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Land for fish: Quantifying the connection between the aquaculture sector and agricultural markets

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ABSTRACT

This study employs a global Computable General Equilibrium (CGE) model to quantify the effects of aquaculture production on agricultural markets, food prices and land use. We conduct a scenario analysis simulating, first, the fish sector developments expected by FAO; second, a rebuilding of sustainable wild fish stocks to achieve SDG 14; and third, a stronger expansion in aquaculture production with varying fishmeal supply. The results show direct effects of aquaculture production and limited fishmeal supply on agricultural production, land use, and food prices. Substituting fishmeal with plant-based feed when rebuilding sustainable fish stocks has lower effects on agricultural markets than growth in aquaculture production comparable to the first decade of this century. In addition, expanding aquaculture production increases prices for capture fish via fishmeal demand, instead of reducing capture fish prices by substituting consumer demand. Finally, rebuilding sustainable fish stocks has significant adverse effects on food prices in marine fish dependent regions in the southern hemisphere, and these regions need support in the transition period until sustainable fish stocks are achieved. The results of this study illustrate the interconnectedness of SDG 14 (life below water), SDG 15 (life on land) and SDG 2 (zero hunger).

1. Introduction

Fish plays a crucial role in the human food basket as a rich source of protein and nutrients (Troell et al., 2014). Global fish consumption has increased considerably in the last few decades (FAO, 2018), leading to criticism concerning the lack of sustainability in fish production from wild fisheries and aquaculture (Smith et al., 2010; Boyd et al., 2020; Costello et al., 2020; FAO, 2020). In the case of wild fisheries, even with regional quotas in place, many wild species are fished at unsustainably high levels (World Bank, 2017).

While the volume of captured wild fish has stagnated at this high level, the increasing demand for fish has been met by the rapid expansion of aquaculture fish production (FAO, 2020). Most of this growth comes from fed species, such as finfish and crustacea (FAO, 2018), which rely on fishmeal for feed (Froehlich et al., 2018a; FAO, 2020). Froehlich et al. (2018a) warned that if the importance of fishmeal as feed is not reduced, the fishmeal demand created by aquaculture production growth will push forage fish capture beyond its ecological limits. In the last decade, fish farmers have begun to replace fishmeal with plant-based protein feed (FAO, 2018). Tacon and Metian (2015) argue that this is a response to high fishmeal prices caused by increasing demand and tightening supply and contend if this trend continues, the fish sector will require alternative feed commodities in the future.

Simultaneously, the use of plant-based feed puts aquaculture production's sustainability into question. Global per capita consumption of animal products is expected to increase in the coming decade, leading to corresponding rise in commercial feed production (OECD/FAO, 2022). Several studies have addressed how agricultural activities shape land use and analyzed the ecological consequences (see Meyer and Turner, 1992; Ramankutty and Foley, 1999; Foley et al., 2005; Lotze-Campen et al., 2008; Hertel, 2011, Václavík et al., 2013; Ramankutty et al., 2018; Zabel et al., 2019). Mottet et al., 2017 analyzed commercial livestock feed production's adverse effects on food availability, highlighting the food surplus if crops are directly consumed by humans. Herrero et al., 2013 provided an overview on ecological effects from global livestock systems, emphasizing the differences by livestock type and production system. However, while the use of plant-based protein feed in aquaculture production is increasing (OECD/FAO, 2022), aquaculture was not considered in either of these studies.

In this study, we address several questions regarding the impact of the fish sector on agriculture: How would replacing fishmeal with plant-based feed impact global land use? How would global agricultural

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markets react if quotas limit wild catches to restore global fish stocks to sustainable levels within 15–20 years? Which regions would be most affected? Finally, what are the implications for global staple crop prices?

This study aims to analyze the impact of feed demand created by global aquaculture production on land use and land-use change, under exogenous scenario assumptions regarding production quantities in the fish sector. We examine the interdependencies and trade-offs involved in achieving sustainable development, as reflected by the UN Sustainable Development Goal (SDG) 14 (*life below water*), SDG 15 (*life on land*) and SDG 2 (*zero hunger*). Our results highlight the potential trade-offs for policymakers so sustainable policy design can assess and consider these while seeking to achieve the SDGs.

We employ a computable general equilibrium (CGE) model to analyze feedback effects from increasing aquaculture fish consumption on capture fishery production and plant-based feed demand. An essential model attribute is the explicit modeling of the aquaculture and fishmeal industries, as well as biofuels and their by-products (e.g., oilseed meal) used in the livestock industry. This allows for a detailed characterization of the feed composition for livestock and aquaculture and therefore the evaluation of feedback effects on land use. Land-use change through land conversion from mangroves or other land types to ponds has not been analyzed.

Section 2 provides an overview of the literature on modeling global fish-feed demand, aquaculture production, and land use with CGE models. Subsequently, Section 3 describes the model and model database construction and presents the scenario design. Further, Section 4 describes the results, and finally, Section 5 presents the discussion and conclusions.

2. Literature review

Numerous studies have highlighted the relevance and benefits of aquatic foods for food systems (Beveridge et al., 2013; Troell et al., 2014; Lem et al., 2014; Chan et al., 2017; Chan et al., 2019; Gephart et al., 2021a; Golden et al., 2021; Naylor et al., 2021; Boyd et al., 2022), and focused on the environmental impacts and sustainability of their production (Klinger and Naylor, 2012; Pahlow et al., 2015; Fry et al., 2016; Gephart et al., 2021b; Troell et al., 2023). Boyd et al. (2022) noted the importance of aquatic foods for global diets and estimated that to meet global needs in 2050, at least 60% more aquaculture production is needed compared to 2018. They stress that aquaculture must reduce fishmeal consumption because future extensive use of small pelagic fish for fishmeal production is likely to adversely affect food security in regions dependent on capture fisheries (Boyd et al., 2022). Gephart et al. (2021b) analyzed the environmental performance of aquatic foods and found most effects on land use are caused by feed production for aquaculture. Relatedly, already Klinger and Naylor (2012) discussed aquaculture production's demands for feed and land, arguing that thoughtful fish-species selection considering feed and ecosystem requirements is crucial for a sustainable expansion of aquaculture production.

Global projections of fish and aquaculture production are regularly estimated by the FAO's fish model and presented in the "State of World Fisheries and Aquaculture" reports (FAO, 2012; FAO, 2018; FAO, 2020). These results are also used in the OECD-FAO Agricultural Outlooks (OECD/FAO, 2022). Delgado et al. (2003) and Kobayashi et al. (2015) analyze global aquatic food supply and demand until 2020 and 2030, respectively. Both studies employed the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)—a partial equilibrium-type model for the global food sector. Kobayashi et al. (2015) modeled the capture fish sector exogenously, and their results showed an increase in total fish production similar to the estimates released by the OECD/FAO (2020), driven by production growth in the aquaculture sector. Nevertheless, although Kobayashi et al. (2015) projected global production and demand for aquaculture fisheries and the corresponding demand for fishmeal/oil as feed, they did not examine the demand for plant-based feed and its impacts on agricultural markets.

Several studies have analyzed the economic connections between capture fisheries and aquaculture. Anderson (1985) derived a formal model reflecting the competition between capture fisheries and aquaculture in a common market. Later studies have integrated the interactions caused by fishmeal and oil consumption in the aquaculture industry (Naylor et al., 2000; Mullon et al., 2009; Tacon and Metian, 2009; Merino et al., 2010; Regnier and Schubert, 2017; Bergland et al., 2019). In line with Merino et al. (2012), these studies stress that the fish in/fish out (FIFO) ratio, which indicates the efficiency of aquaculture in terms of fishmeal consumption, is a crucial factor when addressing such interactions. Moreover, when deriving economic models, the FIFO ratio can be reflected as technological efficiency, as Regnier and Schubert (2017) showed.

