia	1.72	0.26	0.21
(Kissinger et al., 2016)	*Haematococcus pluvialis*	Hawaii	Longfin yellowtail	0.8	0.2	0.12
(Kiron et al., 2016)	*Desmodesmus* sp.	Norway	Atlantic salmon	0.9	0.23	0.18
(Kiron et al., 2012)	*Tetraselmis*	Norway	Atlantic salmon	1.125	0.11	0.2
(Kiron et al., 2012)	*Tetraselmis*	Norway	Common carp	1.7	0.43	0.34
(Kiron et al., 2012)	*Tetraselmis*	Norway	Shrimp	1.81	0.72	0.64

As shown in table 1, effects of DAB inclusion in fish feed have been tested on a number of fed fish species including olive flounder, Nile tilapia, longfin yellowtail, Atlantic salmon, common carp, Atlantic cod and shrimp. Different fish species have different tolerance to algae biomass, e.g. shrimp can have 0.64 kg algae for 1 kg weight gain without impacts on growth performance, while longfin yellowtail only tolerate 0.18 kg algae biomass for 1 kg weight gain. The proportion of fishmeal in the diet that can be displaced by DAB are different to each fish species, too. Fishmeal inputs for olive flounder and juvenile Nile tilapia are reduced by 0.1 kg and 0.88 kg, respectively.

Due to the variation in response of different fed species to DAB feed, the data listed in table 1 are used for modeling displaced PPR in the following sections. The feed conversion ratio (FCR, kg feed/kg fish), as listed in table 1, stands for the dry mass of feed inputs to produce one unit weight gain of fed fish. High FCR indicates low efficiency of feed use. FCR data are adopted from each study for each fed fish (table 1).

2.4 PPR Modeling

The quantification of PPR follows the methodology described by Pauly and Christensen (1995) and Cashion et al. (2016). The reduction fishery PPR is the kg of marine carbon inputs required to grow 1 kg catch fish (equation (1)). A reduction fishery is a fishery targeted for reduction of catch for fishmeal or fish oil used for compound animal and aquaculture feeds (FAO, 2011).

Equation (1) (Adapted from Cashion et al. (2016) and Pauly and Christensen (1995)):

$$Reduction\ Fishery\ PPR\ \ (kg\ C/kg\ fish) = \frac{1}{M} * \ TE^{(1-TL)}$$

In the equation, M is the ratio of wet weight biomass to carbon content (kg fish wet weight/kg C) of the species of interest, TE is trophic transfer efficiency of the ecosystem, and TL is the trophic level of the fish of interest. A low TL value means the fish is lower on the aquatic food chain. Specific ecosystem TE values were obtained from literature (Cashion et al., 2016; Libralato et al., 2008). A general TE of 10% is also tested for comparison. Fishmeal production in the Americas is used for modeling the fishmeal PPR because only countries in the Americas reported fishmeal production at species level, and together Peru and Chile constitute 87% of global fishmeal production, according to the FAO (Tacon, 2009). Data for major reduction fisheries in the Americas and the geographic production for each species are defined in accordance with FAO reports (Huntington & Hasan, 2009). Production data in 2004 are used for estimating the general fish meal PPR calculation due to the limited availability of more recent data. A conservative ratio 9:1 is used for M as in previous LCA studies (Cashion et al., 2016; Farmery et al., 2017; Luong et al., 2015).

The fishmeal PPR for each reduction fishery is proportional to the specific fish species, as shown in equation (2), where meal yield efficiency (kg fishmeal/kg fish) is the mass of fishmeal production from a unit mass of fish.

Equation (2):

$$Fishmeal\ PPR\ (\ kg\ C\ /\ kg\ fishmeal) = \frac{Reduction\ Fishery\ PPR}{Meal\ Yield\ Efficiency}$$

General fishmeal PPR in the Americas is the weighted average value calculated using specific fishmeal PPRs. As expressed in equation (3), the unit of general fishmeal PPR is kg carbon per kg of fishmeal.

