Land for Fish: A scenario based CGE analysis of the effects of aquaculture production on agricultural markets.

by Tobias Heimann and Ruth Delzeit

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Tobias Heimann[1] and Ruth Delzeit[2]

Abstract

Aquaculture fish production is a fast-growing food sector and increasingly relying on plant-based protein fodder to substitute fishmeal utilization. This study employs a global Computable General Equilibrium (CGE) Model to quantify the effects of plant-based fodder consumption by the aquaculture sector on agricultural markets and land use. An important attribute of our model is the explicit modelling of oilseed meals that allows for a detailed characterisation of the fodder composition for aquaculture production. For this evaluation, we conduct a scenario analysis simulating, first, the fish sector developments expected by FAO; second, a rebuilding of sustainable wild fish stocks; and third, a stronger expansion in aquaculture production with varying fishmeal supply. The results show direct effects of aquaculture production, and the reduction of fishmeal in the fodder composition, on agricultural production, land use, and food prices. However, reducing capture fisheries and fishmeal production to rebuild sustainable fish stocks, have lower effects on agricultural markets than aquaculture production comparable to the first decade of this century. Moreover, rebuilding sustainable fish stocks to achieve SDG 14 has significant negative effects on welfare and food prices in marine fish dependent regions.

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1. Introduction

Fish plays a crucial role in the human food basket as it is a rich source of proteins and further important nutrients (Troell, et al., 2014). The global consumption of fish has strongly risen in the last decades (FAO, 2018). However, the sustainability of current fish production is debatable. Even with regional quotas in place, many wild fish species are fished at an unsustainable intensive level, bringing global capture fishing to its natural limits (World Bank, 2017). While the fishing volumes for wild fish have stagnated, the increasing demand for fish is met by the fast expansion of aquaculture fish production (FAO, 2020). In the last two decades aquaculture fish production has expanded stronger than any grains or livestock production (Troell, et al., 2014). Most of this growth comes from fed-fish species, such as finfish and crustacea (FAO, 2018), which still rely on wild catch fishmeal as fodder input (Froehlich, et al., 2018a) (FAO, 2020). Froehlich et al. (2018a) advocate that in case the relevance of fishmeal as fodder is not reduced, fishmeal demand by aquaculture production growth will push forage fish capture above its ecological limits, jeopardizing the sustainability of aquaculture fish production for wild fish stocks. Already in the last years, fish farmers have started to reduce the use of fishmeal and to substitute it with plant-based protein fodder (FAO, 2018). However, this is not rooted in sustainability concerns. Tacon & Metian (2015) argue that this can be rather seen as a reaction to high prices for fishmeal due to increasing demand and decreasing supply of forage. They add, as this trend will continue, the fish sector requires alternative fodder commodities for the future.

Even when considering plant-based feed, the sustainability of aquaculture production remains uncertain. The production factor land is already under great pressure, being demanded for food production for humans and terrestrial animals, biomass provision for material and energy usage, ecosystem service provision, greenhouse gases (GHG) mitigation and capture, and many more. The questions emerge, how severe is the additional pressure on crop production and land if fishmeal is substituted by plant-based fodder? Which regions are most affected by the plant-based fodder demand of aquaculture fish production? How do global markets react if ambitioned quotas limit wild catch, so that global fish stocks may be rebuilt to sustainable levels within 15-20 years? What are the implications for welfare and food prices in developing regions? And finally, is aquaculture production a sustainable alternative for capture fisheries?

This study highlights the interdependencies and trade-offs for achieving sustainable development, as reflected by the UN Sustainable Development Goals (SDG), more precise SDG 14 (*Life under Water*), SDG 15 (*Life on Land*) and SDG 2 (*No Hunger*). Rebuilding sustainable fish stocks is stated by SDG Target 14.4. However, reducing capture fisheries can foster the demand for other animal protein sources, whose production might have effects on land use and land-use change, and thus, negatively affect the achievement of SDG 15. Furthermore, increasing demand for agricultural products can lead to higher prices. So, not only reduced availability of capture fish, but also changes in crop production and increased prices for food and feed crops can have negative effects on food security, and hence, the achievement of SDG 2. In turn, increasing aquaculture production to produce more food (SDG 2), can have negative effects on marine ecosystems through fishmeal demand (SDG 14), and on terrestrial ecosystems by increased demand for fodder crops (SDG 15). Our results put a spotlight on these trade-offs to make them visible for policymakers, so that sustainable policy design can assess and consider such trade-offs while reaching for the achievement of the SDGs.

For the first time, at our best knowledge, we will employ a global computable general equilibrium model (CGE), DART-BIOFISH, to analyse feedback effects from increasing aquaculture fish consumption on capture fisheries production and plant-based fodder demand. An important attribute of DART-BIOFISH is the explicit modelling of biofuels and their by-products (e.g. oilseed meals) which are used in the livestock industry. This allows for a detailed characterisation of the fodder composition for livestock and aquaculture, as well as the evaluation of feedback effects on land use. Land-use change through land conversion from mangroves or other land types into ponds cannot be analysed.

In section two, we provide an overview of the resource economic linkages of capture and aquaculture fisheries. Section three elaborates the model and provides a description of the implementation of the explicit fish sector. The results are described in section four, followed by a discussion and conclusion in section five.

2. Literature review

The main focus of this study is to use an applied model to simulate resource economic linkages between capture fisheries, aquaculture production, and fodder supply, and analyse their implication on agricultural markets. Already several studies highlight the resource economic mechanics between capture and aquaculture fisheries. While Anderson (1985) was the first to derive a formal model capturing the competition of capture and aquaculture fisheries on a common market, later studies also integrate interaction caused by fishmeal and oil consumption in the aquaculture industry (Mullon, et al., 2009) (Merino, et al., 2010) (Regnier & Schubert, 2017) (Bergland, et al., 2019). Most fishmeal production comes from small pelagic forage fish species that play a crucial role in the natural marine food chain (Tacon & Metian, 2009). Naylor et al. (2000) elaborate on the ecological links between aquaculture and capture fisheries, arguing that an extensive and unsustainable expansion of aquaculture farming can pose significant threats for both fishing industries due to ecological overexploitation. Mullon et al. (2009) provide an explicit model of the global fishmeal and fish oil market, which is employed by Merino et al. (2010) and Merino et al. (2012) to analyse feedback effects from aquaculture production on fishmeal production and prices. These studies support the remarks by Naylor et al. (2000), who advocate for smart fisheries governance to protect the ecosystem and meet societal needs, and emphasize the relevance of alternative plant-based protein sources for fish fodder. A crucial factor is the “Fish In - Fish Out” (FIFO) ratio that determines the efficiency of aquaculture in terms of fishmeal consumption (Merino, et al., 2012).

Regnier and Schubert (2017) employ a Lotka-Volterra type model to assess implications of aquaculture farming on biological resources and consumer utility. Also here, a key parameter is the technological efficiency which basically indicates how much fish is required for aquaculture production, and thus reflects the FIFO ratio. This ratio can be reduced by either technological progress, thus feeding efficiency and the substitution of fishmeal by plant-based feed, or by shifting the production to less carnivorous species (Regnier & Schubert, 2017). In our research, the FIFO depends on the input prices of the respective fodder items and their elasticity of substitution, thus this fishmeal efficiency parameter is price-driven. In addition, changes in the FIFO can be interpreted as technological improvements and adjustments in the composition of cultivated species. In fact, the aquaculture industry implemented significant innovations in feed composition and feeding efficiency in recent years, leading to a reduction of the FIFO ratio (Kobayashi, et al., 2015) (FAO, 2020).

Taking into account the results of our paper and the study of Regnier and Schubert (2017), demonstrates how evidence from analytical and applied models can be used complementary to deliver a more holistic picture of the implicit effects of an economic activity. While Regnier and Schubert (2017) conduct a detailed theoretical analysis of effects from aquaculture production on the marine ecology, we concentrate on the key aspect of fishmeal efficiency improvements, and look at their implications on agricultural markets and land use.

The land use of aquaculture fish production has so far been a neglected topic in CGE based food market analysis. Kobayashi et al. (2015) employ the partial equilibrium model IMPACT from the International Food Policy Research Institute (IFPRI) to conduct scenario-based projections on capture and aquaculture fish production until 2030. However, they do not evaluate feedback effects on land-use change and agricultural markets. Froehlich et al. (2018b) use a static agricultural sector model to estimate feed and land-use linkages considering aquaculture in 2050. They conclude that even if one-third of the global protein demand of humans is met by fish, due to the high feed efficiency of aquatic species, the impact on land use compared to livestock is rather low. Nevertheless, Tacon and Metian (2015) state that while compared to the livestock sector aquaculture is yet consuming only a very small fraction of terrestrial compound feed on a global scale, due to the regional concentration of aquaculture production it looks different on regional markets. According to the FAO (2020) Asia accounts for 89% of aquaculture production, while already China alone is responsible for 68% of global production in 2018. With the DART-BIOFISH model, we are able to recognize which regions are most affected by feedback effects through agricultural markets.

3. Method

3.1. The DART Model

The Dynamic Applied Regional Trade (DART) model is a multi-sectoral, multi-regional recursive dynamic Computable General Equilibrium (CGE) model of the world economy (e.g. Springer 1998). It is based on recent data from the Global Trade Analysis Project (GTAP) covering multiple sectors and regions (Aguiar, et al., 2016). The economy in each region is modelled as a competitive economy with flexible prices and market clearing conditions. DART-BIO is the land-use version of the DART model and shares the same core characteristics. However, DART-BIO focuses on the heterogeneity of land, the complex production process chains of biofuels and therefore includes several activities/commodities not present in the original GTAP database.

The DART-BIO model is calibrated based on the GTAP 9 database (Aguiar et al., 2016), which represents the global economy in 2011 and covers 57 sectors and 140 regions. To incorporate biofuels and their by-products into the DART-BIO model, several sectors are split and added to the standard GTAP 9 database as explained in detail in Delzeit et al. (2021). The DART-BIO model includes conventional bioethanol production from sugar cane/beet, wheat, maize, and other grains; and conventional biodiesel production from palm oil, soybean oil, rapeseed oil, and other oilseed oils. It further includes the production of by-products generated during the production process of biofuels like dried distillers grains with solubles (DDGS) of the production of bioethanol from grains and oilseed and meals/cakes of the vegetable oil industry (see Calzadilla et al., 2016 for details). Figure 1 shows the implemented production pathways for biodiesel and the coproduction of feed for the livestock and aquaculture industry.

In order to account for land heterogeneity, the DART-BIO model incorporates the agro-ecological zone (AEZ) database (Lee, et al., 2005) (Baldos, 2017). Thus, we use 18 GTAP-AEZs, covering six different lengths of growing period spread over three different climatic zones. Within each AEZ and region, the land is allocated to different uses (i.e. cropland, pasture, and forest) via a constant elasticity of transformation (CET) structure (for details see Delzeit et al., 2021).

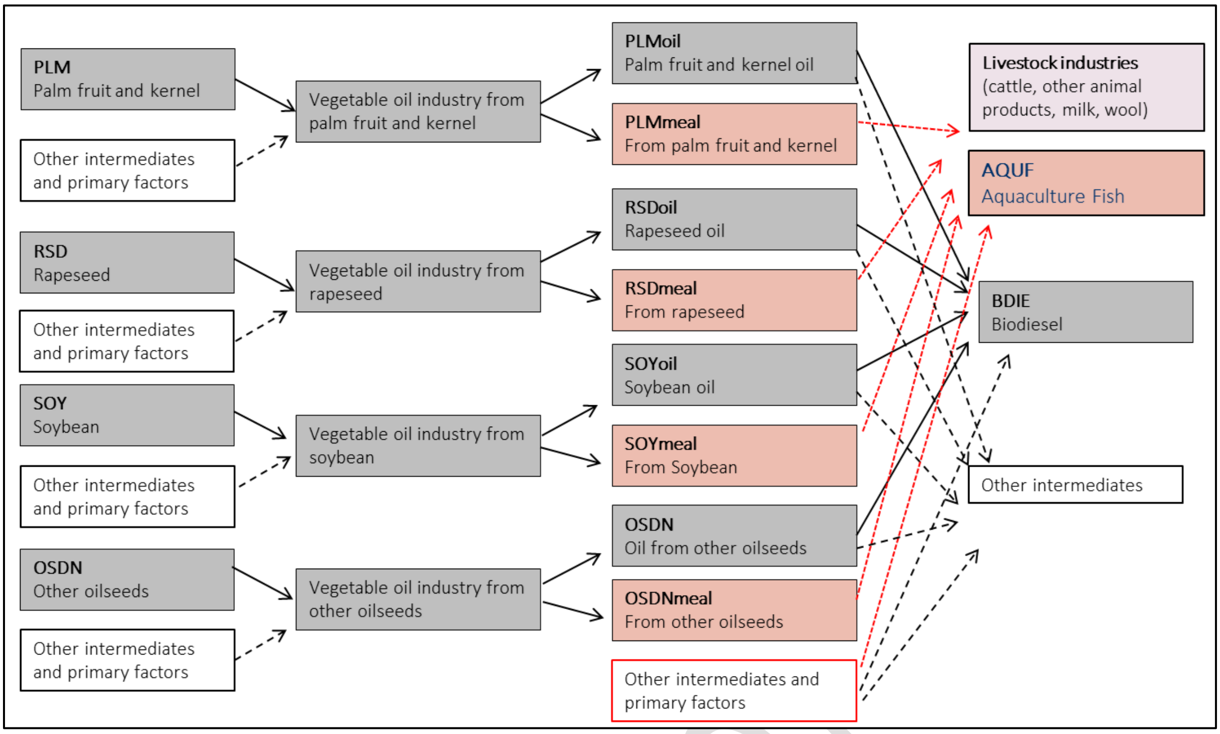

Figure 1: Oilseed oil and meal co-production in the DART-BIO model

In addition to the DART-BIO sectors, three fish sectors (capture fisheries, aquaculture production, fishmeal production) are added for creating the database for the new version called DART-BIOFISH. In this version, we can account for interdependencies of capture fisheries and aquaculture production via consumption preferences for fish products, and substitution possibilities for fishmeal and plant-based fodder in aquaculture fish production. Figure 2 provides an overview of the linkages between the respective sectors. The two sectors for processed capture and aquaculture fish are aggregated to the general food sector, to reduce the number of sectors in the model. The fishmeal sector also captures fish oil production but is referred to as fishmeal within this paper. Furthermore, the appendix holds a precise description of the preparation of the DART-BIOFISH database. We devoted special attention to the construction of realistic feed shares in the aquaculture industry. The fodder composition is based on Pahlow et al. (2015) who provide species-specific estimates on 88% of all global commercial feed-fed fish. The aquaculture sector in the DART-BIOFISH model consists only of species on which we have the information on fodder composition. Compared to the FAO data on aquaculture production (FAO, 2020), this translates to 80% of total fed fish aquaculture.