Contrary to the connection between capture fisheries and aquaculture, the link between aquaculture and plant-based feed and its impact on land use has rarely been addressed by model-based analysis. Froehlich et al. (2018b) examined this linkage using a statistical model to calculate the land requirements for meat and aquaculture production in 2050 if global meat consumption were largely replaced by aquaculture fish consumption. They concluded that even if one-third of human global protein demand were met using fish, the impact on land use compared to livestock would be relatively low because of aquatic species' high feed efficiency. Tacon and Metian (2015) confirmed aquaculture's low impact on land use on a global scale but stressed this percentage could be much higher in regional markets owing to the regional concentration of aquaculture production. This underscores the relevance of using numeric models that can analyze feedback effects via regional feed prices to evaluate the impact on land use and food prices in the respective regions. Moreover, as Froehlich et al. (2018b) applied a statistical model in which the demand-side follows exogenous scenario assumptions, the model does not account for economic growth, trade, income effects, consumer prices and preferences, or price-driven feedback effects on agricultural production and land use, which are endogenously considered in our CGE modeling framework.

3. Methods

3.1. Basic features of the dynamic applied regional trade model

The Dynamic Applied Regional Trade (DART) model is a multi-sectoral, multi-regional recursive dynamic CGE model of the world economy (Springer, 1998). It is based on data from the Global Trade Analysis Project (GTAP) released in 2017 (GTAP 9), which covers multiple sectors and regions (Aguiar et al., 2016). Each region is modeled as a competitive economy with flexible prices and market-clearing conditions. The original DART model has been used to model climate and energy policies (Klepper and Peterson, 2006; Peterson and Weitzel, 2016; Winkler et al., 2021). DART-BIO is the land-use variant of the DART model and shares the same core characteristics. It focuses on land heterogeneity and the complex production process chains of biofuels and therefore includes several activities/commodities lacking in the original GTAP database (see Calzadilla et al., 2016; Delzeit et al., 2018; Delzeit et al., 2021).

The GTAP 9 database (Aguiar et al., 2016) represents the 2011 global economy and includes 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 by Delzeit et al. (2021). The DART-BIO model includes by-products generated during biofuel manufacturing, such as dried distillers grains with solubles from bioethanol production from grains, and oilseeds and meals/cakes in the vegetable oil industry (see Delzeit et al. (2021) for details). Appendix Fig. A.2 shows the implemented production pathways for biodiesel and the coproduction of feed for the livestock and aquaculture industries.

To account for land heterogeneity, the DART-BIO model incorporates the GTAP agro-ecological zone (AEZ) database (Baldos, 2017). Thus, we use 18 GTAP-AEZs, covering six different growing-period lengths spread over three different climatic zones. Within each AEZ and region, land is allocated to different uses (i.e., cropland, pasture, and forest) via a constant elasticity of transformation (CET) structure (for details, see Appendix Fig. A.1 and Table A.1).

On the demand-side of the model, consumer preferences follow the linear expenditure system (LES) based on a Stone-Geary utility function (Stone, 1954). Further information regarding the general DART-BIO specifications can be found in Delzeit et al. (2021).

In DART-BIO, total factor productivity is calibrated to match the resulting gross domestic product (GDP). Data on GDP, workforce development and population dynamics are based on estimates used by the OECD (2019). The average global agricultural productivity growth rate is 1.2%, which is consistent with the estimates of the OECD-FAO Agricultural Outlook (OECD/FAO, 2020).

3.2. *Fish and aquaculture in DART-BIOFISH*

3.2.1. *Model structure*

In DART-BIOFISH, three fish sectors (capture fisheries, aquaculture production, and fishmeal production) are added to the original GTAP database. This makes it possible to account for interdependencies between capture fisheries and aquaculture production via consumption preferences for fish products and the use of fishmeal and plant-based feed in aquaculture fish production, as described in Section 3.2.2. A complete list of DART-BIOFISH sectors (Table A.3) and regional aggregation (Table A.2) can be found in the Appendix.

Fig. 1 provides an overview of the linkages among the respective sectors. Although the fishmeal sector also includes fish oil production, it is referred to as “fishmeal” here.

3.2.2. *Constructing the DART-BIOFISH database*

To model developments in the respective capture fish, fishmeal and aquaculture sectors based on GTAP data, the single sector for fish production (FSH) used in the GTAP must be separated according to FAO FishStat data (FAO, 2019). The GEMPACK software “Splitcom” (Horridge, 2008) was used to implement the requisite division of the GTAP database. The FSH sector includes capture (CAPF) and aquaculture (AQUF) fish. Comparing GTAP data, which are based on FAOSTAT, to FAO FishStat and UN Comtrade data revealed that in some countries, processing fish into fishmeal is accounted for in OFD (other foods), whereas others allocate fishmeal to the FSH sector. Chang et al. (2018) discussed the divergence in FAOSTAT and FAO FishStat data, demonstrating that FAO FishStat generally provides a better representation of processed fish data. To accommodate the given GTAP data structure, we split the fishmeal (FSHMEAL) sector from both FSH and OFD.

In DART-BIOFISH, the aquaculture sector only includes fed species; non-fed species are not explicitly modeled because of their unknown cost functions. Especially in Asia, many filter fish are kept in rice fields or small ponds and produced alongside other farm activities without requiring specific inputs (FAO, 2018). To reveal the linkages between fish consumption and plant-based feed production, the aquaculture sector can be considered as fed aquaculture only, as has also been assumed in other studies, such as Froehlich et al. (2018b). While the demand for and production of fed species are rapidly increasing, the market share of filter fish is decreasing and only significant in China and Oceania (FAO, 2018). Moreover, owing to data complexity and limitations, we cannot distinguish between freshwater and marine fisheries.

We particularly focused on realistically depicting regional feed shares in the aquaculture industry. In the DART-BIOFISH model, the aquaculture sector is an aggregate of species with known feed compositions, which accounts for approximately 80% of total fed aquaculture according to FAO (2019) data. Country-level feed composition is based on Pahlow et al. (2015), who provided species-specific estimates for 88% of global commercial feed-fed fish. These estimates were used to calculate the feed costs by country by weighting the species-specific feed shares against the production volumes of the fish species, taken from FAO FishStat (FAO, 2019), and multiplying the weighted feed volumes by their respective 2011 market prices to arrive at the costs (for feed prices, see Table A.8). This is shown in the following equations:

$$vs_{f,c} = \frac{1}{Q_c}\sum_{s} vs_{f,s} * Q_{s,c}, \tag{1}$$

$$cs_{f,c} = \frac{vs_{f,c} * P_f}{\sum_{f} vs_{f,c} * P_f}, \tag{2}$$

where vs is the volume share, and *cs* is the final cost share; *f* is the feed item, *c* is the country, and *s* is the fish species for aquaculture fish volume *Q* and feed price *P*.