Equation (3):

$$General\ Fishmeal\ PPR\ in\ the\ Americas\ (\ kg\ C\ /\ kg\ fishmeal\ ) = \sum (Fish\ Production\ Weight * Fishmeal\ PPR)$$

where

$$Fish\ Production\ Weight\ (\%) = \frac{Production\ of\ Single\ Reduction\ Fish\ Species\ (kg)}{Sum\ Production\ of\ Reduction\ Fish\ Species\ (kg)} * 100\%$$

Fishmeal PPR in the Americas is weighted by the production of each reduction fish species captured in the Americas (table 2). Reduction fishery production in the Americas is obtained from the FAO (Tacon, 2009), and only dominant reduction species (>1% of total) are included in the current model. Only one year of data (2004) is applied to the calculation due to limited data quality and availability. TE and TL values for specific fish in relevant marine ecosystem are obtained from Libralato et al. (2008). Fishmeal yield rates are adopted from Cashion et al. 2016, except for the jumbo flying squid, which uses an estimation of 0.2 kg meal per kg fish.

Table 2 Fishmeal production in the Americas

Large Marine Ecosystem (LME)	Main Fishing Nations	Reduction Fishery	Specific Transfer Efficiency (TE)	General TE	Fish Trophic Level (TL)	Meal Yield (kg fishmeal/kg fish)	2004 Fish Production (thousand tonnes)	Wet weight to Carbon (M, kg fish/kg carbon)
Humboldt current	Peru	Anchoveta	6.60%	10%	3	0.23	10679	9
Humboldt current	Chile	Jack mackerel	6.60%	10%	3.5	0.194	1638	9
Humboldt current	Chile	Chub mackerel	6.60%	10%	3.5	0.2	730	9
Pacific central	Mexico	Pilchard	6.60%	10%	3.1	0.23	683	9
Eastern Pacific Ocean	Peru, Chile	Jumbo flying squid	12.97%	10%	2.5	0.2	556	9
Gulf of Mexico	US	Gulf menhaden	9.70%	10%	2.2	0.24	464	9
Humboldt current	Chile	Araucanian herring	6.60%	10%	3.2	0.204	356	9
North Sea	Canada, US	Atlantic Herring	11.60%	10%	3.2	0.204	269	9
North Sea	US	Atlantic menhaden	10.90%	10%	2.92	0.24	215	9

Displaced PPR is the PPR savings from reduced wild fish in feed for each fed fish species, expressed as kg of carbon saved in the production of 1 kg fish (equation (4)). Fishmeal reduction proportion (kg reduced fishmeal/kg feed) is the displaced fishmeal mass from 1 kg fish feed by the addition of algae. This value is different for each fed species as indicated in table 1. Therefore, the effect of fishmeal substitution by DAB on each fed fish species is different. Data of FCR of each fed species are shown in table 1. The projected production from fed fisheries are obtained from an FAO report (Tacon et al., 2011).

Equation (4):

$$Displaced\ PPR\ (kg\ C/kg\ \ fed\ fish)$$
$$= Fishmeal\ reduction\ proportion * FCR * General\ Fishmeal\ PPR$$

Assuming algae biomass will substitute fishmeal for fed fish species (olive flounder, Nile tilapia, longfin yellowtail, Atlantic salmon, carp, Atlantic cod and shrimp) as listed in table 1, we can calculate the mass of reduced fishmeal at global scale knowing the production of interested fed fish species. And a reduced global net primary production (NPP) can be estimated (equation (5)). The reduced global marine carbon (reduced NPP) is calculated with the reduced fishmeal inputs for modeled fed species. Projection of each fish species production in 2020 is adopted from FAO (FAO, 2011). Fed fish production data in 2008 is also adopted from FAO (FAO, 2011) to compare with the 2020 projection of potential effects on NPP from algae. The unit of reduced NPP is kg carbon.

Equation (5):

$$Algae\ Effects\ on\ Global\ Marine\ Carbon\ Input\ (Reduced\ NPP, kg\ C)$$
$$= \sum (Production\ of\ \ Fed\ Fish\ Species * Displaced\ PPR)$$

3. Results and Discussion

The results of fishmeal PPR produced in the Americas is shown in table 3, specific PPR stands for PPR using specific TE while general PPR is calculated using the general TE estimate of 10%. There is substantial variation in the PPR of different fish and fishmeal and of PPR using different TEs. The meal yield determines the allocation of PPR into the meal and the rest of the fish by mass. The weighted averaged PPR for 1 kg of fishmeal produced from the Americas is estimated to be 166 kg carbon using the specific PPR, and 67 kg carbon using general PPR. Among estimated reduction fisheries, jack mackerel meal has the highest PPR of 512 kg C per kg fishmeal, while Gulf menhaden meal has the lowest PPR of 8 kg C/kg fishmeal using specific TE. If the general TE is used, jack mackerel still shows the highest PPR of 181 kg C/kg fishmeal and menhaden remains similar PPR at 7.34 kg C/kg fishmeal. The resolution of global data used for modeling makes obvious differences in results. Given the high variability between general and specific PPR, fine resolution spatial data of specific TE and TL for different species is desirable for accurately estimating the ocean impacts.