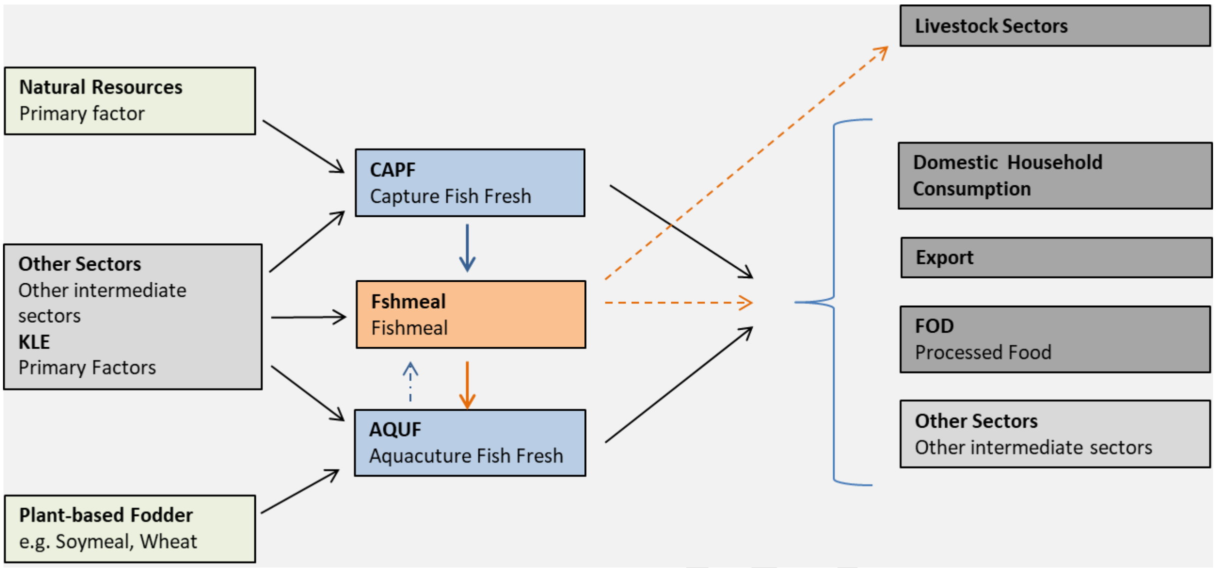

Figure 2: Fish sectors in the DART-BIOFISH model

A full list of sectors can be found in the appendix, as well as the regional aggregation which differentiates the main biofuel producing and consuming countries in line with the focus of the model on analyzing dynamic effects of bioenergy and land-use policies.

3.2. Fish Sector Specifications

As described in Calzadilla et al. (2016) the production of goods and services in the DART model follows a nested production structure with constant elasticities of substitution (CES). When modelling aquaculture fish production, we need to define a production structure of this sector. This is displayed in Figure 3. For protein feed like fishmeal or oilseed crop meal, we use a substitution elasticity of 2, which is the same as for feed in livestock production. That value is chosen because it can be assumed that the feed items are imperfect substitutes and thus, the elasticity should be larger than 1. Since there is no empirical data for these elasticities, we test the sensitivity in a sensibility analysis (see section 4). Considering the nesting of protein and non-protein feed we decided for no substitution. On the one hand, there are no reliable estimations on substitution elasticities between those two food categories, as they may be very fish-specific. And on the other, fish needs a certain protein intake to grow and develop. Thus, we assume that the share of protein feed must remain constant over time, while we allow for substitution within the source for protein. In the sectors for processed food (FOD) and services (SERV) (e.g. restaurants) we allow for an imperfect substitution of meat and fish products. Research has shown that fish consumption is related to marked developments of meat products, in particular poultry and pig meat (Troell, et al., 2014) (FAO, 2018), which are reflected by the sector *"Indoor Livestock"* (ILVS) in our model. Therefore, we also select a substitution elasticity of 2 for animal products in the production structure of FOD and SERV.

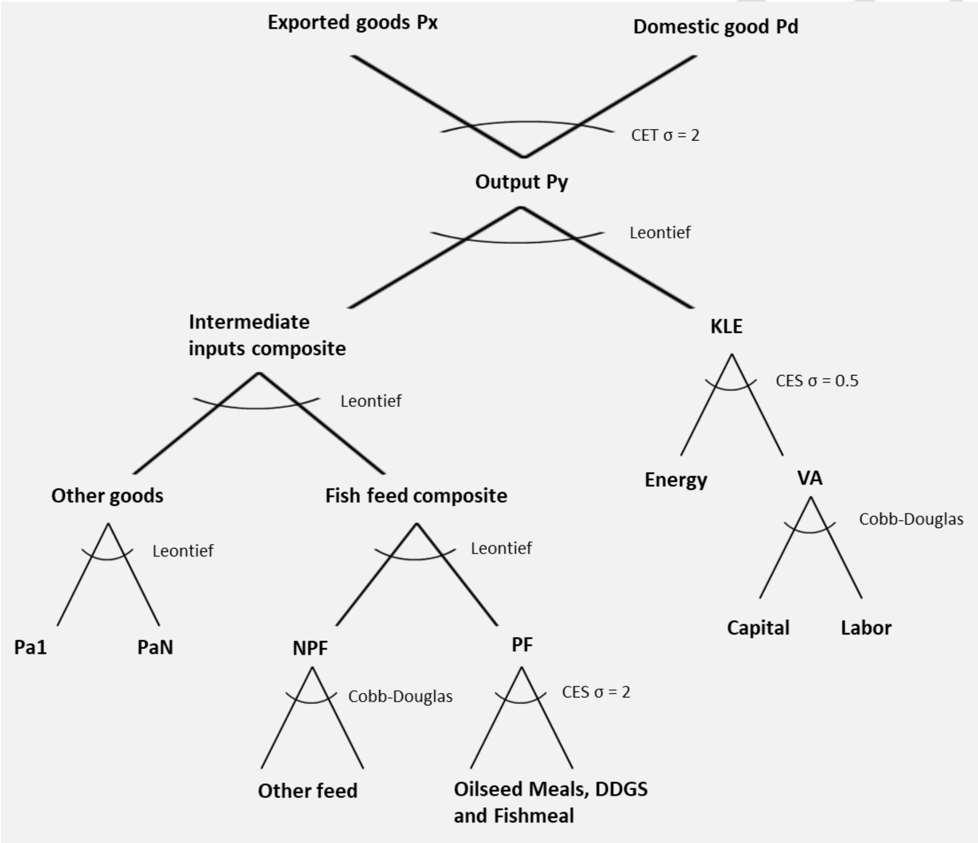

Figure 3: Nesting of aquaculture production in DART-BIOFISH

On the demand side of the model, consumer preferences follow the linear expenditure systems (LES) implemented in DART. Since we cannot differentiate between fish species and catch origin, we assume the same income elasticities for aquaculture and capture fish as provided by GTAP for the initial fish sector.

3.3. Scenarios

To evaluate the interdependencies of capture fisheries, aquaculture, and crop production, a scenario analysis is employed. Table 1 provides an overview of the quantification. While the model runs from 2011 to 2030, the analysis only concentrates on the time span of 2018 to 2030. The years 2011 to 2018 are used to calibrate the fish production shares of 2018 as explained in the appendix. In this period the model is identical for all scenarios.

The *Baseline* follows the FAO estimations from the 2020 version of “The State of World Fisheries and Aquaculture” report. For the *SDG14* scenario, we assume ambitious total allowable catch (TAC) quotas to rebuild sustainable fish stocks until 2030 such that the target 14.4 of the SDGs is achieved. The quantification for rebuilding sustainable marine fish stocks reflects the moderate path of the World Bank Report *“The Sunken Billions Revisited”* (World Bank, 2017).

The share of fish protein in the human diet increases with rising per capita incomes (FAO, 2020). So, not only population growth leads to more fish consumption, but also economic growth. However, production factors like insufficient transport infrastructure and disease control, but also governance and regulatory constraints hinder the growth of aquaculture production (Troell, et al., 2014) (Gentry, et al., 2017) (OECD/FAO, 2017). We assess the impact of overcoming these barriers to growth by two additional scenarios, namely *FGrow* and *LimFishm*. In both scenario we model a stronger growth for the aquaculture sector. We decided to assume a doubled annual growth rate of the FAO projection for aquaculture production, because this approximately reflects the historic growth rate of the aquaculture sector in the first decade of this century (FAO, 2020). In addition, in the *LimFishm* scenario, fishmeal becomes scarce so that the global production quantities remain on the same level as in the FAO projection. This scenario accounts for the projection that with increasing demand, an increase in fishmeal production from fodder fish is not expected due to regulations to protect fish stocks as well as high costs and required effort for enlarging catch activities driven by shrinking fish stocks (FAO, 2020).

Considering the dynamics of the model, total factor productivity (TFP) is calibrated according to the GDP estimation of the OECD, and population growth is also taken from the OECD (FAO/OECD, 2020). The average global agricultural productivity growth is at 1.2% which is in line with the estimations of the FAO/OECD Agricultural Outlook (ebid.). These dynamics are identical for all scenarios.

Table 1: Scenario Quantification

Scenario ***Sector***	**FAO Projection (Baseline)**	**Achieve SDG 14 (SDG14)**	**Fast Growth (FGrow)**	**Limited Fishmeal Supply (LimFishm)**
Capture Fisheries	Region-specific FAO projection	Reduction by 5% p.a. from 2018 – 2023, then constant	Region-specific FAO projection	Region-specific FAO projection
Aquaculture Production	Region-specific FAO projection	Region-specific FAO projection	Double growth rate of region-specific FAO projection	Double growth rate of region-specific FAO projection
Fishmeal Production	Global production constant from 2018 - 2030	Endogenous	Endogenous	Global production constant from 2018 - 2030

4. Results

4.1. Global Perspective

4.1.1. Global Markets

The first section of the results provides an overview of the scenario effects on global agricultural markets. Figure 4 displays the *Baseline* development of fish production, and the most relevant fish feed sectors, over time. By scenario design, capture fisheries and fishmeal production stay nearly constant, while global aquaculture production increases by 2.4% p.a.. This leads to strongly increasing prices for fishmeal, and capture fish prices increase faster than prices for aquaculture fish. In the *Baseline* scenario, soybean meal production expands most with moderately rising prices scoring about half the price level of fishmeal.

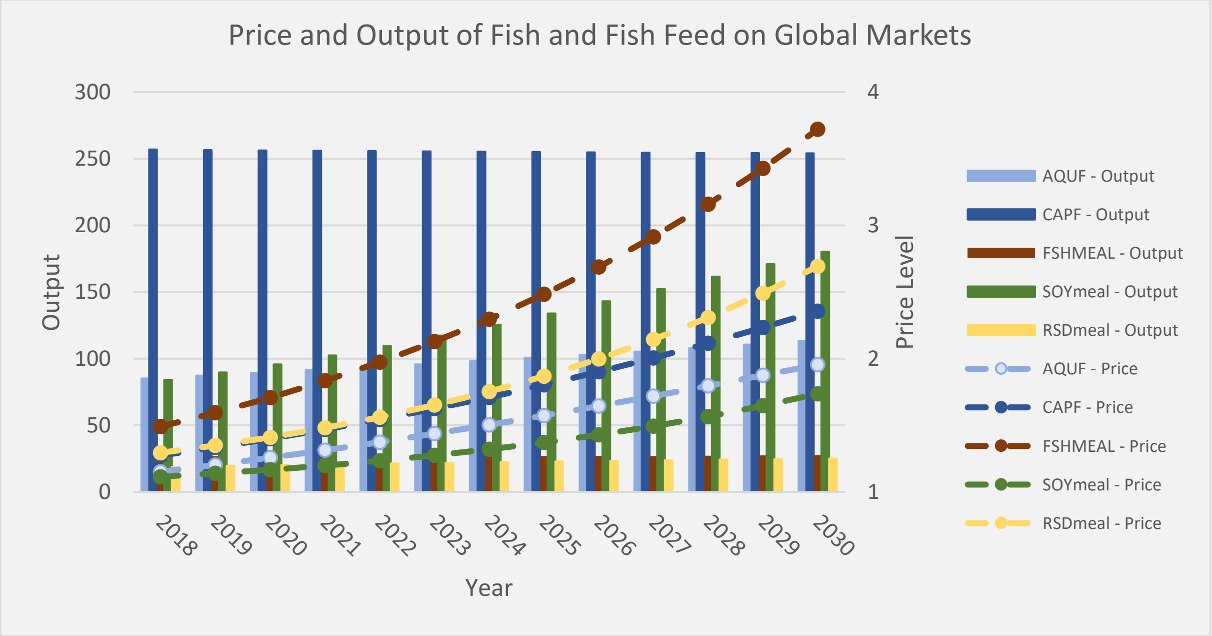

Figure 4: Baseline development of the global production and prices for fish and major fish feed 2018-2030.