For the base year, capture fish and aquaculture production are

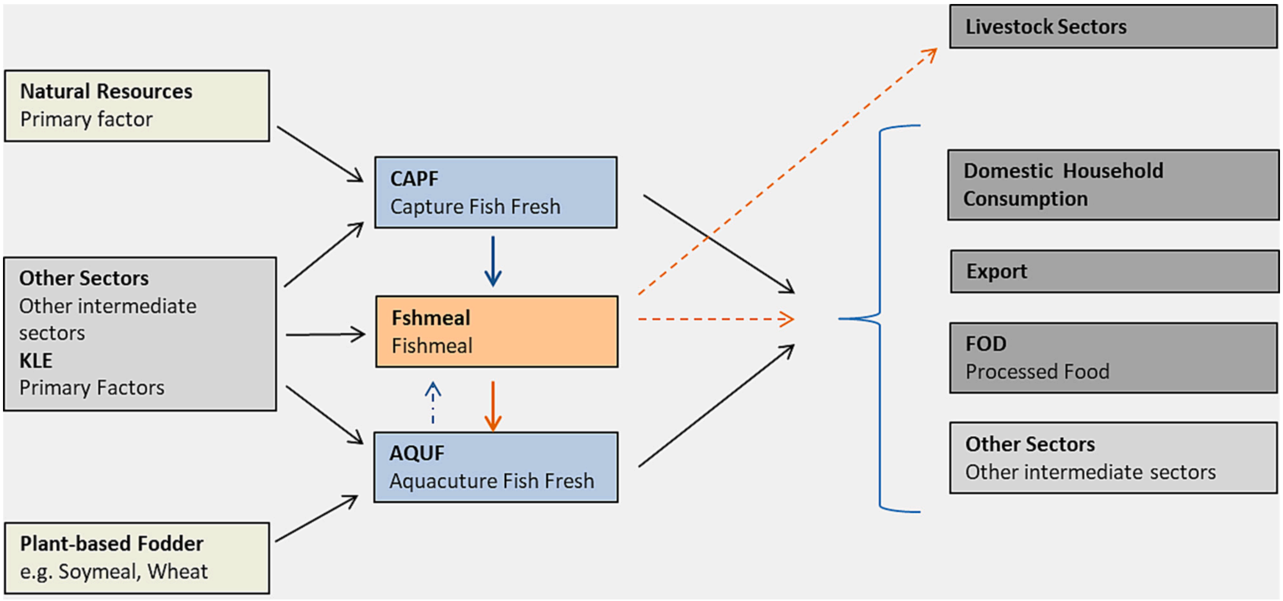

Fig. 1. Fish sectors in the DART-BIOFISH model. **Note:** KLE denotes the primary factors capital (K), labor (L), and energy (E).

calibrated based on their relative production quantities in 2011. To maintain the relative scale provided by the GTAP database, we calculated the 2011 regional production quantity shares for fed aquaculture and capture fish relative to total fish production based on statistics from FAO FishStat (FAO, 2019). Trade shares were assumed equal to the share of production, a commonly used assumption when detailed bilateral trade data are unavailable (Natale et al., 2015).

The original GTAP database does not account for aquaculture fisheries in many regions; for several countries, plant-based intermediate inputs into the FSH sector are extremely low compared to the statistics. Consequently, insufficient feed enters the FSH sector to reach the FAO production share for fed aquaculture production. Therefore, when splitting the sector from FSH, aquaculture production must be scaled down to a level at which the estimated feed input shares are consistent. A "save-and-restart procedure" was developed to calibrate the base data to the fish sectors' 2011 production ratio while maintaining the aquaculture feed composition. First, the model was run for several periods without the dynamics (such as population and GDP growth) being active. In this model run, only the production of capture fish and aquaculture was calibrated. The results of the fish sector calibration model were used to recalculate the values required to construct the DART-BIOFISH base data for 2011, which were used to execute the scenarios.

3.2.3. Model assumptions for fish sectors

The production of goods and services in the DART model follows a nested production structure with constant elasticity of substitution (CES), as described in Calzadilla et al. (2016). When modeling aquaculture fish production, we needed to define a specific nested production structure for the sector (Fig. 2). For protein feed like fishmeal or oilseed meal, we used a substitution elasticity of $\sigma = 2$—also used by Calzadilla et al. (2016) for feed in livestock production. This value was selected because the feed items can be assumed as imperfect substitutes. The elasticity augments technological efficiency, which can be improved by technological advances in breeding and feeding, or changing the product portfolio to fewer species that require fishmeal, as demonstrated by Regnier and Schubert (2017). Nonetheless, as there were no empirical data for the specific elasticity value, we tested its impact on the results using a sensitivity analysis (see the results in Section 4.3).

There is no substitution between protein and non-protein feeds. On the one hand, there are no reliable estimates of substitution elasticities between the two feed categories, as they may be highly fish-specific. On the other, fish require a certain level of protein intake for growth and development (Naylor et al., 2009). Thus, we assumed that the share of protein feed must remain constant over time while allowing for substitution of the protein source.

In the sectors for processed food (FOD) and services (SERV, e.g., restaurants), we allowed for imperfect substitution of meat and fish products. Research has shown that fish consumption is related to market developments of meat products, in particular poultry and pork (Troell et al., 2014; FAO, 2018), which are reflected by the sector *"Indoor Livestock"* (ILVS) in our model. Therefore, we selected a substitution elasticity of $\sigma = 2$ for animal products in the production structures of FOD and SERV. Regarding direct household demand, we assumed identical income elasticities for aquaculture and capture fish as provided by the GTAP for the initial fish sector (Appendix Table A.4).

3.3. Scenarios

To evaluate the interdependencies of forage fish supply, aquaculture, and crop production, a scenario analysis was employed. Table 1 provides an overview of the scenario quantification. Although the model runs from 2011 to 2030, the analysis focuses on 2018–2030. The years 2011–2018 are used to calibrate the observed fish production shares in

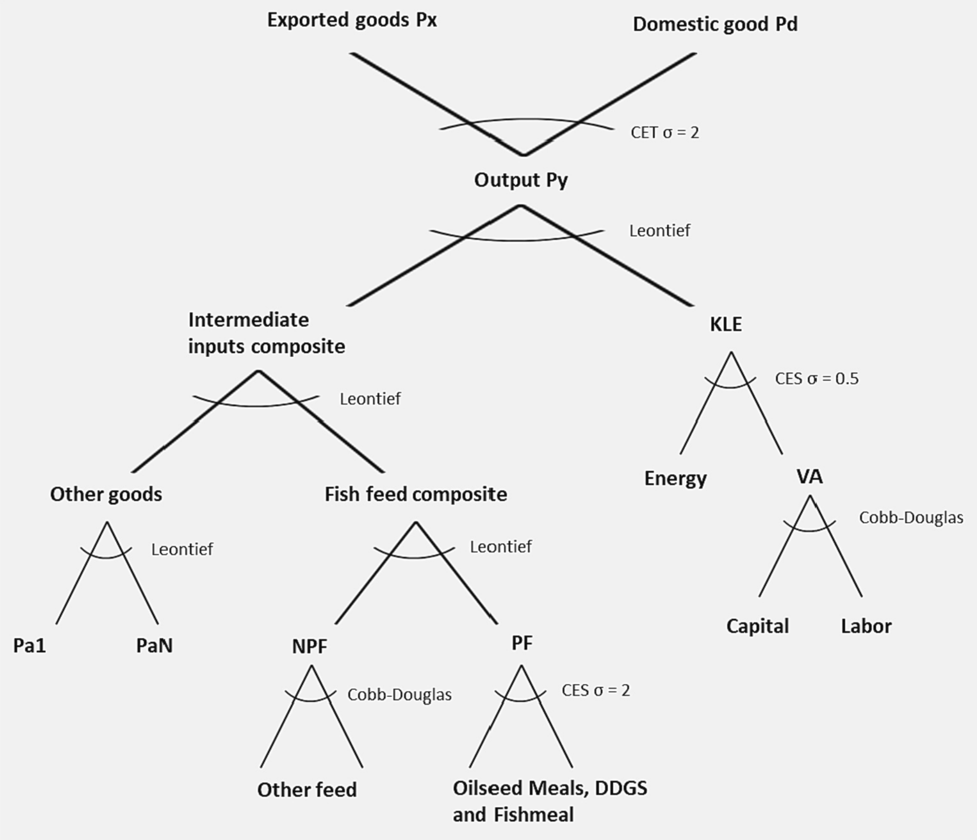

Fig. 2. Nesting of aquaculture production in DART-BIOFISH.

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% per annum from 2018 to 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 to 2030	Endogenous	Endogenous	Global production constant from 2018 to 2030

2018, as retrieved from FAO FishStat (FAO, 2019). During this period, the model is identical for all scenarios.