Table 3 PPR of 1 kg Fishmeal production in the Americas

Reduction Fisheries	Anchoveta	Jack mackerel	Chub mackerel	Pilchard	Jumbo flying squid	Gulf menhaden	Araucanian herring	Atlantic Herring	Atlantic menhaden
General Fishmeal PPR (kg C/kg fishmeal)	48.31	181.12	175.68	60.82	17.57	7.34	86.32	86.32	86.32
Specific Fishmeal PPR (kg C/kg fishmeal)	110.90	511.79	496.44	145.54	11.89	7.61	215.34	62.28	62.28
Production weights (%)	68%	11%	5%	4%	4%	3%	2%	2%	1%
Average Specific PPR	**166.00**	kg C/kg fishmeal in America							
Average General PPR	**67.32**	kg C/kg fishmeal in America							

The consequential effects of 1 kg DAB used as aquaculture feed on marine biotic resources are shown in table 4. Depending on different microalgae species, 1 kg of algal biomass displaces different amounts of primary production due to the different performances as fish feed. Algae strain Haematococcus *pluvialis* shows the highest potential in PPR conservation (200 kg C/kg DAB) as fish feed because of its high displacement ratio of fishmeal when feeding longfin yellowtail (as shown in table 1). The Teraselmis with lowest PPR displacement value is due to the low displacement ratio when feeding Atlantic salmon, which requires 0.2 kg DAB addition to make up the deduction of 0.1 kg fishmeal in feed.

Table 4 Displaced fishmeal PPR by 1 kg DAB (kg C/kg DAB)

Algae strain	PPR displaced
Chlorella vulgaris	66.4
Desmochloris sp.	126.8
Haematococcus	96.84
Haematococcus pluvialis	200.01
Desmodesmus sp	149.4
Tetraselmis (salmon)[a]	26.71
Tetraselmis (carp)[a]	32.95
Tetraselmis (shrimp)[a]	29.03

[a] parentheses indicate fed fish species

Differences in the fed fish result in different levels of tolerance for DAB and feed conversion efficiency. Figure 2 shows the marine carbon inputs to grow 1 kg of fed fisheries. The blue bar is the initial PPR of fishmeal inputs for 1 kg fish growth, the orange bar is the reduction of PPR by inclusion of DAB in feed to replace fishmeal, and the black dot represents the PPR of using the reduced fishmeal amount for feeding 1 kg of fish by using DAB. The effect of PPR reduction by DAB is the most significant for Nile tilapia fishery because 75% of fishmeal inputs can be replaced by DAB. Atlantic salmon shows low tolerance to DAB, so only 10% of fishmeal is replaceable. Therefore, the effect of DAB on the marine resource conservation for Atlantic salmon is relatively small.