Fehler! Verweisquelle konnte nicht gefunden werden. shows the differences in the scenario result in 2030 compared to the *Baseline* scenario. Rebuilding sustainable fish stocks in scenario *SDG14* results in 21.8% lower wild fish catches and causes a price spike of 37.6%. This strong price jump must be kept in mind, when analyzing the effects of the *SDG14* scenario on food security, especially in coastal regions. Furthermore, we see 17.6% lower fishmeal production. The reaction of the fishmeal sector is mirrored by the oilseed meal sectors, which show a moderate price effect but a larger expansion in production by 4.8% to 12.5%. Interesting is the strong joined reaction of fishmeal and oilseed meal sectors in scenario *FGrow*, in which aquaculture production is 32.9% higher than in the *Baseline*. In scenario *LimFishm* fishmeal is much more expensive, and as a result, production and price of the oilseed meals are the highest of all scenarios. In all scenarios we can observe feedback effects on crop production and prices, as shown in the upper third of table 2.

Table 2: Global production and prices for agricultural commodities and feed. Differences to Baseline Scenario. Output in bill. USD.

Sector	**Baseline Output 2030**	**Output**			**Price**		
		Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
WHT	321.27	0.1%	0.3%	0.2%	0.8%	1.6%	2.1%
MZE	311.80	0.1%	-0.4%	-0.6%	0.9%	1.7%	2.5%
AGR	2311.08	-0.2%	-0.1%	-0.3%	0.7%	1.5%	2.0%
RSD	70.68	2.1%	4.5%	7.3%	1.3%	2.8%	4.1%
SOY	252.64	1.6%	2.5%	3.9%	1.3%	2.2%	3.1%
OSDN	130.56	0.7%	1.2%	2.0%	0.8%	1.5%	2.1%
OLVS	986.74	0.8%	-0.5%	-0.6%	1.4%	-0.5%	-0.3%
ILVS	1388.51	1.2%	-1.8%	-2.1%	0.6%	0.7%	1.1%
AQUF	113.14	1.6%	32.9%	32.9%	3.9%	-18.3%	-18.1%
CAPF	254.00	-21.8%	0.0%	0.0%	37.6%	2.7%	3.6%
FSHMEAL	27.58	-17.6%	22.8%	0.0%	27.8%	4.2%	31.1%
RSDmeal	24.89	7.3%	16.0%	26.2%	3.2%	8.1%	10.6%
SOYmeal	180.22	4.8%	7.4%	11.6%	1.4%	2.7%	3.8%
OSDNmeal	16.24	12.5%	25.2%	34.4%	2.1%	4.2%	8.2%

Considering the livestock and fish sectors, two observations need to be pointed out. First, changes in the fish sector have implications on the livestock sector, in particular for indoor livestock (ILVS) like poultry and pig meat. A reduction in capture fisheries increases, and expanding aquaculture production decreases, the production of livestock. Therefore, in all scenarios the price for indoor livestock rises, in scenario *SDG14* due to higher demand for meat, and in *FGrow* and *LimFishm* because of higher feed prices. Second, expanding aquaculture production leads to higher prices for capture fish. The negative price effect from substituting wild catch fish by aquaculture fish in consumer diets is overcompensated by the higher demand for fishmeal that causes higher fishmeal, and thus higher capture fish, prices. As a result, in our model aquaculture production does not relieve, but rather intensify pressure on wild fish stocks.

It needs to be emphasized that aquaculture production is implemented in the model via a production quota, which absorbs the price effect of aquaculture production between scenario *FGrow* and *LimFishm*. While the price does not change significantly, the endogenous quota in scenario *LimFishm* is 10% higher than in *FGrow*, and can be interpreted as augmented price change. In addition, in scenario *SDG14* the aquaculture production quota is not binding for the region "Rest of Asia" (ROA) and we have a 1.6% higher production than intended. The reason is that outdoor livestock (OLVS) and capture fish get very expensive in that region. In this scenario and that region, aquaculture fish is in relative terms so cheap that it substitutes a large share of OLVS and CAPF consumption. A higher substitution elasticity in the intermediate production of food (FOD) would let the other even cheaper animal product sectors (ILVS, PCM) substitute a larger share of what is now covered by aquaculture fish, and thus keep the quota binding. However, implementing a customized elasticity for one region would lead to inconsistencies in the scenario design. Furthermore, it is also an interesting result that in case of achieving SDG 14 the FAO aquaculture production estimate for ROA is simulated to be too low by our model.

Furthermore, due to oilseed oil and meal being co-products from one production process, we see higher oilseed oil production and lower oilseed oil prices, as displayed in table 3. The lower prices for oilseed oil are passed through to biodiesel production. In scenario *LimFishm*, high aquaculture production combined with low fishmeal production leads to an over 20% increase in biodiesel production. However, in this study biofuel consumption is not calibrated to any climate or biofuel policy, and thus much lower than in reality. Nevertheless, the results demonstrate how the DART-BIO Model works, and that biofuel and the animal feed industry are connected.

Table 3: Global production and prices for vegetable oils and biodiesel. Differences to Baseline Scenario. Output in bill. USD.

Sector	**Baseline Output 2030**	**Output**			**Price**		
		Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
RSDoil	22.93	2.9%	5.9%	9.7%	-4.8%	-12.0%	-16.5%
SOYoil	75.79	3.9%	6.6%	10.3%	-3.8%	-5.9%	-9.2%
OSDNoil	20.74	4.5%	8.1%	10.7%	-3.0%	-5.2%	-7.2%
BDIE	22.96	8.4%	18.2%	23.4%	-1.9%	-3.6%	-4.6%

4.1.2. *Fish Feed Composition*

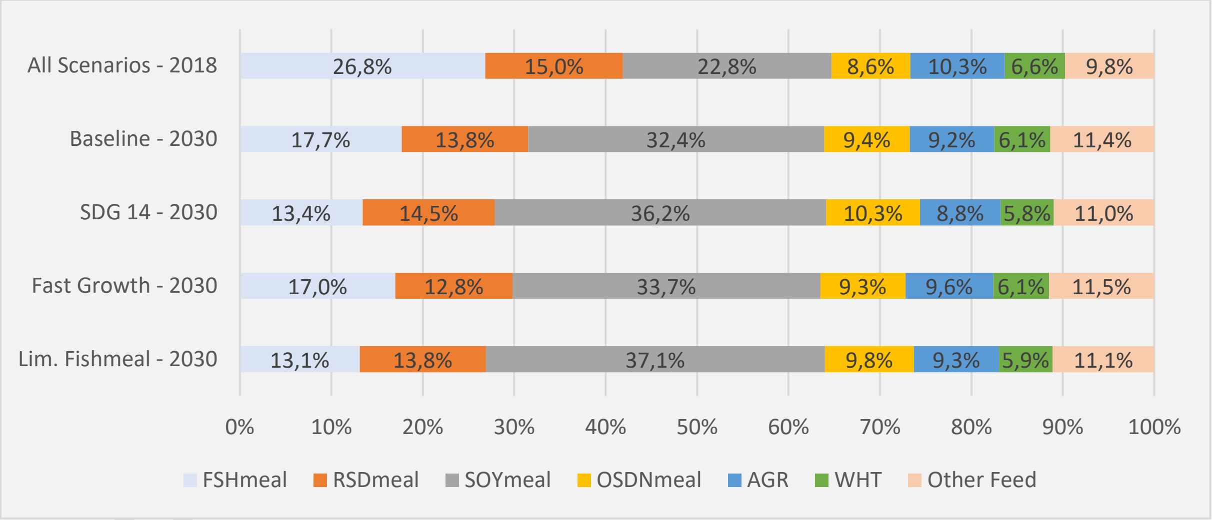

Figure 5 displays the initial global aggregated aquaculture fish sector composition in 2018, and the shares of the composition in 2030. Due to total factor productivity growth, the share of non-feed production goods and factors decrease by 6%. Considering feed stuff, already in the *Baseline* there is a clear substitution of fishmeal by soybean meal. The share of rapeseed meal stays constant, while other oilseed meals (OSDN) and other feed stuff get slightly higher shares. We can observe the expected reactions caused by the developments of prices shown in the subsection above. When fishmeal becomes increasingly expensive, it gets mainly substituted by soybean meal.

The largest substitution of fishmeal by soybean meal can be observed in the region RNE, which includes Norway. The share of fishmeal falls from 52% in 2018 to 31.3% in the *Baseline*, and 21.6% for scenario *LimFishm*, in 2030. Therefore, the soybean meal share increases from 8% in 2018 to 36% in the *Baseline*, and 52% in *LimFishm*, in 2030. The shares for scenarios *SDG14* and *FGrow* are in between the numbers of *Baseline* and *LimFishm*. Also, in ROA the share of fishmeal is reduced from 7% in 2018 to 2.6% and 2% in *Baseline* and *LimFishm* in 2030, respectively. Here, the variation between the scenarios is small as the fishmeal share is already very low in the *Baseline*. In China, we see a medium reduction of the fishmeal share from 25% in 2018 to 18% in the *Baseline* and 13% in *LimFishm*. The weaker reduction of the fishmeal share compared to RNE is rooted in lower fishmeal and high soybean meal prices in China. Thus, the incentive to substitute fishmeal is higher in RNE.

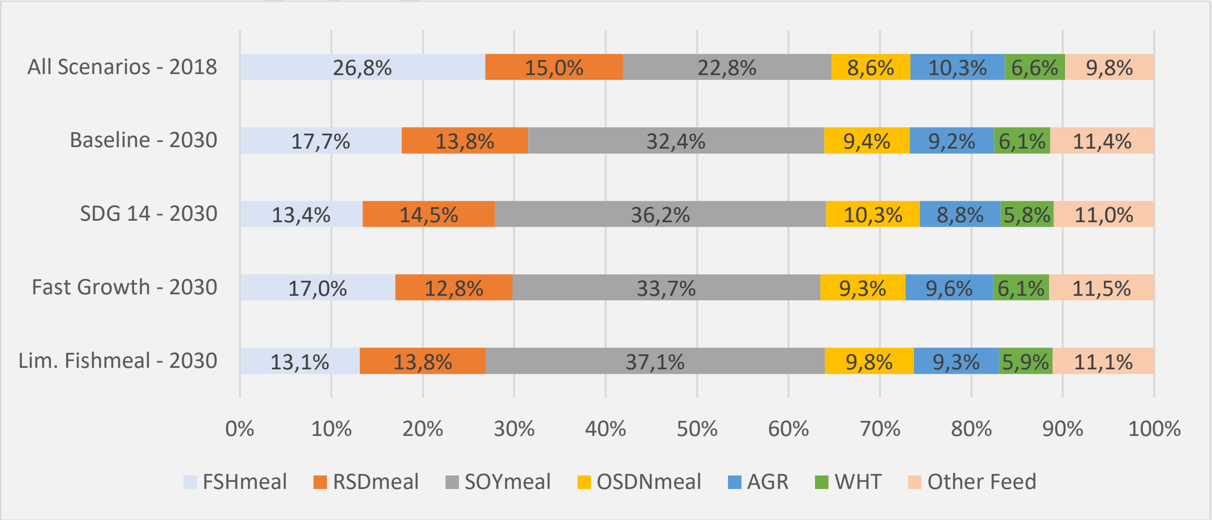

Figure 5: Fish Feed Composition Shares in 2018 and 2030, Global Aggregate.

4.1.3. *Global Fish Trade*

China is not only the biggest producer, but also the biggest net importer of captured fish and aquaculture. In case of aquaculture, second biggest importer is the EU. Figure 6 shows the net trade for aquaculture fish. Interestingly, China has fewer net imports compared to the *Baseline* in scenario *SDG14*, while ROA and the EU increase their net imports. A reason for this is the relative prices for animal products in the respective region. While aquaculture production is constant and capture fisheries reduced, for EU and ROA it is relative cheaper to substitute the capture fish reduction by importing aquaculture fish. In contrast, for China it is more beneficial to decrease net aquaculture imports due to increased prices, and substitute capture and aquaculture fisheries with indoor livestock and processed meat.

However, in scenario *FGrow* and *LimFishm* net imports rise by about 38% in China and 64% in the EU, whereas LAM and ROA switch from net importers in the *Baseline* to net exporters. Especially ROA improves its trade balance by expanding aquaculture by double the expected growth rate. In RNE, we can observe a drop in net exports between scenario *FGrow* and *LimFishm*. The aquaculture production in no other region has such a high share of fishmeal usage as in RNE. When reducing the availability of fishmeal, this region is hit particularly hard by increasing cost, making their product less competitive on global markets, and thus leading to less exports and more domestic consumption.