3.3.1. Baseline scenario

The *Baseline* scenario follows the FAO estimates from the 2020 version of "The State of World Fisheries and Aquaculture" report (FAO, 2020). This describes a world in which today's policies remain in place, and no further action is taken to support aquaculture production or rebuild wild fish stocks.

3.3.2. SDG14 scenario

The second scenario assumes that sustainable wild fish stocks will be restored by 2030 so that SDG Target 14.4 is achieved. The quantification for rebuilding sustainable marine fish stocks reflects the moderate path described in the World Bank (2017) report "The Sunken Billions Revisited". This path calls for a global reduction in wild catches by 5% per annum for five years, after which the level remains constant until fish stocks are restored by 2030. After 2030, fishing activities could increase; however, this is beyond the time horizon of this study. As the path suggested by the World Bank (2017) is not region- or species-specific in terms of simulating the reduced availability of captured fish in the global market, we assume that all global regions would contribute equally to rebuilding efforts. This allows us to determine which regions would be most affected if every region reduced fisheries at the same rate. Worm et al. (2009) discussed management strategies for rebuilding fish stocks and concluded they should be chosen based on regional and stock-specific characteristics. Nonetheless, as doing so is beyond the scope of this study, we did not assume any management strategy.

3.3.3. FGrow and LimFishm scenarios

The proportion of fish protein in the human diet increases as per capita income increases (FAO, 2020). Hence, population and economic growth lead to increased fish consumption (Zeller and Pauly, 2019; FAO, 2020). However, production factors such as insufficient transport infrastructure, disease control, governance, and regulatory constraints hinder aquaculture production growth (Troell et al., 2014; Gentry et al., 2017). Costello et al. (2020) argued that ineffective policies have limited the supply of mariculture fish and show that production at current prices could be significantly increased through policy reforms and technological advances. In their view, higher aquaculture production, as projected by the FAO and OECD, is possible. In line with this study, we model the overcoming of these barriers to production growth in two additional scenarios involving extensive aquaculture production: *FGrow* and *LimFishm*. For both scenarios, we assumed an annual growth rate twice as high as the FAO projection for aquaculture production because this approximately reflects the historical growth rate of the aquaculture sector in the first decade of this century (FAO, 2020). Contrary to *FGrow*, in the *LimFishm* scenario, fishmeal remains scarce; therefore, global production quantities remain at the same level as in the FAO projection. This scenario accounts for the projection that, with increasing demand for fishmeal, increased production of reduction fisheries is not expected because of constantly shrinking fish stocks leading to regulations to protect fish stocks, as well as high costs and substantial effort required to expand catch activities (FAO, 2020).

For all scenarios, we use all other exogenous drivers (see Section 3.1) in an unchanged form.

4. Results

4.1. Global markets

Fig. 3 shows the *Baseline* development of fish production and most relevant fish-feed sectors over time. Owing to the scenario's design, capture fisheries and fishmeal production remain nearly constant, while global aquaculture production increases by 2% per annum. This leads to higher fishmeal prices and a greater increase in capture fish prices than in aquaculture fish prices. In the *Baseline* scenario, soybean meal production expands the most, with moderately rising prices reaching approximately half the price level of fishmeal.

Table 2 shows the differences in the scenario results compared to the *Baseline* scenario for 2030. Rebuilding sustainable fish stocks in scenario *SDG14* results in 22% lower wild fish production and a price spike of 38%. This substantial price increase must be considered when analyzing the *SDG14* scenario's effects on food security. Furthermore, an 18% reduction in fishmeal production is observed. The development of the fishmeal sector is mirrored by that of the oilseed meal sector, which shows a moderate price effect but a larger change in production (5–13%).

Under the *FGrow* scenario, in which aquaculture production is 33% higher than in the *Baseline* scenario, the production and prices of fishmeal (23%; 4%) and oilseed meals (7–25%; 3–8%) increase. In the case of soymeal, prices rise by 3%, causing indoor livestock production to decline by 2%. With higher demand for oilseeds, their production increases at the cost of maize.

In the *LimFishm* scenario, fishmeal prices rise by 31% compared to the *Baseline* caused by constant fishmeal production from 2018 to 2030. Consequently, oilseed meal production and price are the highest of all scenarios, and the impacts on the crop and livestock sectors are greater than those in the *FGrow* scenario.

Comparing impacts on the livestock and fish sectors across scenarios, two observations can be made. First, changes in the fish sector have implications for the livestock sector, particularly for indoor livestock (ILVS) such as poultry and pork. A reduction in capture fisheries increases, and expanding aquaculture production decreases livestock production. Therefore, in all scenarios, the price for indoor livestock rises – in scenario *SDG14* because of higher demand for meat, and in *FGrow* and *LimFishm* because of higher feed prices. Second, expanding aquaculture production leads to higher capture fish prices. The negative price effect from replacing capture fish with aquaculture fish in consumer diets is more than compensated for by the higher demand for fishmeal, which leads to higher prices for fishmeal and capture fish. Consequently, aquaculture production does not relieve but rather intensifies pressure on wild fish stocks in our model, unless fishmeal can be substantially replaced with another protein source.

Notably, in the model, aquaculture production was calibrated by a production quota, which absorbs the price effect of aquaculture

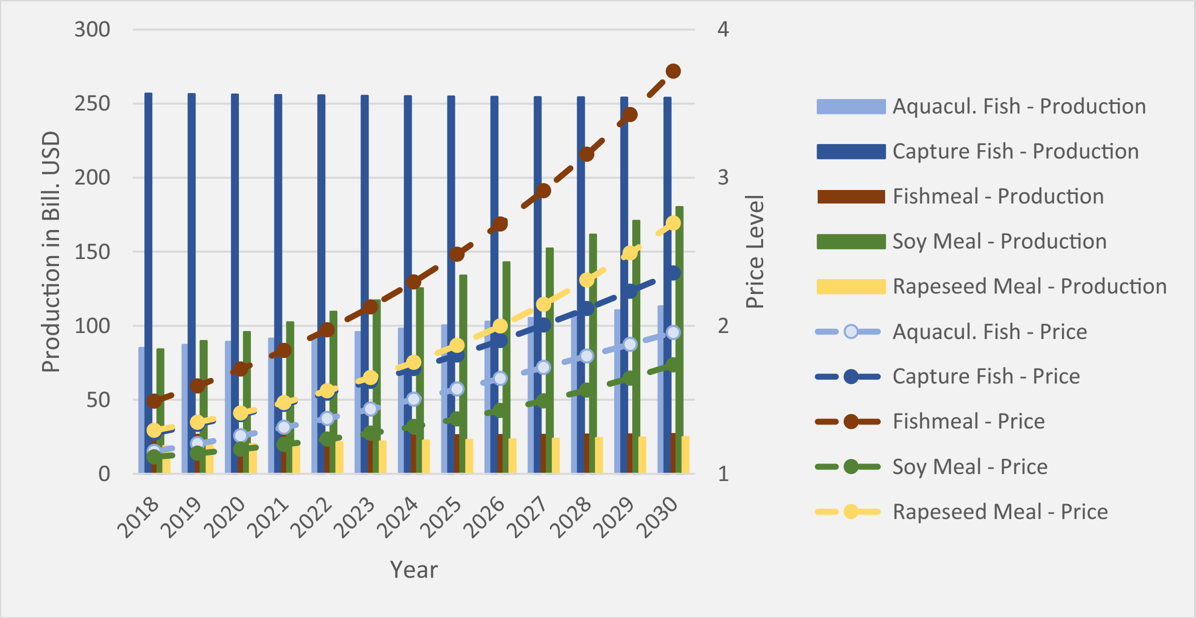

Fig. 3. Baseline development of global production and prices for fish and main fish feed in 2018–2030.

Table 2
Global production and prices for agricultural commodities and feed. Differences from *Baseline* scenario. Production in billions of USD.