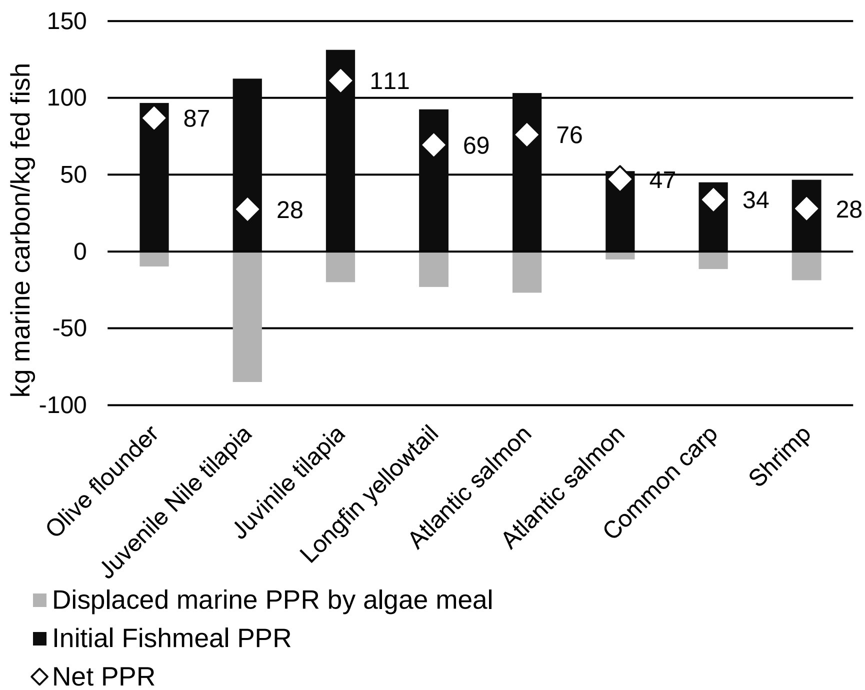

Figure 2 PPR of growing 1 kg fed fish by feeding DAB

3.1 Projection of Global NPP Displaced by DAB

Aquaculture production of tilapia, salmon, shrimp, carp, flounder, and longfin yellowtail in 2008 and 2020 (projected) is used to estimate the marine carbon resource depletion (figure 3). An estimated 465 and 1100 million tonnes of carbon can be conserved by using DAB in fish feed for the listed 6 types of aquaculture farms in 2008 and 2020. To meet this NPP reduction for fish feed, 17 million tonnes of algae biomass will be required in 2020. Assuming the biodiesel yield from microalgae is 75 tonne/(hectare · y), to produce the targeted fish feed, the biodiesel produced from algae would be 1.2 billion gallons. A land input of 0.35 million hectares would be required assuming algae are grown in open ponds and assuming today's expected algal productivity. To put this in perspective, the U.S. cultivates about 100 times this amount (36 million hectares of land) for corn each year, of which about 40% is used for corn ethanol production (USDA Economic Research Service, 2018).