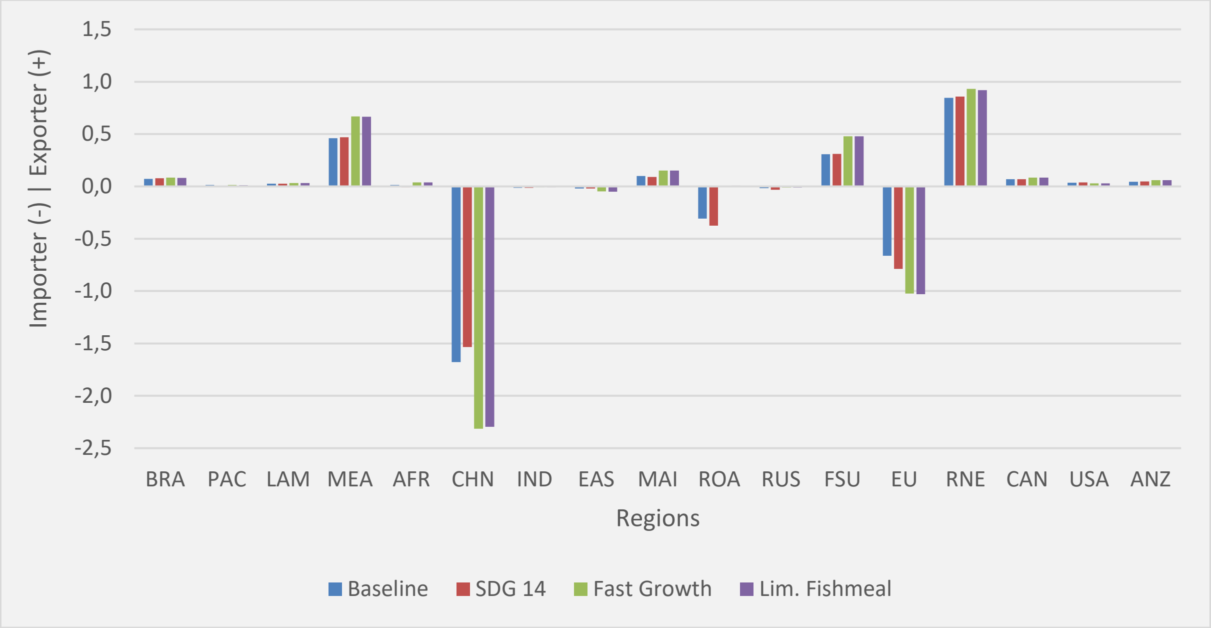

Figure 6: Net Trade of Aquaculture Fish in 2030, including trade within region. In bill. USD.

For capture fisheries, China and the EU are the largest net importer, while several regions are net exporter on comparable high levels. The net trade for capture fisheries is displayed in Figure A1 in the appendix. Figure A2 in the appendix shows net trade for soy and rapeseed. China is the main importer of both crops and import quantities increase further in each scenario, while subsequent exports of soy from Brazil and USA increase.

4.2. Regional Perspective

4.2.1. Regional Markets

The regional distribution of aquaculture and capture fisheries in the *Baseline* is demonstrated in Figure 7. China is the largest producer of both, aquaculture and capture fisheries, followed by ROA. It needs to be emphasized that aquaculture production only covers commercial feed fed fish. In Asia, and particular in China, small-scale filter fish cultivation has a long tradition (FAO, 2020), and the production shares considering total aquaculture would be much higher for these regions.

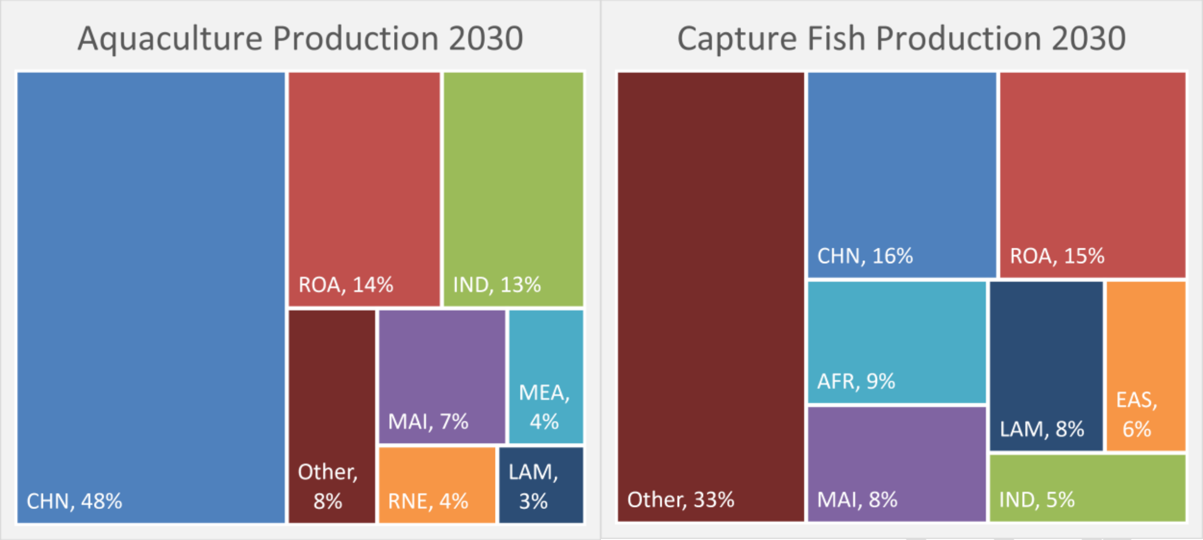

Figure 7: Aquaculture and capture fisheries production shares by region in 2030.

Table 4shows the scenario results on oilseed production in the major producing regions. The strongest relative feedback effects take place in the regions with the largest aquaculture sector. Especially China is expanding its oilseed crop and oilseed meal production. However, in absolute terms the biggest expansion of production happens for soy in Brazil. Soy production is already large in this country, and in scenario *FGrow* and *LimFishm* soy production increases by 2.2% and 3.4% respectively, compared to the *Baseline*.

Table 4: Changes in Regional Production of Oilseeds in Selected Regions.

Diff. to Baseline	**Sector**	**Region**							
		BRA	LAM	AFR	CHN	ROA	EU	CAN	USA
Δ SDG14	RSD	0.2%		1.0%	6.7%	0.2%	-0.1%	2.7%	0.1%
	SOY	1.5%	1.4%	3.5%	3.0%	11.6%	2.5%	2.7%	2.1%
	OSDN	0.1%	0.4%	0.3%	1.7%	2.0%	0.8%	0.0%	0.3%
Δ FGrow	RSD	-0.2%		2.9%	14.2%	0.7%	0.0%	5.4%	-0.1%
	SOY	2.2%	2.1%	3.8%	3.3%	22.0%	2.7%	1.8%	2.9%
	OSDN	-0.9%	1.2%	0.9%	3.0%	5.6%	1.8%	-1.7%	0.2%
Δ LimFishm	RSD	0.1%		4.8%	23.6%	1.3%	-0.1%	9.0%	0.2%
	SOY	3.4%	3.6%	6.8%	5.8%	26.1%	5.1%	2.5%	4.7%
	OSDN	-1.0%	1.2%	1.7%	5.4%	6.9%	2.4%	-2.6%	0.6%

The reduction of capture fish in scenario *SDG14* and expansion of oilseed crop production in *FGrow* and *LimFishm*, have direct implications on the prices of staple crops and the food sector. Figure 8 provides an overview on the scenario-based price differences for food, meat and staple crops in 2030. The decreased availability for fish in scenario *SDG14* leads to significant higher prices in the food sector in Sub-Saharan Africa (AFR) and the southern part of Latin America (PAC). In addition, the prices for processed meat increase in several regions, as this is a substitute for fish. In contrast, the expansion of aquaculture production in scenario *FGrow* and *LimFishm* lead to small positive and even negative price effects in the food and processed meat sectors. Therefore, we observe larger price increases for the staple crops wheat, maize, and paddy rice. The different reactions of the sectors are mainly rooted in two reasons. On the one hand, besides being substituted by cultivating oilseed crops, wheat and maize are also used as fish fodder and thus, demand and price increases when expanding aquaculture production. On the other, a large share of the aquaculture production goes into the food sector, where it is a substitute for more expensive capture fish and outdoor livestock. Staple crops, therefore, are to a much larger share directly consumed. Hence, increasing the production of aquaculture can lead to lower prices in the food sector, in particular where outdoor livestock is very expensive, like in India, MAI and ROA, but in turn lead to higher local prices for the staple crops.

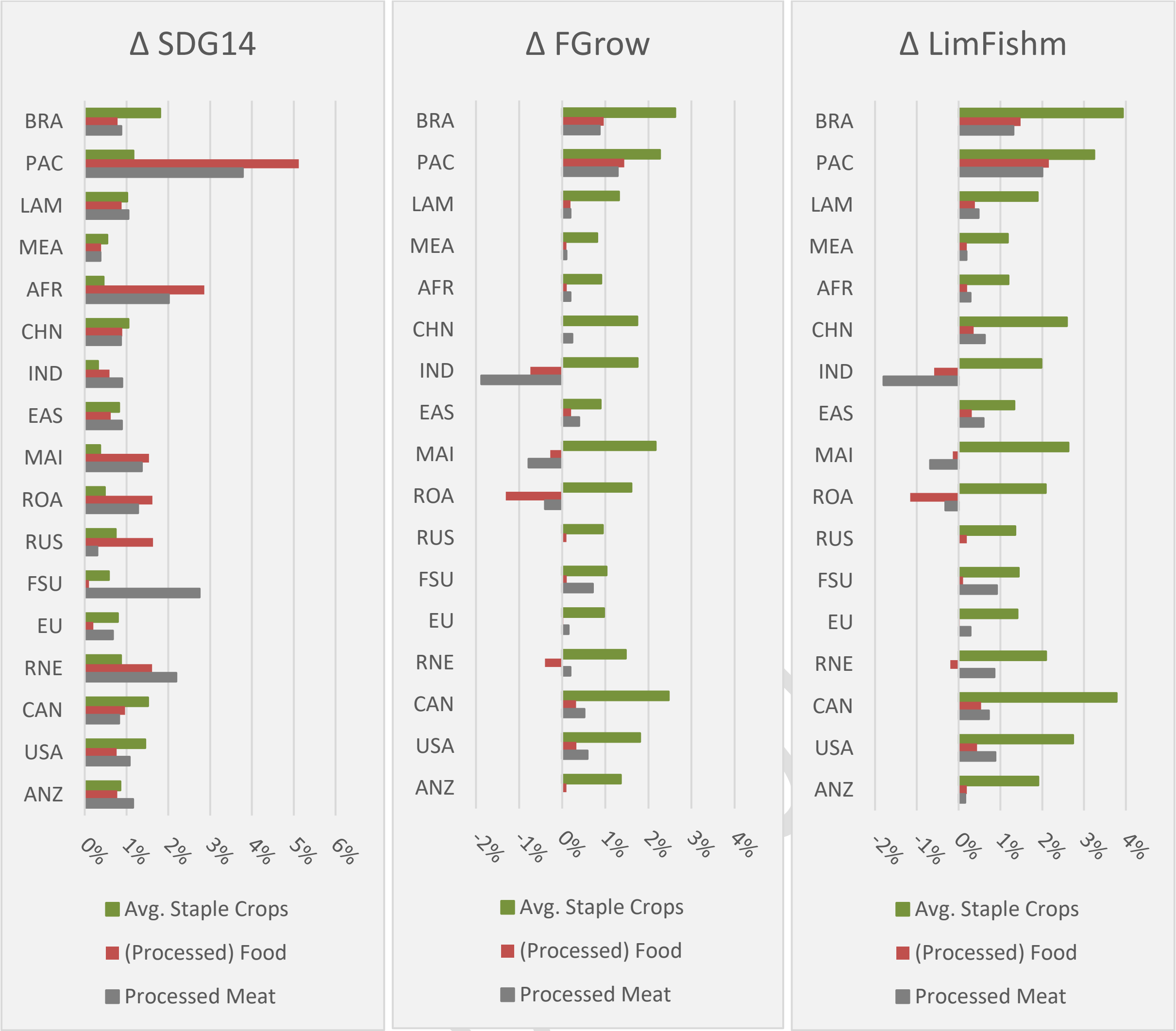

Figure 8: Regional Price Changes of Food Sectors. Change compared to Baseline in 2030. Staple Crops: Maize, Wheat, Paddy Rice.

4.2.2. Land Use

The reactions on regional and global agricultural markets of course have feedback effects on land use. Table 5 displays major changes in land use for the most affected regions. The effects are in line with the results on crop production. Increased production of aquaculture fish, and/or increased prices for fishmeal, lead to an expansion of crop land for oilseed crops. In particular for soybeans in the Americas and India, and rapeseed in the Asian regions. Already reducing capture fisheries to rebuild sustainable wild fish stocks causes a 6.6% expansion of rapeseed production area in China, compared to the Baseline. Taking twice the expected growth rate for aquaculture production while keeping fishmeal production constant, leads to 2.7% (BRA) and 4.4% (USA) more area used for soybean cultivation, and 23.4% (CHN) more area used for rapeseed production. The land expansion in these sectors mainly goes at the expense of cultivating AGR, which is a collective sector for various crops, including cash crops like coffee and cotton, but also vegetables and fruits.

Table 5: Scenario-based differences in land use in 2030. Percentage difference to baseline.