Sector	Baseline Production 2030	Production			Price		
		Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
Wheat	321.27	0.1%	0.3%	0.2%	0.8%	1.6%	2.1%
Maize	311.80	0.1%	−0.4%	−0.6%	0.9%	1.7%	2.5%
Other Agriculture	2311.08	−0.2%	−0.1%	−0.3%	0.7%	1.5%	2.0%
Rapeseed	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%
Other Oilseeds	130.56	0.7%	1.2%	2.0%	0.8%	1.5%	2.1%
Outdoor Livestock	986.74	0.8%	−0.5%	−0.6%	1.4%	−0.5%	−0.3%
Indoor Livestock	1388.51	1.2%	−1.8%	−2.1%	0.6%	0.7%	1.1%
Aquaculture Fish	113.14	1.6%	32.9%	32.9%	3.9%	−18.3%	−18.1%
Capture Fish	254.00	−21.8%	0.0%	0.0%	37.6%	2.7%	3.6%
Fishmeal	27.58	−17.6%	22.8%	0.0%	27.8%	4.2%	31.1%
Rapeseed Meal	24.89	7.3%	16.0%	26.2%	3.2%	8.1%	10.6%
Soy Meal	180.22	4.8%	7.4%	11.6%	1.4%	2.7%	3.8%
Other Oilseed Meal	16.24	12.5%	25.2%	34.4%	2.1%	4.2%	8.2%

production between the *FGrow* and *LimFishm* scenarios. While the price does not change significantly, the endogenous quota in *LimFishm* is 10% higher than that in *FGrow,* which can be interpreted as an augmented price change for aquaculture fish. Additionally, in *SDG14*, the aquaculture production quota is not binding for the region “other Asian countries” (ROA). Therefore, production is 2% higher than intended. The underlying reason is that outdoor livestock (OLVS) and capture fish become extremely expensive in the region, and aquaculture fish becomes cheap such that they supplanted a large share of OLVS and CAPF consumption.

4.2. *Aquaculture production and feed composition*

The regional distribution of aquaculture in the *Baseline* scenario is shown in Fig. 4. China is the largest producer of aquaculture, followed by ROA and India. The regional concentration of aquaculture production indicates that the impact of changes in aquaculture production on food markets could differ between global regions.

Furthermore, the relevance of different feed items for regional aquaculture production may be crucial for feedback effects on regional food markets. Fig. 5 shows the initial fish-feed composition of the global aggregated aquaculture sector in 2018 and the respective share in 2030.

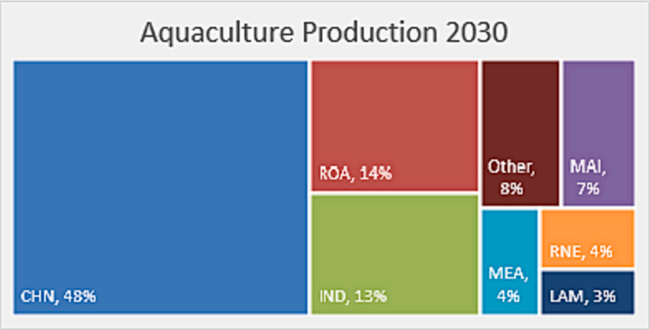

Fig. 4. Aquaculture production shares by region in 2030 under the *Baseline* scenario. Note: Consider the definitions of included fish in Section 3.2.2. Regions: CHN = China, ROA = other Asian countries, IND = India, MEA = Middle East and Northern Africa, MAI = Malaysia and Indonesia, RNE = other European countries, LAM = Latin America (without Argentina, Chile, Paraguay, Uruguay, and Brazil).

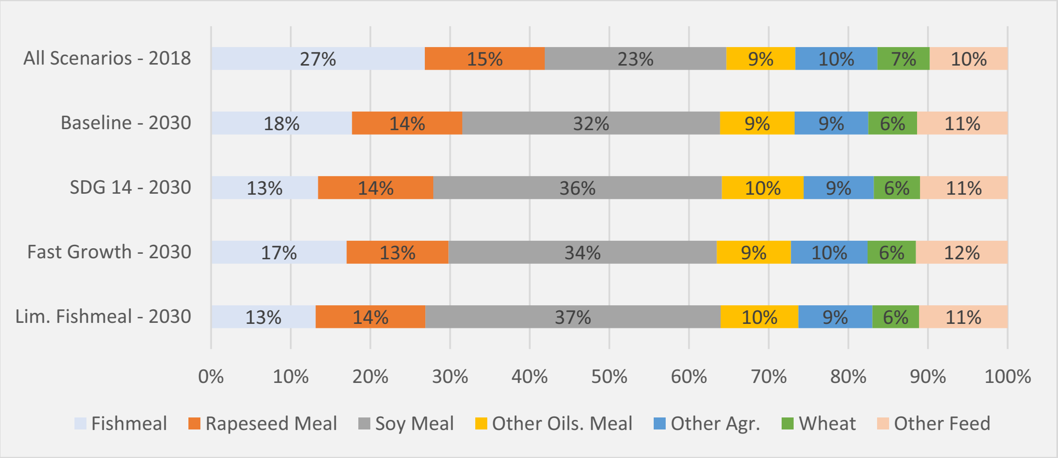

Fig. 5. Fish-feed composition shares in 2018 and 2030, global aggregate.

Even in the *Baseline* scenario*,* there is a clear trend of fishmeal being replaced by soybean meal. The share of rapeseed meal remains constant, whereas other oilseed meals (OSDN) and feeds show slightly higher shares. We can observe the expected reactions caused by developments in prices. When fishmeal becomes increasingly expensive, it is largely replaced with soybean meal.

At the regional level, the most significant substitution of fishmeal by soybean meal can be observed in the region "other European countries" (RNE), which includes Norway. The share of fishmeal falls from 52% in 2018 to 31% in the *Baseline* scenario and 22% in the *LimFishm* scenario by 2030. Therefore, the soybean meal share increases from 8% in 2018 to 36% in *Baseline* and 52% in *LimFishm* by 2030. The shares for scenarios *SDG14* and *FGrow* lie between those of the *Baseline* and *LimFishm* levels. In ROA, the fishmeal share decreases from 7% in 2018 to 3% and 2% by 2030 in *Baseline* and *LimFishm*, respectively. In contrast to RNE, the variation between the scenarios is negligible because the fishmeal share is already low in *Baseline*. In China, we observe a moderate reduction in the fishmeal share from 25% in 2018 to 18% in *Baseline* and 13% in *LimFishm*. The more moderate reduction in the fishmeal share in China compared to RNE is because of lower fishmeal and high soybean meal prices in China, driven by extensive local livestock production. Thus, the incentive to substitute fishmeal is lower than in RNE.

4.3. *Impacts on trade flows*

Changes in production and input shares have implications for agricultural commodity trade (Fig. 6). The greatest increase in oilseed imports is in RNE. However, in absolute terms, China increases imports of soy and rapeseed the most; already in the *Baseline* scenario, it is by far the biggest importer of oilseeds. Soy imports in ROA also substantially increase. The major producers of soy—Brazil, Paraguay, Argentina, Chile (PAC), and the US—satisfy the increased global soy demand by increasing exports. In this regard, the US can increase exports the most, both in relative and absolute terms. For rapeseed, a major share of China's increased import demand would be met by increased exports from Canada.