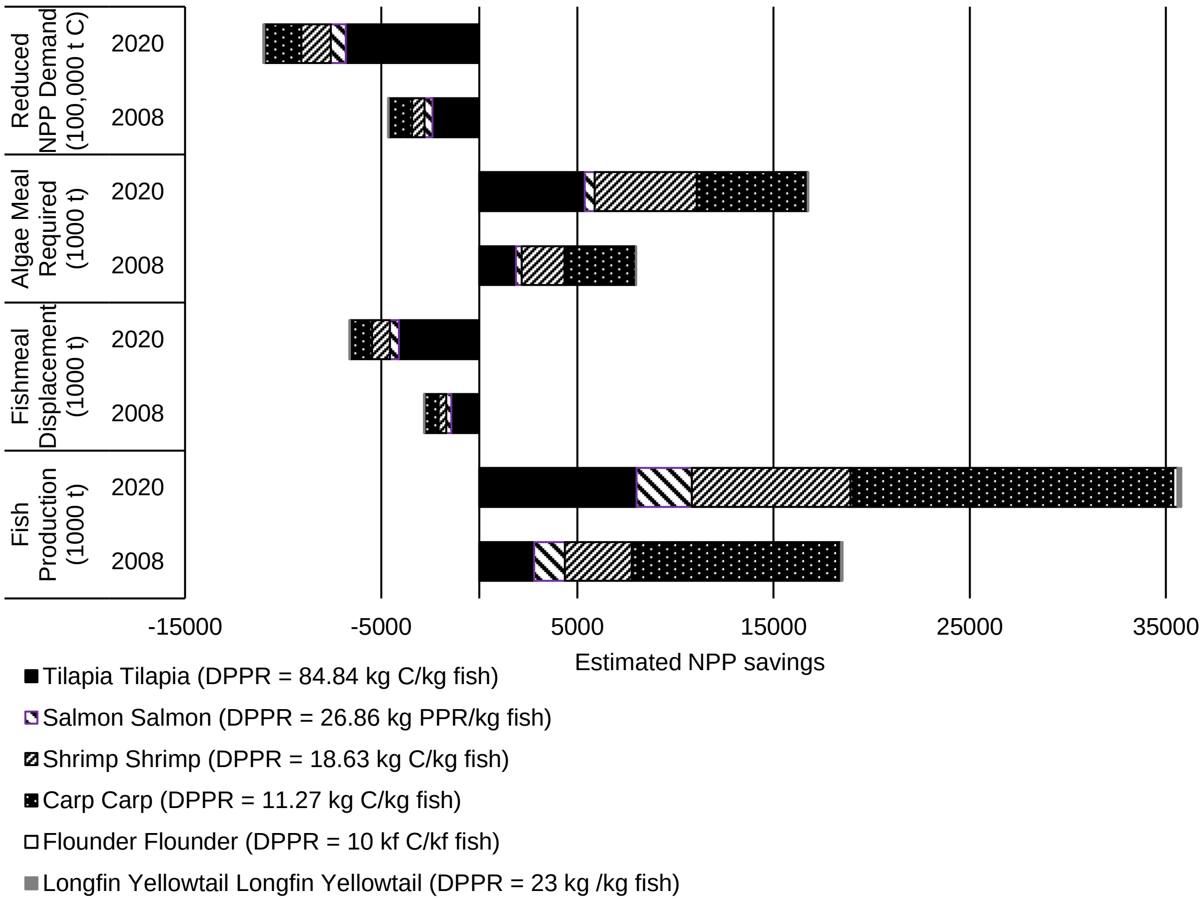

Figure 3. Estimated global NPP savings in 2008 and 2020 from algae displacing fishmeal for tilapia, salmon, shrimp, carp, flounder, yellowtail and cod. Note units on NPP reduction shown in vertical axis titles.

4. Conclusions

This study estimates the potential impacts of supplying DAB, a coproduct of algal-based biofuel, on ocean primary production depletion effects. NPP offers an innovative and useful indicator for understanding the influence of algal biofuel production on marine ecosystems.

When algae biomass is used as a fishmeal substitute, reduction fishery catch can be reduced, ocean resources are then conserved, but terrestrial resources are used. Thus there is a potential trade-off between ocean and terrestrial resources. To resolve this potential trade-off, reuse of waste resources is recommended for algae cultivation which reduces raw material inputs and decreases discharges into the ocean. In particular, considering the use of wastewater and waste nutrients as inputs to cultivation of algae could significant reduce the resource demands and costs of algae production.

Maintaining the productivity of ocean ecosystem is important for humans' growing population and demand for protein. Thus it may be necessary to look for fish species that can accept high proportions of DAB as feed, and which have good feed conversion ratios. Additional scenarios with different substitution rates between marine fishery and fishmeal from algae should be tested. Cultivation of such fish with algae biomass would result in improved ocean resource conservation. Other mechanisms for improving consumer choice could include pricing fishmeal and fish species with higher PPR at higher prices than those with lower PPR, which could encourage ocean resource conservation.

This study models the consequential displacement effects in a very simple way; problems such as spatial and temporal limitations of algae biomass availability are excluded in current estimation. Aquaculture in Asia is expanding rapidly with exclusive feeding of low-value fish in whole fish form with a high FCR (Huntington & Hasan, 2009). However, because data are limited for this region, this study focused on the Americas. The implications of understanding the impacts of biofuel production are significant at the global scale, and particularly for Asia. More interesting issues such as using innovation in gene-modified algae for specific fish ingredient supply and human nutrition additives, and the impacts on displacing fish oil and fishmeal are future research that should be investigated to understand the potential role of algae and algae biofuels and their potential effects on aquaculture, the food system, and ocean resources.

5. References

Audsley, E., Brander, M., Chatterton, J.C., Murphy-Bokern, D., Webster, C., Williams, A.G. 2010. How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope reduction by 2050. Report for the WWF and Food Climate Research Network.

Avadí, A., Fréon, P. 2013. Life cycle assessment of fisheries: A review for fisheries scientists and managers. *Fisheries Research*, **143**(Supplement C), 21-38.

Bird, D.N., Zanchi, G., Pena, N. 2013. A method for estimating the indirect land use change from bioenergy activities based on the supply and demand of agricultural-based energy. *Biomass and Bioenergy*, **59**, 3-15.

Brander, M., Tipper, R., Hutchison, C., Davis, G. 2009. Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels. *Technical paper TP-090403-A, Ecometrica Press, London, UK*.

Brennan, L., Owende, P. 2010. Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and sustainable energy reviews*, **14**(2), 557-577.

Cashion, T., Hornborg, S., Ziegler, F., Hognes, E.S., Tyedmers, P. 2016. Review and advancement of the marine biotic resource use metric in seafood LCAs: a case study of Norwegian salmon feed. *The International Journal of Life Cycle Assessment*, **21**(8), 1106-1120.

Cederberg, C., Persson, U.M., Neovius, K., Molander, S., Clift, R. 2011. Including carbon emissions from deforestation in the carbon footprint of Brazilian beef. *Environmental Science & Technology*, **45**(5), 1773-1779.