Region	Crop / Land Use	Area Baseline 2030 (in 1000 ha)	Δ SDG14	Δ FGrow	Δ LimFishm
BRA	SOY	44833	1.2%	1.8%	2.7%
	C_B	7814	-0.4%	-0.6%	-0.9%
	AGR	11160	-1.2%	-1.6%	-2.5%
	Pasture	174717	-0.1%	-0.5%	-0.7%
PAC	SOY	32524	0.3%	1.8%	2.4%
	AGR	9179	-1.0%	-1.7%	-2.4%
	Pasture	140668	1.8%	-0.2%	-0.3%
CHN	RSD	6903	6.6%	14.1%	23.4%
	SOY	3657	3.0%	3.2%	5.7%
	OSDN	6022	1.6%	2.9%	5.3%
	AGR	59942	-0.5%	-0.8%	-1.3%
	Pasture	376264	0.1%	-0.7%	-0.9%
USA	SOY	54524	1.9%	2.7%	4.4%
	AGR	48502	-1.3%	-1.0%	-1.8%
	WHT	14496	-2.3%	-1.6%	-2.8%
	MZE	26116	0.5%	-1.0%	-1.5%
ROA	OSDN	11641	2.0%	5.6%	6.9%
	AGR	28348	-0.2%	-0.3%	-0.4%
IND	WHT	36969	-0.2%	1.4%	1.3%
	RSD	6069	-0.1%	1.4%	1.4%
	SOY	8314	0.1%	2.4%	2.5%
	Pasture	9185	0.1%	-0.8%	-0.9%

The effect on wheat, maize, and pasture land are ambiguous across regions and scenarios. While we can see an expansion of pasture land in the *SDG14* Scenario, driven by the reduced supply of capture fish that leads to a higher demand for outdoor livestock, in *FGrow* and *LimFishm* the use of pasture land shrinks. This is the result of the increased supply of aquaculture fish that substitutes more expensive outdoor livestock but also driven by increased prices and demand for cropland for fish feed production. We can draw this conclusion by comparing *FGrow* with *LimFishm*. In the USA the area for maize decreases when aquaculture production increases. Also here, the substitution of capture fisheries with other animal products, for which maize is an important fodder item, plays a crucial role in scenario *SDG14*. It needs to be noted, that when comparing *SDG14* to the Baseline in general, we observe an effect from replacing the reduced fishmeal in aquaculture production (replacement effect) on the one hand, but also a substitution effect from an increased consumption of other livestock products (substitution effect).

For wheat, we see opposing developments in the USA and India. Comparing *SDG14* and *FGrow* shows that wheat and AGR in the USA are the only items that have stronger negative reactions on reducing capture fisheries, than on expanding aquaculture production. This might be the result of a strong combination of replacement and substitution effect in that region, as explained above. Also, for wheat in India, we have a unique reaction, as the expansion in *LimFishm* is lower than in *FGrow*. The is caused by small adjustments in the food sector. In contrast to wheat, fishmeal does not play a significant role in the fish fodder composition for India. Therefore, we also do not see any major effects in land-use change in scenario *SDG14*, and between *FGrow* and *LimFishm*.

4.3. Welfare Effects

A major advantage of CGE models compared to partial equilibrium and other sectoral models is that they can reflect economy-wide feedback and welfare effects. Table 6 displays the changes in real gross domestic product (GDP), aggregated income of the representative agent (AI), and consumer price index (CPI), compared to the *Baseline*. In case AI is reduced less than

CPI, or AI increases stronger than CPI, we have a positive welfare effect from an intervention, which is also reflected in a positive change in GDP.

In general, we can see that the scenarios change GDP by less than 1%. An exception is the *SDG14* Scenario in ROA, caused by reactions of their relatively big fishing industry. Sub-Saharan Africa and Asian regions are most affected by the reduction of capture fish, each experiencing loss in income and rising consumer prices. Brazil, Canada, USA and Oceania are the regions which profit from each scenario. These are regions that supply feed for livestock and aquaculture. While they profit from a higher demand for livestock and reduced fishmeal availability in the *SDG14* scenario, they benefit from increased aquaculture production in the two other scenarios. Southern America (PAC) shows particular interesting results, as in this region capture fish plays an important role, but also soybean production for animal feed. Under *SDG14* the losses from reduced capture fishery are larger than the profits from increased feed production. Therefore, in scenario *FGrow* and *LimFishm* the expanded soybean production lead to welfare gains.

The results on the *SDG14* scenario demonstrate why economic welfare indicators from CGE models may not be the best welfare measure for resource policies. Producers and consumers of capture fish lose in terms of welfare. Only regions that profit stronger from the increased price and production of capture fish substitutes experience a positive effect. However, we cannot account for changes in the health and the value of an ecosystem like the ocean, as it is not captured in our model. Moreover, rebuilding sustainable fish stocks provide long term profits, which are not reflected in the GDP of 2030. Thus, while the measurable welfare effect is negative, the unobserved intertemporal real welfare effect could be positive.

Table 6: Welfare Effects. Change compared to Baseline in 2030.

Region	**Real GDP**			**Aggregated Income**			**Consumer Price Index**		
	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
BRA	0.14%	0.22%	0.33%	0.56%	0.75%	1.11%	0.42%	0.52%	0.76%
PAC	-0.19%	0.36%	0.44%	-0.11%	0.94%	1.15%	0.19%	0.56%	0.70%
LAM	0.00%	0.02%	0.00%	0.11%	0.00%	-0.04%	0.14%	-0.02%	-0.04%
MEA	-0.17%	-0.08%	-0.12%	-0.22%	-0.23%	-0.34%	0.02%	-0.12%	-0.18%
AFR	-0.49%	0.06%	0.06%	-0.05%	0.20%	0.24%	0.76%	0.15%	0.20%
CHN	-0.43%	-0.48%	-0.74%	-0.51%	-0.92%	-1.37%	0.02%	-0.36%	-0.51%
IND	-0.43%	-0.56%	-0.61%	-0.15%	-1.19%	-1.30%	0.36%	-0.59%	-0.63%
EAS	-0.07%	-0.03%	-0.05%	-0.16%	-0.20%	-0.31%	-0.06%	-0.17%	-0.25%
MAI	-0.48%	-0.26%	-0.32%	-0.08%	-0.60%	-0.73%	0.56%	-0.29%	-0.36%
ROA	-1.24%	-0.17%	-0.28%	-0.66%	-0.52%	-0.71%	0.82%	-0.37%	-0.43%
RUS	-0.15%	-0.06%	-0.09%	-0.29%	-0.25%	-0.37%	-0.04%	-0.16%	-0.23%
FSU	-0.13%	0.01%	0.01%	-0.20%	-0.03%	-0.08%	-0.01%	-0.03%	-0.07%
EU	-0.01%	0.02%	0.03%	-0.05%	-0.09%	-0.15%	-0.03%	-0.12%	-0.18%
RNE	-0.12%	-0.10%	-0.42%	-0.19%	-0.28%	-0.79%	-0.01%	-0.17%	-0.31%
CAN	0.04%	0.13%	0.19%	0.06%	0.14%	0.20%	0.05%	0.01%	0.02%
USA	0.01%	0.05%	0.08%	0.00%	0.00%	0.00%	-0.01%	-0.05%	-0.07%
ANZ	0.03%	0.06%	0.09%	0.01%	-0.03%	-0.07%	-0.01%	-0.10%	-0.16%

Considering the *FGrow* and *LimFishm* scenario, the negative welfare effects in major aquaculture producing regions, in particular Asia, seem unexpected on a first sight. By expanding aquaculture production, one could expect increasing aggregated income from a higher activity level, decreasing prices through increased supply, and thus, a higher GDP. However, while CPI decreases, AI decreases stronger, leading to a lower GDP compared to the *Baseline*. This is rooted in two reasons. First, doubling the aquaculture growth rate is introduced as a production shock, and is not productivity or demand driven. As we shift the supply curve while the demand curve stays constant, increasing production leads to decreasing prices. Moreover, this also causes reduced demand and prices for aquaculture substitutes, and thus, to reduced income for their producers, while their costs increase due to higher feed prices from increased feed demand of the aquaculture sector. Second, we observe a small pass-through effect. While aquaculture production mainly consists of imported feed, capital and labor, the substitutes need a larger share of other sectors for their production, i.e. energy and services. As a result, also the demand for those sectors decreases slightly. Since these are very large sectors, already minor changes can have small effects on GDP. Summarized, aquaculture producing regions suffer from the production shock due to decreasing product prices and increasing feed prices, and the losses for producer (income) trump the gains for consumers (price reduction). Regions producing aquaculture feed, and regions importing aquaculture products, benefit.

For the *LimFishm* scenario these effects are fortified, as fishmeal gets scarce and expensive, which leads to higher production costs and more imports of feed from feed producing regions. Especially in China and Northern Europe we see a negative effect on GDP by this shock. Therefore, Southern America strongly profits. Here as well, potential positive welfare effects from reduced pressure on marine ecosystems by limiting the use of fishmeal compared to the *FGrow* scenario are not reflected by our economic welfare indicators.

4.4. Sensitivity Analysis

The sensitivity analysis concentrates on the elasticity of substitution for protein feed in the aquaculture production function. As explained in the section above, we decided to use an elasticity of 2 for our evaluation. However, as this decision may have impacts on the results, we conducted a sensitivity analysis by running each scenario with half (σ=1) and double (σ=4) elasticity of substitution for protein fish feed. In addition, we split the fishmeal and oilseed meal nest and assume σ^{os}=2 for the elasticity within the oilseed meals, and σ^{fm}=1 for the elasticity between oilseed meals and fishmeal. A low elasticity assumes a slow technological development in enabling the substitutability of fishmeal in fish feed, while a high elasticity assumes a fast technological development.

The results show the expected reactions of the model. Figure A3 in the appendix provides the new shares of fish fodder composition in 2030 for each scenario conditional on the elasticity of substitution. The variation of fodder composition between the scenarios very similar across the different elasticities. With the low elasticity, the share of fishmeal is reduced from 23% (*Baseline*) to 19% (*LimFishm*), and from 11% (*Baseline*) to 7% (*LimFishm*) in case of a high substitution elasticity. Thus, the changes in fishmeal shares are relative robust across scenarios, while we see large differences comparing the elasticities within a scenario. In the model with the high elasticity, the share of fishmeal in the fodder composition is already 5.5% lower in 2018, and throughout all scenarios 12% lower in 2030, compared to the model with the low elasticity. The model with the split nesting delivers similar results as the model with the low elasticity, but we can observe a higher substitution between soybean meal and rapeseed meal. Conclusively, the aggregated oilseed meals are cheaper than in low elasticity model, which causes a slightly higher consumption of total oilseed meals and a lower usage of fishmeal.

The results of the sensitivity analysis for global production and prices are presented in the appendix Table A4 and Table A5. Sectors that are not directly affected by aquaculture and capture fish production do not show any large variation caused by the different elasticities. For the fish and fish feed sectors, it looks different. The low elasticity leads to higher prices for fish products, and lower prices for their substitutes, while it is the opposite when applying the higher substitution elasticity. Also, the differences in prices and production in the scenarios compared to the respective *Baseline* indicate the expected outcomes. With a high substitution elasticity, quantity effects are larger and price effects smaller for the fish sectors and relatively expensive feed, like rapeseed meal. For relative cheap feed, like soybean meal, the opposite is the case. The quantity and price changes of the model with the split nesting lies between the model with low elasticity and the standard model with $\sigma=2$. The only exception is the production quantity of rapeseed and rapeseed meal, because while it substitutes fishmeal in the standard model, it is substituted by soybean meal in the split nest model. In general, besides for livestock production, the results are closer oriented towards the standard model than to the low elasticity model.

5. Discussion and Conclusion

This study reveals the linkages of the marine and aquaculture fish sectors with agricultural markets. We have shown that expanding aquaculture production and/or reducing the share of fishmeal used in fish feed, leads to increased production of oilseed crops. In case of the most extreme *LimFishm* scenario, the additional cultivated soybean area equates to 1.2 times the area of the Netherlands. The land required for this production expansion is absorbed from maize, sugar, and various other crops. As a result, we also see rising prices for staple crops. Especially in the Americas, and China regional effects for land-use change and price reactions are observed.

A shortcoming of this model is that we do not control for consumers' preferences for fish species, and allow fishmeal to be largely substituted in the regional specific fish fodder composition. As shown by the sensibility analysis, the feedback effects of aquaculture on land use depend on the technical substitutability of fishmeal. Soybean meal production is much cheaper and can be easily expanded, compared to fishmeal production. Thus, if technically feasible, it is profitable for fish farmers to abstain from using fishmeal as fodder. However, not all protein intake of fish can be substituted by plant-based feed, and especially fish oil is difficult to replace (Naylor, et al., 2009), which is a co-product of fishmeal production (Mullon, et al., 2009). Also, consumers rather prefer carnivorous fed fish species that makes it difficult for producers to change the production portfolio towards more herbivorous or filter fish species (Regnier & Schubert, 2017) (FAO, 2020). The future will show to which extent fodder formulations can be optimized to minimize the dependencies on fishmeal, or if fish breeding techniques can lead to the cultivation of more herbivorous fed fish aquaculture that satisfies consumer preferences. Expectations on the technical progress is determined by the elasticity of substitution in the feed nest, and therefore the reaction of producers towards changes in relative (input) price, which ultimately impacts on the resulting changes in production and prices. However, for the scenario comparison, the elasticities play only a minor role because the changes between the scenarios only show low variations when applying different elasticities. Thus, the results of the scenario analysis can be considered reasonable robust.