The modeled scenarios show different impacts on global agricultural commodity trade and aquaculture trade (Fig. 7). China is the largest producer and net importer of aquaculture products. The second largest importer is the EU. Interestingly, China has lower net imports in scenario *SDG14* than in *Baseline*, whereas ROA and the EU increase their net imports. One reason for this is the relative prices of animal products in the respective regions. When aquaculture production is constant, and capture fisheries are reduced, for the EU and ROA, it is cheaper to compensate for the capture fish reduction by importing aquaculture fish

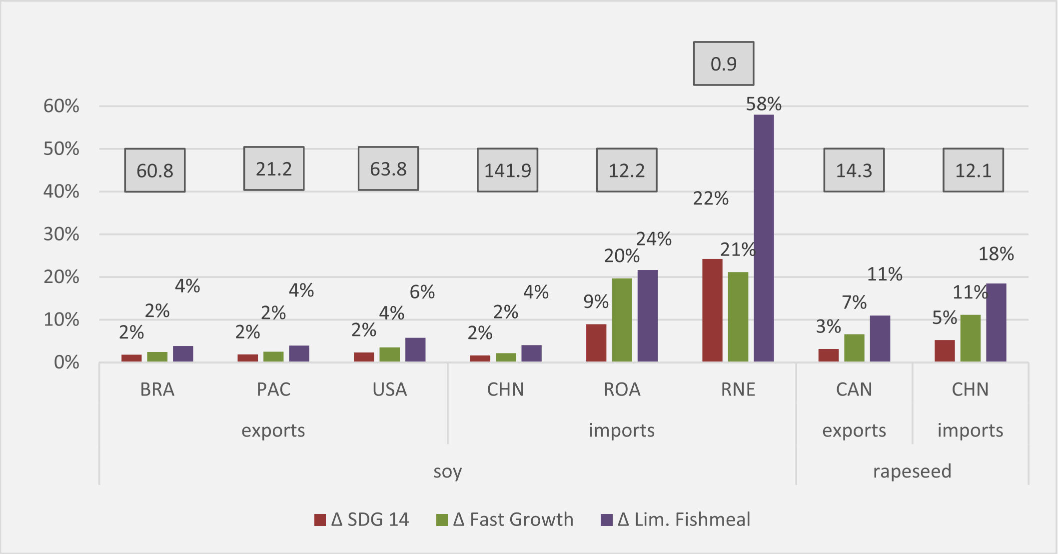

Fig. 6. Change of exports and imports in 2030 compared to the *Baseline* scenario. Note: The boxes state the 2030 *Baseline* values in bill. USD. Regions: BRA = Brazil; PAC=Paraguay, Uruguay, Argentina, Chile; CHN=China; ROA = other Asian countries; RNE = other European countries; CAN=Canada.

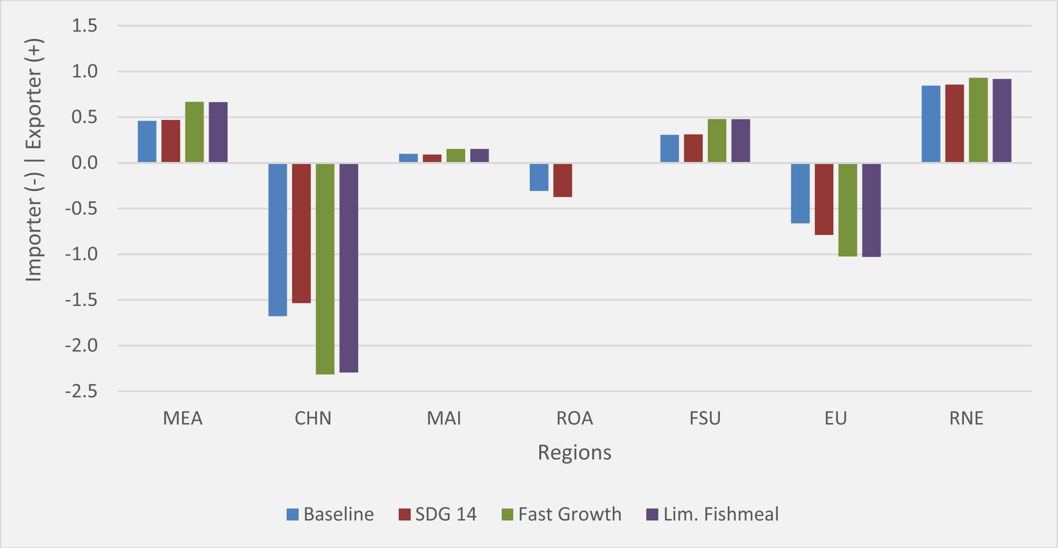

Fig. 7. Net trade of aquaculture fish in 2030, including trade within regions. In billions of USD. Regions: MEA = Middle East and North Africa, CHN=China, MAI = Malaysia and Indonesia, ROA = other Asian countries, FSU = former Soviet Union, EU = European Union, RNE = other European countries.

than to consume more livestock products. Conversely, for China, it is more beneficial to decrease net aquaculture imports with higher prices, and replace capture and aquaculture fisheries with meat.

However, in scenarios *FGrow* and *LimFishm,* net imports rise by approximately 38% in China and 64% in the EU, whereas ROA switch from being a net importer in the *Baseline* scenario to a net exporter in the other scenarios. In RNE, net exports drop between *FGrow* and *LimFishm*. No other region has a higher share of fishmeal use in aquaculture production than RNE. If the availability of fishmeal is reduced, this region will be impacted particularly hard by increasing costs, making its aquaculture products less competitive in global markets and leading to fewer exports and higher domestic consumption.

4.4. *Regional agricultural markets and land use*

We observe regional adjustments in agricultural production and land use, driven by global market dynamics. Table 3 shows the scenario results for oilseed crop production in major oilseed-producing regions. We can observe the greatest increases in oilseed crop production in major exporting regions, such as Brazil, the US, PAC, and Canada, and major aquaculture-producing regions, such as China and ROA. China expands its oilseed production relative to its production in the *Baseline* scenario. However, in absolute terms, the greatest increase in oilseed production is soy production in Brazil. It is already prominent in this country, and in scenarios *FGrow* and *LimFishm,* soy production increases by 2% and 3%, respectively, compared to the *Baseline*. Notably, although Sub-Saharan Africa (AFR) is neither a major exporter of oilseeds nor a major producer of fed-fish aquaculture, the region would increase its production of oilseed crops. This is rooted in spillover effects from global markets that require it to compensate for reduced oilseed imports caused by higher global oilseed prices.

Table 4 shows major land-use changes in land use for the most affected regions. Reducing capture fisheries to rebuild sustainable wild fish stocks alone would lead to a 7% increase in China's rapeseed production area, compared to the *Baseline*. The *LimFishm* scenario led to a 3% and 4% increase in soybean cultivation area in Brazil and the US respectively, and a 24% increase in the area used for rapeseed production in China. The land expansion in these sectors comes mainly at the expense of cultivating various other crops (AGR).

The effects on wheat, maize, and pasture land are somewhat ambiguous, depending on the region and scenario. While pasture land in PAC expands in the *SDG14* scenario, driven by the reduced supply of capture fish, which, in turn, leads to higher demand for outdoor livestock, pasture land area declines in all regions in *FGrow* and *LimFishm* scenario. In the US, the areas for maize and wheat production decrease as global aquaculture production increases. Nonetheless, in the *SDG14* scenario, the maize area in the US expands, driven by the substitution of capture fisheries with other animal products, for which maize is an essential feed source. In turn, the wheat area declines by 2% under the same scenario.

Finally, there is a unique effect on wheat cultivation in India, as the extent increases under the *FGrow* and *LimFishm* scenarios. Wheat is an important component of fish feed in India but not for fishmeal; consequently, no significant effects occurred for land-use change in scenario

Table 3

Changes in regional production of oilseeds in selected regions. Regions: BRA = Brazil; PAC=Paraguay, Uruguay, Argentina, Chile; AFR = Sub-Saharan Africa; CHN=China; ROA = Other Asian Countries; CAN=Canada.