Earles, J.M., Halog, A. 2011. Consequential life cycle assessment: a review. *The International Journal of Life Cycle Assessment*, **16**(5), 445-453.

Edwards, R., Mulligan, D., Marelli, L. 2010. Indirect land use change from increased biofuels demand. *Comparison of models and results for marginal biofuels production from different feedstocks., EC Joint Research Centre, Ispra*.

Efole Ewoukem, T., Aubin, J., Mikolasek, O., Corson, M.S., Tomedi Eyango, M., Tchoumboue, J., van der Werf, H.M.G., Ombredane, D. 2012. Environmental impacts of farms integrating aquaculture and agriculture in Cameroon. *Journal of Cleaner Production*, **28**(Supplement C), 208-214.

FAO. 2011. Aquaculture development. 5. Use of wild fish as feed in aquaculture. . Food and Agricultural Organization of the United Nations.

Farmery, A.K., Jennings, S., Gardner, C., Watson, R.A., Green, B.S. 2017. Naturalness as a basis for incorporating marine biodiversity into life cycle assessment of seafood. *The International Journal of Life Cycle Assessment*, 1-17.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C. 2011. Solutions for a cultivated planet. *Nature*, **478**(7369), 337-342.

García-Ortega, A., Martinez-Steele, L., Gonsalves, D., Wall, M.M., Sarnoski, P.J. 2015. Use of biofuel by-product from the green algae Desmochloris sp. and diatom Nanofrustulum sp. meal in diets for nile tilapia Oreochromis niloticus.

Gnansounou, E., Panichelli, L., Dauriat, A., Villegas, J.D. 2008. Accounting for indirect land-use changes in GHG balances of biofuels: Review of current approaches. *Working Paper*. Laboratoire de Systèmes Énergétiques, Ècole Polytechnique Fèdèrale de Lausanne.

Hasan, M. 2012. *Transition from low-value fish to compound feeds in marine cage farming in Asia*. Food and Agriculture Organization of the United Nations.

Hertel, T., Golub, A., Jones, A., O'Hare, M., Plevin, R., Kammen, D. 2009. Global land use and greenhouse gas emissions impacts of US Maize ethanol: the role of market-mediated responses. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University.

Huntington, T., Hasan, M.R. 2009. Fish as feed inputs for aquaculture–practices, sustainability and implications: a global synthesis. in: *Fish as feed inputs for aquaculture: practices, sustainability and implications*, Vol. 518, FAO Rome, pp. 1-61.

Ju, Z.Y., Davis, S., Ramm, K., Steck, M., Soller, F., Fox, B.K. 2017. Effects of microalgae‐added diets on growth performance and meat composition of tilapia (Oreochromis mossambicus). *Aquaculture Research*.

Kiron, V., Phromkunthong, W., Huntley, M., Archibald, I., Scheemaker, G.d. 2012. Marine microalgae from biorefinery as a potential feed protein source for Atlantic salmon, common carp and whiteleg shrimp. *Aquaculture Nutrition*, **18**(5), 521-531.

Kiron, V., Sørensen, M., Huntley, M., Vasanth, G.K., Gong, Y., Dahle, D., Palihawadana, A.M. 2016. Defatted biomass of the microalga, Desmodesmus sp., can replace fishmeal in the feeds for Atlantic salmon. *Frontiers in Marine Science*, **3**, 67.

Kissinger, K.R., García-Ortega, A., Trushenski, J.T. 2016. Partial fish meal replacement by soy protein concentrate, squid and algal meals in low fish-oil diets containing Schizochytrium limacinum for longfin yellowtail Seriola rivoliana. *Aquaculture*, **452**, 37-44.

Langlois, J., Fréon, P., Steyer, J.-P., Delgenès, J.-P., Hélias, A. 2015. Sea use impact category in life cycle assessment: characterization factors for life support functions. *The International Journal of Life Cycle Assessment*, **20**(7), 970-981.

Lapola, D.M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., Priess, J.A. 2010. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the national Academy of Sciences*, **107**(8), 3388-3393.

Libralato, S., Coll, M., Tudela, S., Palomera, I., Pranovi, F. 2008. Novel index for quantification of ecosystem effects of fishing as removal of secondary production. *Marine Ecology Progress Series*, **355**, 107-129.