Questions considering the consequences of our scenarios for marine and terrestrial ecosystems are answered superficially by this study. As shown in the results section, aquaculture production causes land-use change for oilseed crop production. However, ecological effects from constructing fish and shrimp ponds (Ali, 2006) (Tran, et al., 2015), water pollution, diseases, and intermixture of wild and farmed species are not part of this study but need to be considered for a holistic evaluation (Naylor, et al., 2000) (Klinger & Naylor, 2012). A further aspect is the sustainable management of marine resources. On the one hand, in our model aquaculture production leads to increasing capture fish prices due to fishmeal demand. This confirms the misgivings stated by Froehlich et al. (2018a) that forage fish demand may push wild fish stocks beyond their ecological limits. On the other, we see negative welfare effects from rebuilding sustainable fish stocks to achieve the SDG target 14.4 but cannot account for positive welfare effects from maintaining the marine ecosystem. This adds to the “Beyond GDP” debate, as it shows that common economic welfare indicators are unable to capture all assets that are crucial for sustainable human welfare (Dasgupta, 2021).

Including the value of ecosystems and biodiversity into economic models is one of the most pressing topics for interdisciplinary modelers.

While our model allows only limited derivation on the effects on ecosystems, we provide valuable insights on the impacts on agricultural markets and land use. It is interesting to note that the effects on agricultural markets are lower when reducing the capture fishing activities to rebuild sustainable wild fish stocks, than when expanding aquaculture production at the same rate as in the first decade of this century. Thus, substituting the reduced capture fish in human diets has a lower impact, than increasing aquaculture production, whose products substitute meat as well as vegetarian food. Furthermore, as already mentioned above, the expansion of the aquaculture industries is not restricted by a lack of demand, but by production barriers which hinder a stronger growth (Gentry, et al., 2017). If the production barriers can be overcome, developments compared to our extreme scenarios *FGrow* and *LimFishm* could become realistic, leading to increased pressure on agricultural markets. In addition, in case of the *LimFishm* scenario, our results show a strong increase in prices for fishmeal. The literature sees two different implications of high fishmeal prices on the fishing sector: a) if the high prices are driven by fish scarcity, more investments into fishing efforts and hence further depletion of already scarce wild fish stocks will take place or b) in case the high prices are consequences from binding TACs, we observe resource inefficiencies due to overcapacities in the fishing sector (Mullon, et al., 2009) but in turn might be able to protect natural fish stocks (Regnier & Schubert, 2017) (Bergland, 2019).

Regarding the impact on welfare, in our scenarios expanding aquaculture production has GDP reducing effects, because in aquaculture producing regions rising prices for feed and decreasing prices for aquaculture fish overcompensate the gains for consumers from lower aquaculture prices. However, it needs to be noted that removing the barriers for aquaculture growth only allows the expansion of aquaculture production and does not improve cost efficiency. Therefore, only oilseed producing and net aquaculture importing regions profit from the aquaculture production expansion in terms of welfare.

Finally, the results of this study reveal the linkages and trade-offs between SDG 14 (*Life under Water*), SDG 15 (*Life on Land*), and SDG 2 (*No Hunger*). As results from the *SDG14* and *LimFishm* scenarios illustrate, policies to achieve SDG 14 can lead to land-use change which causes trade-offs for achieving SDG 15. But also improving the availability of fish-based protein food to support SDG 2, as assumed in scenario *FGrow* and *LimFishm*, lead to implications for achieving SDG 15 and 14 via fodder production for aquaculture cultivation. Furthermore, we show that fishing policies and aquaculture production affect regional staple food and consumer prices. Especially achieving SDG Target 14.4 can harm the achievement of SDG 2, as it causes crop prices to increase, and therefore impede access to food in particular in Sub-Saharan Africa and South-East Asia, where capture fish plays a crucial role for food security in coastal regions (FAO, 2020). However, rebuilding sustainable fish stocks leads, in the long term, to sustainable and higher catch levels than the unsustainable catch levels that are fished today (World Bank, 2017). Here, the time dimension needs to be considered, as the SDGs are targeted towards the year 2030. Rebuilding sustainable fish stocks will cause restraints in this period and conflict SDG 2, but provide benefits later on (World Bank, 2017). The findings of this paper demonstrate that the regions whose food security depend on marine fishing activities need support in the transition period until sustainable fish stocks are achieved, as they are the ones who suffer most by introducing global TACs for reaching SDG 14.

Further research needs to be conducted to find out how these trade-offs can be minimized. As an example, dietary patterns and the substitution of animal products in a human diet play a crucial role when analyzing effects on food security. It is well known that meat production requires more feed than producing the same amount of aquaculture fish (Froehlich, et al., 2018b), and energy efficient feed conversion is an important attribute in favor for aquaculture fish production (Merino, et al., 2012) (Regnier & Schubert, 2017). Thus, if aquaculture fish consumption substitutes meat consumption, we may observe falling food prices. But they might increase if aquaculture fish consumption mainly replaces vegetarian diets. To analyze such assumptions and derive more precise conclusions on food security and the potential role of aquaculture for achieving the SDGs, the food and meat sector needs to be modelled in more detail. An in-depth analysis of interactions between the meat and fish sectors, the consequences for food security, as well as the role of biofuel policies are topics for future research.

6. Literature

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Appendix

Table A1: List of Regions in DART-BIOFISH

Central and South America		Europe	
BRA	Brazil	FSU	Rest of former Soviet Union
PAC	Paraguay, Argentina, Uruguay, Chile	CEU	Central European Union with Belgium, France, Luxembourg, Netherlands
LAM	Rest of Latin America	DEU	Germany
		MEE	Eastern European Union with Austria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Romania, Bulgaria, Croatia
Middle East and Northern Africa		MED	Mediterranean with Cyprus, Greece, Italy, Malta, Portugal, Spain
MEA	Middle East and Northern Africa	NWE	North-Western European Union with Denmark, Finland, Ireland, Sweden, United Kingdom
AFR	Sub-Saharan Africa	RNE	Rest of Northern Europe: Switzerland, Norway, Lichtenstein, Iceland
Asia		Northern America	
CHN	China, Hong Kong	CAN	Canada
IND	India	USA	United States of America
EAS	Eastern Asia with Japan, South Korea, Taiwan, Singapore		
MAI	Malaysia, Indonesia	Oceania	
ROA	Rest of Asia	ANC	Australia, New Zealand, Rest of Oceania
RUS	Russia		

Table A2: List of Sectors in DART-BIOFISH

Agricultural related products (28)	
Crops	
PDR	Paddy rice
WHT	Wheat
*MZE**	*Maize*
*PLM**	*Oil Palm fruit*
*RSD**	*Rapeseed*
*SOY**	*Soy bean*
OSDN	Other oil seeds
C_B	Sugar cane and sugar beet
AGR	Rest of crops
Processed agricultural products	
VOLN	Other vegetable oils
FOD	Rest of food
*PLMoil**	*Palm oil*
*RSDoil**	*Rapeseed oil*
*SOYoil**	*Soy bean oil*
*OSDNoil**	*Oil from other oil seeds*
*SOYmeal**	*Soy bean meal*
*OSDNmeal**	*Meal from other oil seeds*
*PLMmeal**	*Palm meal*
*RSDmeal**	*Rapeseed meal*
*DDGSw**	*DDGS from wheat*
*DDGSm**	*DDGS from maize*
*DDGSg**	*DDGS from other cereal grains*
Meat, dairy and fish products	
OLVS	Outdoor livestock and related animal products (cattle and other grazing animals, raw milk and wool)
ILVS	Indoor livestock (swine, poultry and other animal products from indoor livestock)
PCM	Processed animal products
*AQUF***	*Aquaculture Fish Production*
*CAPF***	*Capture Fish Production*
*Fshmeal***	*Fishmeal*

Energy products (14)	
COL	Coal
CRU	Oil
GAS	Gas
MGAS	*Motor gasoline*
MDIE	*Motor diesel*
OIL	Petroleum and coal products
ELY	Electricity
*ETHW**	*Bioethanol from wheat*
*ETHM**	*Bioethanol from maize*
*ETHG**	*Bioethanol from other grains*
ETHS	*Bioethanol from sugar cane*
ETHL	*Bioethanol from lignocellulosic biomass*
Biofuels	
BETH	*Bioethanol*
BDIE	*Biodiesel*

Non-energy products (2)	
SERV	Services
OTH	Other goods

Forest and forest products (1)	
FRS	Forest

Table A3: Global production and prices. Differences to Baseline Scenario.

Sector	Baseline Output 2030	Output			Price		
		Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
PDR	359.24	-0.1%	-0.1%	-0.1%	0.4%	0.6%	0.8%
WHT	321.27	0.1%	0.3%	0.2%	0.8%	1.6%	2.1%
MZE	311.80	0.1%	-0.4%	-0.6%	0.9%	1.7%	2.5%
PLM	55.81	0.0%	-0.2%	-0.2%	0.8%	0.4%	0.8%
RSD	70.68	2.1%	4.5%	7.3%	1.3%	2.8%	4.1%
SOY	252.64	1.6%	2.5%	3.9%	1.3%	2.2%	3.1%
OSDN	130.56	0.7%	1.2%	2.0%	0.8%	1.5%	2.1%
C_B	118.46	-0.1%	-0.2%	-0.3%	0.3%	0.7%	0.9%
AGR	2311.08	-0.2%	-0.1%	-0.3%	0.7%	1.5%	2.0%
OLVS	986.74	0.8%	-0.5%	-0.6%	1.4%	-0.5%	-0.3%
ILVS	1388.51	1.2%	-1.8%	-2.1%	0.6%	0.7%	1.1%
PCM	1803.43	0.8%	-0.6%	-0.7%	1.0%	0.2%	0.4%
AQUF	113.14	1.6%	32.9%	32.9%	3.9%	-18.3%	-18.1%
CAPF	254.00	-21.8%	0.0%	0.0%	37.6%	2.7%	3.6%
FSHmeal	27.58	-17.6%	22.8%	0.0%	27.8%	4.2%	31.1%
PLMmeal	0.10	-0.4%	-0.3%	-0.5%	8.7%	17.1%	23.4%
RSDmeal	24.89	7.3%	16.0%	26.2%	3.2%	8.1%	10.6%
SOYmeal	180.22	4.8%	7.4%	11.6%	1.4%	2.7%	3.8%
OSDNmeal	16.24	12.5%	25.2%	34.4%	2.1%	4.2%	8.2%
DDGSw	0.55	-0.7%	-1.9%	-2.5%	2.0%	1.9%	2.8%
DDGSm	2.94	-0.9%	-2.9%	-4.2%	2.6%	2.7%	4.1%
DDGSg	0.11	-0.7%	-2.1%	-2.7%	2.0%	2.0%	2.9%
PLMoil	39.00	-0.2%	-0.2%	-0.3%	0.6%	0.2%	0.5%
RSDoil	22.93	2.9%	5.9%	9.7%	-4.8%	-12.0%	-16.5%
SOYoil	75.79	3.9%	6.6%	10.3%	-3.8%	-5.9%	-9.2%
OSDNoil	20.74	4.5%	8.1%	10.7%	-3.0%	-5.2%	-7.2%
VOLN	660.10	-0.2%	-0.6%	-0.8%	1.2%	0.9%	1.5%
BETH	19.08	-2.3%	-3.5%	-5.1%	0.1%	0.2%	0.4%
BDIE	22.96	8.4%	18.2%	23.4%	-1.9%	-3.6%	-4.6%
BDIE_PLM	0.09	-4.6%	-4.4%	-3.8%	0.2%	0.3%	0.1%
FOD	7912.91	-0.4%	-0.1%	-0.2%	0.8%	0.0%	0.1%

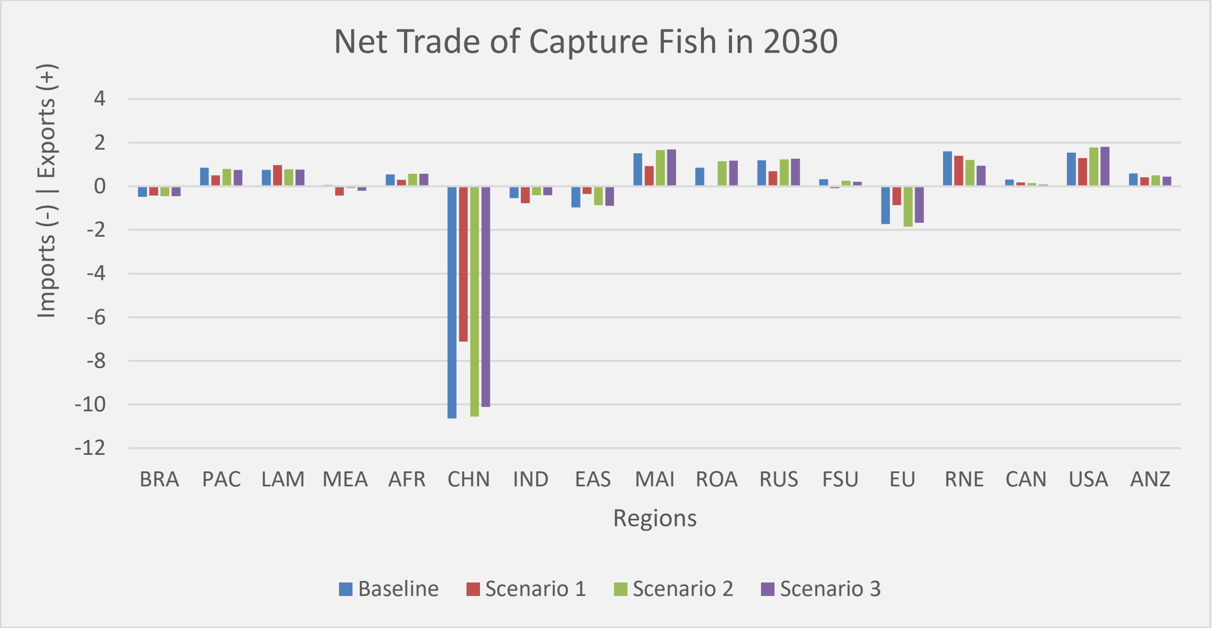

Figure A1: Net Trade of Capture Fish in 2030, in bill. USD.