Different to Baseline	**Sector**	**Regions**						
		BRA	PAC	AFR	CHN	ROA	CAN	USA
Δ SDG 14	Rapeseed	0.2%	2.5%	1.0%	6.7%	0.2%	2.7%	0.1%
	Soy	1.5%	0.5%	3.5%	3.0%	11.6%	2.7%	2.1%
	Other Oils	0.1%	−1.8%	0.3%	1.7%	2.0%	0.0%	0.3%
Δ Fast Growth	Rapeseed	−0.2%	3.9%	2.9%	14.2%	0.7%	5.4%	−0.1%
	Soy	2.2%	2.0%	3.8%	3.3%	22.0%	1.8%	2.9%
	Other Oils	−0.9%	−3.6%	0.9%	3.0%	5.6%	−1.7%	0.2%
Δ LimFishm	Rapeseed	0.1%	8.0%	4.8%	23.6%	1.3%	9.0%	0.2%
	Soy	3.4%	2.8%	6.8%	5.8%	26.1%	2.5%	4.7%
	Other Oils	−1.0%	−4.2%	1.7%	5.4%	6.9%	−2.6%	0.6%

Table 4

Scenario-based differences in land use in 2030. Percentage difference to the *Baseline* scenario. Regions: BRA = Brazil; PAC=Paraguay, Uruguay, Argentina, Chile; CHN=China; ROA = Other Asian Countries; IND=India.

Region	Crop/Land Use	Area *Baseline* 2030 (in 1000 ha)	Δ SDG14	Δ FGrow	Δ LimFishm
BRA	Soy	44,833	1.2%	1.8%	2.7%
	Sugar Crops	7814	−0.4%	−0.6%	−0.9%
	Other Crops	11,160	−1.2%	−1.6%	−2.5%
	Pasture	174,717	−0.1%	−0.5%	−0.7%
PAC	Soy	32,524	0.3%	1.8%	2.4%
	Other Crops	9179	−1.0%	−1.7%	−2.4%
	Pasture	140,668	1.8%	−0.2%	−0.3%
CHN	Rapeseed	6903	6.6%	14.1%	23.4%
	Soy	3657	3.0%	3.2%	5.7%
	Other Oilseeds	6022	1.6%	2.9%	5.3%
	Other Crops	59,942	−0.5%	−0.8%	−1.3%
	Pasture	376,264	0.1%	−0.7%	−0.9%
USA	Soy	54,524	1.9%	2.7%	4.4%
	Other Crops	48,502	−1.3%	−1.0%	−1.8%
	Wheat	14,496	−2.3%	−1.6%	−2.8%
	Maize	26,116	0.5%	−1.0%	−1.5%
ROA	Other Oilseeds	11,641	2.0%	5.6%	6.9%
	Other Crops	28,348	−0.2%	−0.3%	−0.4%
	Wheat	36,969	−0.2%	1.4%	1.3%
IND	Rapeseed	6069	−0.1%	1.4%	1.4%
	Soy	8314	0.1%	2.4%	2.5%
	Pasture	9185	0.1%	−0.8%	−0.9%

SDG14, nor were there major differences in this regard between *FGrow* and *LimFishm*.

4.5. Implications for food market prices

The reduction of capture fish in scenario *SDG14* and the expansion of oilseed crop production in *FGrow* and *LimFishm* directly affect staple crop prices and the food sector more generally. Fig. 8 summarizes the scenario-based price differences for food, meat, and staple crops in 2030. The decreased availability of fish in scenario *SDG14* leads to significantly higher prices in the food sector for Sub-Saharan Africa and PAC. Additionally, the price of processed meat as a substitute for fish increases in several regions. Conversely, aquaculture production expansion in scenarios *FGrow* and *LimFishm* leads to negligible positive and even negative price effects in the food and processed meat sectors. Therefore, there were larger price increases for the staple crops of wheat, maize, and paddy rice in all regions, except India, in the *FGrow* scenario.

There are two main reasons for the distinct responses of the respective sectors. Wheat and maize production can be replaced by oilseed crop cultivation, and grains can also be used as fish feed; thus, demand and prices increase if aquaculture production is expanded. Moreover, a large share of aquaculture production enters the processed food sector, where it substitutes more expensive outdoor livestock. Conversely, staple crops bypass to a much larger extent the processed food sector and go directly to the consumer. Hence, increasing aquaculture production can lead to lower prices in the food sector and higher local prices for staple crops, particularly in regions such as India, Malaysia and Indonesia, and ROA, where outdoor livestock are expensive.

4.6. Sensitivity analysis

Sensitivity analysis focuses on the elasticity of substitution of protein feed in the aquaculture production function. We use an elasticity of 2 for our evaluation. A sensitivity analysis was conducted by running each scenario with half ($\sigma = 1$) and double ($\sigma = 4$) elasticity of substitution for protein fish feed. We also split the fishmeal and oilseed meal nests and assumed $\sigma^{os} = 2$ for the elasticity within the oilseed meals and $\sigma^{fm} = 1$ for the elasticity between the oilseed meals and fishmeal. Low elasticity assumes slow technological advancement regarding the substitutability of fishmeal in fish feed, whereas high elasticity assumes rapid technological advancement.

Results indicate the model's expected reactions. Appendix Fig. A.3 shows the new shares of fish-feed composition in 2030 for each scenario, conditional on the elasticity of substitution. The variation in feed composition between the scenarios is similar across different elasticities. Fishmeal share decreases from 23% (*Baseline*) to 19% (*LimFishm*) with low elasticity and from 11% (*Baseline*) to 7% (*LimFishm)* with high substitution elasticity. Thus, changes in fishmeal share are relatively robust across scenarios, whereas there were major differences when comparing elasticities within a single scenario. Compared to the low-elasticity model, in the high-elasticity model the share of fishmeal in the feed composition is already 6% lower in 2018; in all scenarios, it is approximately 12% lower in 2030. The split-nesting model shows results similar to the low-elasticity model, but there is higher substitution between soybean meal and rapeseed meal. Finally, aggregated oilseed meals are cheaper than in the low-elasticity model, which causes a slightly increased consumption of total oilseed meals and lower fishmeal usage.

The sensitivity analysis results for global production and prices are presented in the Appendix (Table A.6 and Table A.7). Sectors not directly affected by aquaculture and capture fish production do not show considerable variation owing to different elasticities. For the fish and fish-feed sectors, low elasticity leads to higher prices for fish products and lower prices for their substitutes, whereas applying higher substitution elasticity has the opposite effect. Moreover, the differences in prices and production in the scenarios compared to the *Baseline* has the expected outcomes: With high substitution elasticity, quantity effects are greater and price effects lower for the fish sector and relatively expensive feeds, such as rapeseed meal. For relatively cheap feeds, such as soybean meal, the opposite is true. The quantity and price changes in the split-nesting model are between those of the low-elasticity model and standard model with $\sigma = 2$; the only exceptions are the quantity of rapeseed and rapeseed meal produced. While it substitutes fishmeal in the standard model, it is substituted by soybean meal in the split-nesting model. In general, the results are closer to those of the standard model than the low-elasticity model, except for livestock production.

5. Discussion

As shown by the sensitivity analysis, the feedback effects of aquaculture on land use depend on the technical substitutability of fishmeal. Our results show that soybean meal production is much cheaper and can be expanded more easily than fishmeal production. Thus, if technically feasible, limiting the use of fishmeal as feed would be profitable for fish farmers. However, not all fish protein can be replaced by plant-based feed, especially fish oil, a co-product of fishmeal production (Mullon et al., 2009; Naylor et al., 2009).