Luong, A.D., Schaubroeck, T., Dewulf, J., De Laender, F. 2015. Re-evaluating Primary Biotic Resource Use for Marine Biomass Production: A New Calculation Framework. *Environmental Science & Technology*, **49**(19), 11586-11593.

Metian, A.G.T.M. 2009. Fishing for feed or fishing for food: increasing global competition for small pelagic forage fish. *AMBIO: A Journal of the Human Environment*, **38**(6), 294-302.

Miara, A., Pienkos, P.T., Bazilian, M., Davis, R., Macknick, J. 2014. Planning for Algal Systems: An Energy-Water-Food Nexus Perspective. *Industrial Biotechnology*, **10**(3), 202-211.

Mohr, A., Raman, S. 2013. Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. *Energy Policy*, **63**, 114-122.

Muller-Feuga, A. 2000. The role of microalgae in aquaculture: situation and trends. *Journal of Applied Phycology*, **12**(3-5), 527-534.

Olsen, R.L., Hasan, M.R. 2012. A limited supply of fishmeal: Impact on future increases in global aquaculture production. *Trends in Food Science & Technology*, **27**(2), 120-128.

Pauly, D., Christensen, V. 1995. Primary production required to sustain global fisheries. *Nature*, **374**(6519), 255-257.

Plevin, R.J., Delucchi, M.A., Creutzig, F. 2014. Using attributional life cycle assessment to estimate climate‐change mitigation benefits misleads policy makers. *Journal of Industrial Ecology*, **18**(1), 73-83.

Pulz, O., Gross, W. 2004. Valuable products from biotechnology of microalgae. *Applied microbiology and biotechnology*, **65**(6), 635-648.

Qiao, H., Wang, H., Song, Z., Ma, J., Li, B., Liu, X., Zhang, S., Wang, J., Zhang, L. 2014. Effects of dietary fish oil replacement by microalgae raw materials on growth performance, body composition and fatty acid profile of juvenile olive flounder, Paralichthys olivaceus. *Aquaculture nutrition*, **20**(6), 646-653.

Rahimnejad, S., Lee, S.M., Park, H.G., Choi, J. 2017. Effects of Dietary Inclusion of Chlorella vulgaris on Growth, Blood Biochemical Parameters, and Antioxidant Enzyme Activity in Olive Flounder, Paralichthys olivaceus. *Journal of the World Aquaculture Society*, **48**(1), 103-112.
Sanchez, S.T., Woods, J., Akhurst, M., Brander, M., O'Hare, M., Dawson, T.P., Edwards, R., Liska, A.J., Malpas, R. 2012. Accounting for indirect land-use change in the life cycle assessment of biofuel supply chains. *Journal of The Royal Society Interface*, rsif20110769.
Schmidt, J.H., Weidema, B.P., Brandão, M. 2015. A framework for modelling indirect land use changes in Life Cycle Assessment. *Journal of Cleaner Production*(0).
Searchinger, T., Heimlich, R., Houghton, R., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H. 2008. *Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change*.
Shah, M.R., Lutzu, G.A., Alam, A., Sarker, P., Kabir Chowdhury, M.A., Parsaeimehr, A., Liang, Y., Daroch, M. 2017. Microalgae in aquafeeds for a sustainable aquaculture industry. *Journal of Applied Phycology*.
Shurson, J. 2012. Maize dried distillers grains with solubles (DDGS)-a new alternative ingredient in aquafeeds. *World Aquaculture*, **43**(3), 54-58.
Spolaore, P., Joannis-Cassan, C., Duran, E., Isambert, A. 2006. Commercial applications of microalgae. *Journal of Bioscience and Bioengineering*, **101**(2), 87-96.
Tacon, A.G. 2009. Use of wild fish and other aquatic organisms as feed in aquaculture–a review of practices and implications in the Americas. Food and Agriculture Organization of the United Nations.
Tacon, A.G., Metian, M.R., Tacon, M.A.G., Hasan, M.R., Metian, M. 2011. *Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects*.
Thomassen, M.A., Dalgaard, R., Heijungs, R., de Boer, I. 2008. Attributional and consequential LCA of milk production. *The International Journal of Life Cycle Assessment*, **13**(4), 339-349.
USDA Economic Research Service. 2018. Corn and other Feedgrains: Background, (Ed.) USDA. https://www.ers.usda.gov/topics/crops/corn-and-other-feedgrains/background/.

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