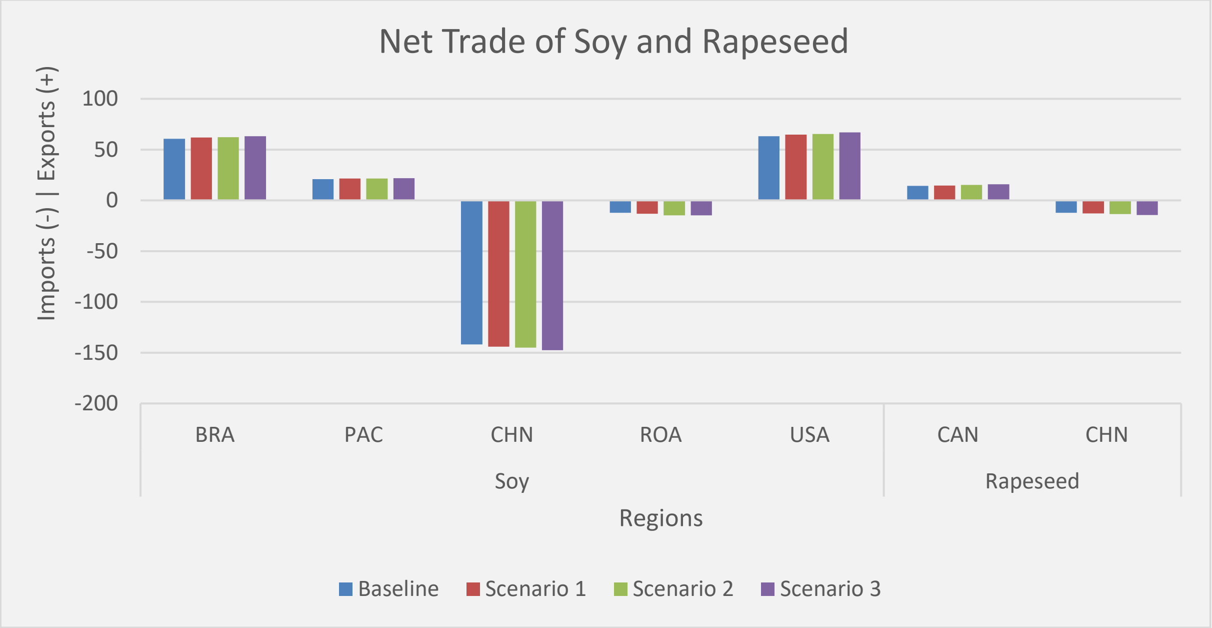

Figure A2: Net Trade of Soy and Rapeseed in 2030, in bill. USD.

Table A4: Sensitivity Analysis: Global Production with Varying Elasticity of Substitution. Differences to Baseline in 2030. Note: σ=Elasticity within fishmeal and oilseed meal nest; For analysis with split fishmeal and oilseed meal nesting: σ^{fm} = Elasticity between fishmeal and oilseed meals nets, σ^{os} = Elasticity within oilseed meals nest.

Sector	**Baseline Output 2030 (in bill. USD)**			**Output**								
	σ = 1	σ^{fm} = 1; σ^{os} = 2	σ = 4	σ = 1			σ^{fm} = 1; σ^{os} = 2			σ = 4		
				Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
PDR	359,20	359,29	359,31	-0,1%	-0,1%	-0,1%	-0,1%	-0,1%	-0,1%	0,0%	0,0%	-0,1%
WHT	321,20	321,68	321,47	0,1%	0,2%	0,2%	0,2%	0,3%	0,3%	0,1%	0,3%	0,3%
MZE	312,23	312,37	311,33	0,1%	-0,3%	-0,5%	0,1%	-0,3%	-0,5%	0,1%	-0,4%	-0,6%
PLM	55,82	55,82	55,80	0,0%	-0,2%	-0,2%	0,0%	-0,2%	-0,2%	0,0%	-0,2%	-0,2%
RSD	71,07	69,65	68,75	2,1%	5,6%	8,6%	1,7%	4,1%	6,6%	1,2%	2,5%	4,1%
SOY	249,07	250,88	257,79	1,2%	1,9%	2,9%	1,4%	2,4%	3,6%	1,8%	3,2%	4,9%
OSDN	131,34	130,13	129,81	0,7%	1,5%	2,5%	0,5%	1,1%	1,8%	0,4%	0,7%	0,9%
C_B	118,51	118,50	118,40	-0,1%	-0,2%	-0,2%	-0,1%	-0,2%	-0,2%	-0,1%	-0,2%	-0,3%
AGR	2311,70	2312,27	2310,69	-0,2%	-0,1%	-0,3%	-0,2%	-0,1%	-0,2%	-0,2%	-0,1%	-0,2%
OLVS	988,92	988,88	983,84	0,9%	-0,5%	-0,4%	0,9%	-0,5%	-0,4%	0,7%	-0,6%	-0,8%
ILVS	1394,78	1394,87	1381,12	1,5%	-1,7%	-1,7%	1,5%	-1,7%	-1,7%	1,1%	-1,9%	-2,3%
PCM	1807,87	1807,81	1798,07	1,0%	-0,5%	-0,5%	1,0%	-0,5%	-0,5%	0,8%	-0,7%	-0,9%
AQUF	113,14	113,14	113,52	0,4%	32,9%	32,9%	0,4%	32,9%	32,9%	2,3%	32,5%	32,5%
CAPF	254,00	254,00	254,00	-21,8%	0,0%	0,0%	-21,8%	0,0%	0,0%	-21,8%	0,0%	0,0%
FSHMEAL	33,75	33,29	19,36	-9,9%	24,2%	11,0%	-9,9%	24,2%	11,1%	-27,6%	21,9%	-13,5%
PLMmeal	0,10	0,10	0,10	-0,5%	-0,3%	-0,5%	-0,5%	-0,3%	-0,5%	-0,4%	-0,2%	-0,4%
RSDmeal	25,18	23,57	22,72	7,2%	19,0%	29,5%	6,1%	15,5%	24,5%	4,5%	10,3%	16,6%
SOYmeal	172,98	175,83	190,35	3,5%	5,9%	8,8%	3,8%	6,8%	10,2%	4,9%	8,8%	13,3%
OSDNmeal	15,92	15,29	16,98	10,2%	26,1%	36,4%	9,9%	25,1%	34,0%	10,8%	22,0%	26,5%
DDGSw	0,55	0,55	0,55	-0,6%	-1,9%	-2,5%	-0,6%	-1,8%	-2,3%	-0,6%	-1,8%	-2,2%
DDGSm	2,96	2,95	2,91	-0,6%	-2,7%	-3,7%	-0,6%	-2,8%	-3,8%	-0,9%	-3,1%	-4,3%
DDGSg	0,11	0,11	0,11	-0,6%	-2,0%	-2,6%	-0,6%	-1,9%	-2,5%	-0,7%	-2,0%	-2,6%
PLMoil	39,00	39,00	39,00	-0,2%	-0,2%	-0,3%	-0,2%	-0,2%	-0,3%	-0,1%	-0,2%	-0,2%
RSDoil	23,10	22,49	22,18	2,8%	7,6%	11,5%	2,3%	5,4%	8,6%	1,8%	3,3%	5,6%
SOYoil	72,95	74,19	79,93	2,7%	5,0%	7,3%	3,0%	6,0%	8,7%	4,4%	7,9%	12,2%
OSDNoil	20,17	20,36	21,58	3,2%	7,6%	10,2%	3,3%	7,8%	10,2%	4,4%	8,2%	9,8%
VOLN	660,90	660,78	659,14	-0,2%	-0,5%	-0,7%	-0,2%	-0,5%	-0,7%	-0,2%	-0,6%	-0,8%
BETH	19,23	19,20	18,90	-2,1%	-3,3%	-4,7%	-2,2%	-3,4%	-4,9%	-2,3%	-3,7%	-5,2%
BDIE	21,31	22,09	25,21	5,8%	16,9%	21,3%	6,1%	17,8%	22,1%	9,0%	18,6%	23,2%
BDIE_PLM	0,09	0,09	0,10	-5,1%	-4,6%	-4,5%	-5,1%	-4,5%	-4,2%	-4,0%	-4,0%	-3,0%
FOD	7908,93	7910,29	7919,38	-0,4%	-0,1%	-0,2%	-0,4%	-0,1%	-0,2%	-0,3%	0,0%	-0,1%

Table A5: Sensitivity Analysis: Global Prices with Varying Elasticity of Substitution. Differences to Baseline in 2030. Note: σ=Elasticity within fishmeal and oilseed meal nest; For analysis with split fishmeal and oilseed meal nesting: σ^{fm} = Elasticity between fishmeal and oilseed meals nets; σ^{os} = Elasticity within oilseed meals nest.

Sector	Baseline Prices 2030 (const. USD)			Prices								
	σ = 1	σ^{fm} = 1; σ^{os} = 2	σ = 4	σ = 1			σ^{fm} = 1; σ^{os} = 2			σ = 4		
				Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
PDR	3,26	3,26	3,26	0,4%	0,6%	0,9%	0,4%	0,6%	0,8%	0,4%	0,5%	0,6%
WHT	2,34	2,34	2,34	0,8%	1,7%	2,2%	0,73%	1,6%	2,1%	0,7%	1,5%	1,9%
MZE	2,63	2,62	2,63	0,8%	1,8%	2,5%	0,8%	1,7%	2,3%	0,8%	1,6%	2,1%
PLM	3,76	3,76	3,75	0,9%	0,5%	1,0%	0,8%	0,4%	0,9%	0,7%	0,3%	0,6%
RSD	2,82	2,80	2,79	1,2%	3,3%	4,6%	1,1%	2,7%	3,8%	1,0%	2,1%	2,9%
SOY	2,32	2,32	2,34	1,2%	2,0%	2,8%	1,2%	2,1%	3,0%	1,3%	2,3%	3,2%
OSDN	2,74	2,73	2,73	0,8%	1,7%	2,4%	0,7%	1,4%	2,0%	0,6%	1,1%	1,5%
C_B	2,31	2,31	2,31	0,3%	0,7%	0,9%	0,2%	0,6%	0,9%	0,3%	0,6%	0,8%
AGR	2,84	2,84	2,84	0,7%	1,5%	2,1%	0,6%	1,4%	1,9%	0,6%	1,4%	1,7%
OLVS	2,19	2,19	2,18	1,5%	-0,4%	0,0%	1,5%	-0,4%	-0,1%	1,3%	-0,6%	-0,5%
ILVS	1,17	1,17	1,17	0,6%	0,7%	1,1%	0,6%	0,6%	1,0%	0,6%	0,6%	0,9%
PCM	1,08	1,08	1,08	1,1%	0,2%	0,6%	1,1%	0,2%	0,5%	0,9%	0,1%	0,2%
AQUF	1,97	1,97	1,93	5,5%	-18,0%	-17,2%	5,5%	-18,0%	-17,3%	2,9%	-18,3%	-18,5%
CAPF	2,50	2,48	2,20	44,0%	5,5%	12,3%	43,9%	5,3%	12,0%	34,1%	0,4%	-1,5%
FSHMEAL	4,06	4,04	3,26	35,9%	7,2%	45,6%	35,9%	7,1%	45,4%	23,1%	2,1%	22,0%
PLMmeal	2,94	2,37	2,14	11,2%	35,0%	45,0%	7,1%	17,4%	22,4%	5,7%	9,8%	13,9%
RSDmeal	2,75	2,63	2,56	3,0%	9,7%	11,9%	3,1%	8,7%	11,2%	2,8%	6,8%	9,1%
SOYmeal	1,71	1,73	1,76	1,3%	2,4%	3,4%	1,3%	2,7%	3,8%	1,5%	3,0%	4,3%
OSDNmeal	2,01	1,76	1,55	2,3%	4,5%	8,1%	2,2%	4,3%	7,8%	1,1%	2,5%	4,9%
DDGSw	1,61	1,60	1,60	2,0%	1,9%	3,0%	2,0%	1,9%	2,9%	1,9%	1,7%	2,3%
DDGSm	2,86	2,86	2,89	2,4%	2,6%	4,0%	2,5%	2,6%	4,1%	2,4%	2,8%	4,0%
DDGSg	1,67	1,67	1,67	2,0%	2,1%	3,2%	1,9%	2,0%	3,0%	1,8%	1,8%	2,5%
PLMoil	2,28	2,28	2,28	0,6%	0,2%	0,6%	0,6%	0,2%	0,6%	0,5%	0,1%	0,3%
RSDoil	1,26	1,35	1,41	-4,7%	-15,0%	-19,3%	-4,2%	-12,0%	-16,1%	-3,3%	-8,1%	-11,6%
SOYoil	0,72	0,70	0,65	-2,8%	-4,7%	-7,0%	-3,1%	-5,6%	-8,2%	-4,1%	-7,1%	-10,6%
OSDNoil	0,94	0,96	0,97	-1,9%	-4,1%	-5,6%	-2,4%	-5,2%	-7,0%	-3,4%	-6,6%	-8,5%
VOLN	1,73	1,72	1,72	1,2%	0,9%	1,6%	1,2%	0,9%	1,6%	1,0%	0,8%	1,3%
BETH	1,08	1,08	1,08	0,1%	0,2%	0,3%	0,1%	0,2%	0,3%	0,1%	0,3%	0,4%
BDIE	0,88	0,88	0,85	-1,3%	-3,1%	-4,0%	-1,5%	-3,5%	-4,4%	-2,2%	-4,1%	-4,8%
BDIE_PLM	1,09	1,09	1,09	0,3%	0,3%	0,1%	0,3%	0,3%	0,1%	0,2%	0,3%	0,0%
FOD	1,17	1,17	1,17	0,9%	0,0%	0,3%	0,9%	0,0%	0,2%	0,7%	-0,1%	-0,1%

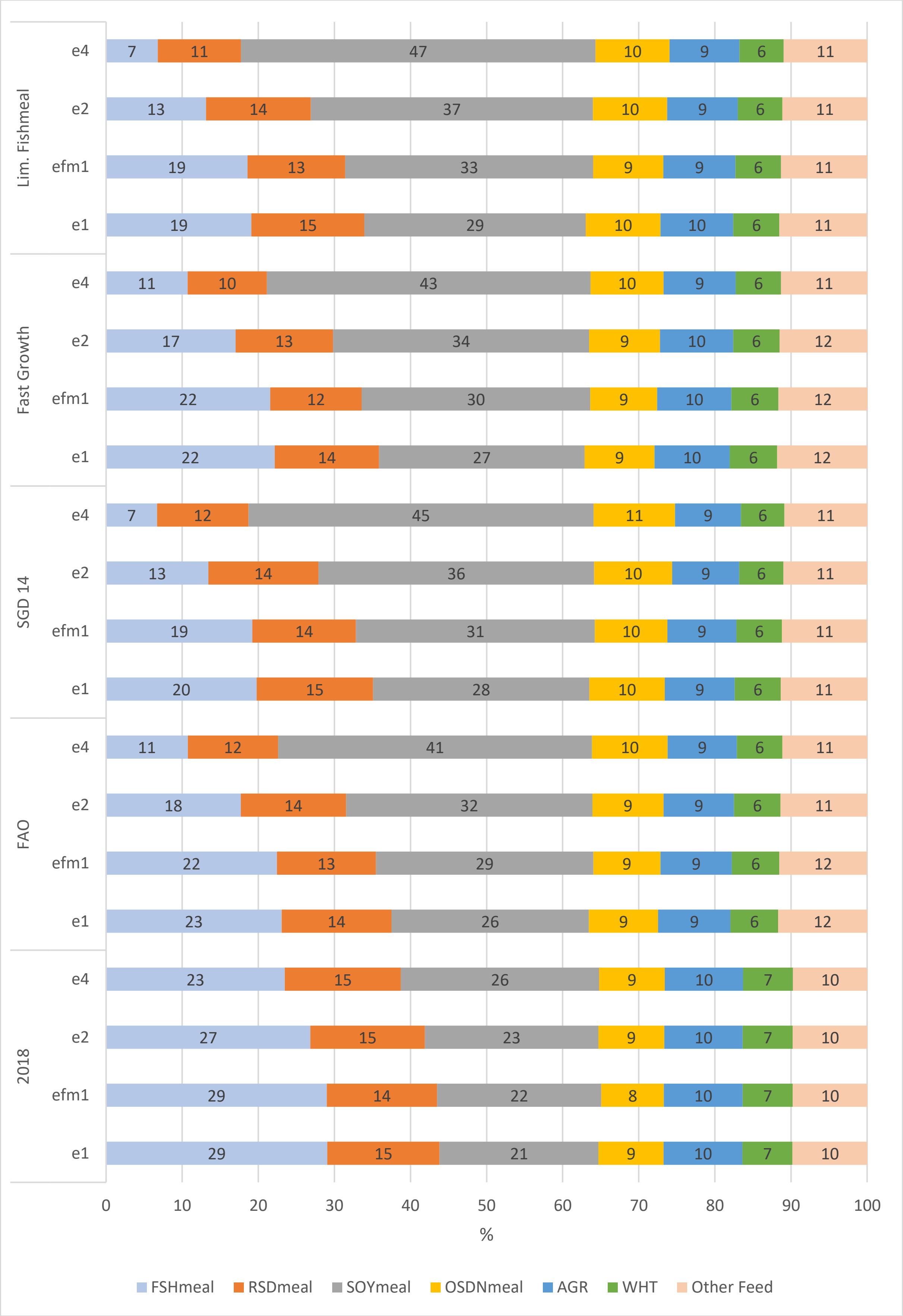

Figure A3: Results of the Sensitivity Analysis on Fish Feed Composition; Volume Shares in 2018 and 2030 in Percent. Note: e1: σ=1; e2: σ=2; e4: σ=4; efm1: Split nesting for fishmeal and oilseed meals: = Elasticity between fishmeal and oilseed meals nets σ^{fm}*;=1, Elasticity within oilseed meals nest* σ^{os} *=2.*

Preparation of the dataset

To observe developments in a capture fish and an aquaculture fish sector, the existing fish sector (FSH) must be separated. In addition, an explicit fishmeal sector is required to model substitution effects between fish-based and plant-based protein fodder. For the separations in the GTAP database the gempack software “Splitcom” is employed (Horridge, 2008). At first, five new sectors are created, namely fresh capture and aquaculture fish, processed capture and aquaculture fish and fishmeal. In the final mode, the two processed fish sectors are aggregated to the food sector. While the sectors for fresh capture (CAPF) and fresh aquaculture (AQUF) fish are originated in the original FSH sector, the sectors for processed fish are separated from the GTAP sector “other foods” (OFD). The fishmeal (FSHMEAL) sector is fueled by both sectors, FSH and OFD. Comparing the GTAP data to FAO FishStat and UN Comtrade data, the distribution of fish between the original sectors FSH and OFD is very heterogeneous across countries. Amongst others, this could be due to different interpretations of “processed fish” by the statistical authorities of the respective countries. Also, the values for fishmeal are for some countries accounted in FSH and for others in OFD. To get the targeted shares between capture and aquaculture, fresh and processed, domestic production and imports, in a first step all production processes of fish are extracted from their initial sectors, and then redistributed to the five new sectors. It is important to note that the aquaculture sector only includes fed-fish species. Non-fed species are not explicitly modelled due to unknown cost functions. Up to now, there is no information on the cost structure of filter fish production. Especially in Asia, many filter fish are kept on rice fields or in small ponds, and are produced alongside other farm activities without requiring specific inputs (FAO, 2018). Furthermore, while the demand and production for fed-fish is strongly increasing, the market share of filter fish is significantly decreasing and plays only a major role in China and Oceania (ibid.). Including filter fish in the aquaculture sector would jeopardize the here derived assumption of the production technology for aquaculture, and water down feedback effects from higher aquaculture demand on fodder production. Thus, to reveal the linkages of fish consumption on plant-based fodder production the aquaculture sector can be considered as fed-fish aquaculture only, as it is also the case in other studies, such as Froehlich, et al. (2018b). To improve the treatment of non-fed fish, it is planned to include more explicit fish sectors in a later version.

Disaggregating the Fish Sectors

FAO only reports country level production values for aquaculture fish production and fishmeal production, but not for capture fisheries. It was decided to split the sector in a three-step process. At first, with a sketchy separation of aquaculture and capture values, by taking the GTAP data as total fish production and subtracting the aquaculture values for fed fish given by FAO FishStat. Second, with an adjustment of the aquaculture production values so that the total production is in line with the correct input shares for capital, labor and fodder in the production process. And finally, the production of aquaculture and capture fish is rescaled to match the regional production volume shares in 2011.

Since species and region specific production cost shares are not available, it is assumed that in the aquaculture sector 75% of the total cost come from fodder inputs. Estimations assume a share of 50-80% in 2010 (Rana, et al. (2009), Hasan (2017)). Assuming technological progress, increasing raw material costs and strongly increasing aquaculture cultivation in Asian low-income countries (e.g. Thailand, Vietnam) in the last 10 years, a global average production cost share of 75% for fodder seems realistic. The fodder composition is based on a study by

Pahlow et al. (2015). They provide species specific estimates on 88% of all global commercial feed fed fish. Those estimates are used to calculate the fodder costs on a country base, by weighting the species-specific fodder shares with the production volumes of the fish species retrieved from FAO FishStat, and then multiply the weighted fodder volumes with their 2011 market prices. Apparently, the GTAP database does not account for aquaculture fisheries in many regions, as for several countries the plant-based intermediate inputs into the FSH sector are much too low to come even near the FAO production value for aquaculture production. Therefore, the aquaculture production in scaled down so that the estimated fodder input shares are consistent.

In the next step, the model rescales capture and aquaculture production until 2018. For the evaluation of the aquaculture feed linkages, it is important to keep the relative shares within the GTAP database consistent. A weakness of the GTAP database is that the regional output of the individual production sectors is sometimes not consistent with data from other sources, such as FAO, UN COMTRADE, USDA. To evaluate developments over time the values of all sectors should match on a relative scale. Thus, when calibrating new sectors, it is important to make sure that their production volume fits to the scale of other sectors. To maintain the relative scale given by the GTAP database, the 2011 regional production quantity shares for fed-aquaculture and capture fish on total fish production are taken from FishStat to calculate the production volumes for the GTAP based data. Considering trade, it is assumed, the share in trade is equal to the share in production. This is a common assumption when detailed bilateral trade data is absent (Natale, et al., 2015).

Manipulation of the GTAP SAM

As already indicated above, a major issue of calibrating the inputs of the aquaculture sector according to the shares in fodder composition, is that the available fodder quantities limit the initial aquaculture production in the base year. In other words, if it is assumed that in a certain country 20% of fish fodder is based on soymeal, but after the default separation of aquaculture and capture fish (according to FAO aquaculture production data) the fodder share of soymeal is lower, the production quantity is reduced, so that the share of soymeal in the fodder compositions approaches the targeted 20%. Thus, the available quantity of the fodder item with the largest deviation from its targeted fodder share determines the initial production quantity of aquaculture in the year 2011. The excess aquaculture production is shifted back to capture fisheries. Therefore, when calibrating the model to the 2011 production shares, a very high substitution elasticity between capture and aquaculture in private as well as intermediated consumption is implemented. This allows the model to easily move consumption from capture to aquaculture fish sector.

The calibration of the capture fish sector is implemented by scaling the endowment natural resources. This endowment is nested Leontief in the highest nest of the production structure. Thus, a decrease/increase of the availability of natural resources immediately translates into a decrease/increase of total production. The aquaculture and fishmeal sectors do not have natural resources as endowment. Here, an artificial endowment at the price of zero is included in the production block. This technique is borrowed from the application of emissions in a production structure. Also, the artificial endowment is nested in the highest nest with a Leontief substitution elasticity. Similar to the natural resources, a change in the endowment is fully transferred to a change in total production of the respective sector.

The calibration of the fish sectors bears two major shortcomings considering further evaluations. On the one hand, after scaling production to a multiple of its initial quantities, the output prices of those sectors are highly distorted. Even while allowing for easy substitution in consumption of capture fish and aquaculture, the prices of the sectors are strongly affected. On the other, by introducing the endowment the production structure, aquaculture and fishmeal production are unable to evolve freely when conducting scenario analyses from 2018 to 2030. The endowment determines the production and cannot be just removed from the production structure.

To deal with these two obstacles the save-and-restart procedure has been developed. First, we let the model run from 2011 for 8 years and calibrate towards the FAO fish sector production shares in 2011. This run is conducted without implementing any dynamics in the model. Population and total factor productivity growth are zero for all periods. Thus, in theory we could just let the model run for one year as we are only focused on shifting production factors and intermediates to/from the fish sectors to reflect 2011 production shares. But the shock size, in particular on the aquaculture sector, is too high for the model to handle within one period. Hence, we allow the model to smoothly adjust the sectors over multiple periods. While calibrating the fish sector, we only allow for very low substitution (0.1-0.5) between the intermediate inputs of the aquaculture sector, to hold the cost shares constant. The substitution elasticities are big enough to give the model some flexibility when increasing the production of the sector, but sufficient small to not significantly alter the desired cost share distribution.

The results of this fish sector calibration run are saved, and we read out all relevant parameters to recalculate the values needed to construct a new basedata for 2011. A CGE model naturally works with relative prices, so that in the initial start year all prices must be equal to 1. Thus, the GTAP basedata can be understood in terms of values with the price of 1. To obtain a new basedata, we just need to multiply quantities with prices to get the new values. Since there are no dynamics in the model, all sectors not affected by the calibration of the fish sector have very similar values compared to the original basedata. Sectors affected by aquaculture production receive higher values now. However, this is intuitive considering that the aquaculture sector is only covered fractional by the original database. After recalculating the basedata, the values of aquaculture and capture fish sectors differ from the targeted production 2011 volumes. Especially increasing aquaculture production by a factor of 30-40, as done for some regions, leads to low prices and thus to too low values in the new basedata. As a result, for every model run after the restart we include a quota that calibrates the production shares of the fish sectors until 2018. All scenario analyses start from that year on, and vary only in the period from 2018 to 2030.

Why do we not directly calibrate the fish sectors in the model with the dynamics, and then keep on running the model until 2030 for scenario evaluation? The point is, that in the fish sector calibration run we must increase aquaculture production in most regions by more than factor 10. As already mentioned, this strongly distorts the sector prices which in turn would affect the scenario analyses. After the restart we only have to adjust by max. 1.3 for the major aquaculture producing countries to match 2018 FAO production volume shares.