Protein feed's role in aquaculture is in the focus of the debate by Costello et al. (2020) and Zhang et al. (2022) regarding the future relevance of freshwater and mariculture aquaculture. While freshwater fish species, which require less protein feed than mariculture fish, are largely consumed in China and developing countries (Costello et al., 2020; Zhang et al., 2022), as income increases, consumers prefer carnivorous species (FAO, 2020). Regnier and Schubert (2017) argued that, in terms of the positive demand and growth potential for

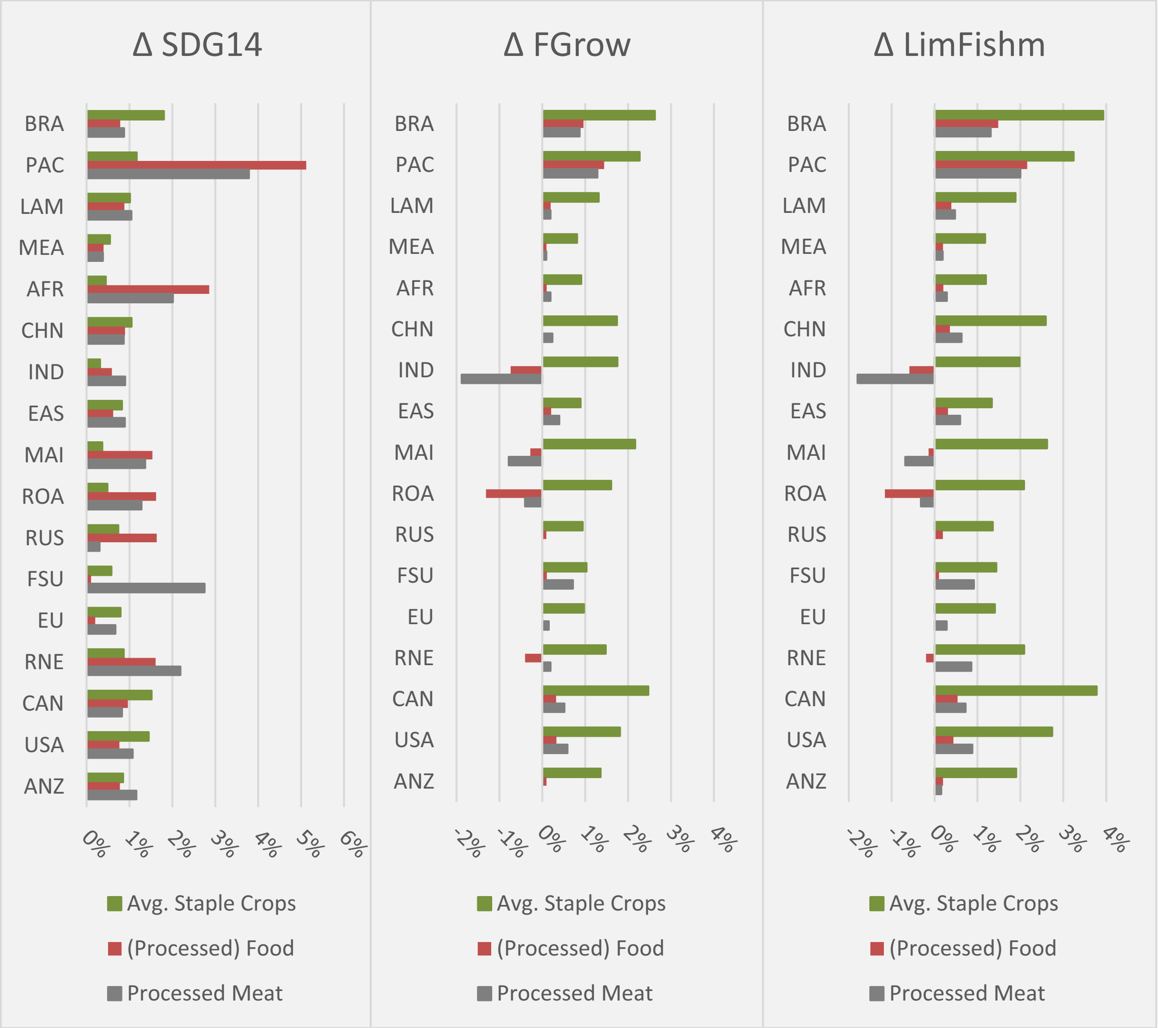

Fig. 8. Regional price changes in food sectors. Price in 2030 compared to *Baseline* scenario. Staple crops: maize, wheat, paddy rice. Regions: BRA = Brazil; PAC=Paraguay, Argentina, Chile; LAM = other Latin American countries; MEA = Middle East and North Africa; AFR = Sub-Saharan Africa; CHN=China; IND=India; EAS = East Asia; MAI = Malaysia and Indonesia; ROA = other Asian countries; RUS = Russia; FSU = former Soviet Union; EU = European Union; RNE = other northern European countries; CAN=Canada; USA = United States; ANZ = Australia and Oceania.

mariculture, it is questionable whether producers will invest more in herbivorous or filter-fish species. Therefore, protein feed will remain crucial for aquaculture production.

However, the extent to which feed formulations can be optimized to minimize dependency on fishmeal and if fish breeding techniques can lead to less protein-dependent aquaculture that satisfies consumer preferences are questions for the future. Further, alternative feed sources, such as insects, are promising but are currently applied only on a small scale (Barroso et al., 2014; Nogales-Mérida et al., 2019; Alfiko et al., 2022). Recently, the aquaculture industry has made considerable innovations in terms of feed composition and efficiency, leading to a reduction in the FIFO ratio (Kobayashi et al., 2015; FAO, 2020). In our model, expectations concerning technical advances are reflected by the elasticity of substitution in the feed nest, which determines producers' responses to changes in relative (input) prices and ultimately impact the resulting changes in aquaculture production and prices. Nevertheless, elasticities play a minor role in the scenario comparison because the changes between the scenarios showed only minor variations when applying different elasticities. Thus, the scenario analysis results can be considered reasonably robust.

This analysis does not show a comparable reduction in land use owing to increased aquaculture consumption as in Froehlich et al. (2018b). While our analysis focuses on the effects of aquaculture production on agricultural markets under current consumer preferences, with varying extent of and feed availability for aquaculture production, Froehlich et al. (2018b) conducted a scenario analysis of a shift in consumer preferences. In their scenarios, consumers only reduced their meat consumption by consuming aquaculture fish. As fish have more energy-efficient feed conversion than livestock (Merino et al., 2012; Regnier and Schubert, 2017), this substitution would lead to a lower demand for feed and less land use (Froehlich et al., 2018b). Nonetheless, the argument that consumers only consume less meat if they consume more fish can be challenged. In the DART-BIOFISH model, consumers respond to supply changes according to income elasticities in the linear expenditure system. When fish becomes relatively cheaper, they consume more fish and less meat, as in Froehlich et al. (2018b), but also less plant-based food, depending on income, domestic prices, and preferences. Consequently, increasing aquaculture fish production would only lead to a marginal reduction in total land use (−0.03%), as we observed a global 0.2% increase in total animal protein consumption (fish and livestock).

This study complements Kobayashi et al. (2015) by exogenously assuming comparable aggregated aquaculture production, and in addition evaluating endogenous feedback effects on land-use change and agricultural markets based on demand for plant-based feed. However, the model cannot account for land use change by the conversion of natural land, such as mangroves and forests, and crop land into aquaculture production sites. In particular in Southeast Asia, this is an additional driver for land-use change that should be considered (Ali, 2006; Tran et al., 2015; OECD/FAO, 2017). Moreover, the highly aggregated aquaculture sector in the DART-BIOFISH model only implicitly accounts for species substitution within aquaculture consumption. Naylor et al. (2021) argue that models should include more than one sector representing aquatic food but also demonstrate barriers to such an undertaking. To increase precision, CGE models with an integrated multi-species fish module are required that can treat capture fish supply endogenously.

6. Conclusion

This study demonstrates the connection between the aquaculture sector and agricultural markets. It also indicates how aquaculture production affects global trade patterns for oilseed crops. We show that expanding aquaculture production, and reducing the share of fishmeal used in fish feed, can lead to increased oilseed crop production and trade. Countries in South America and the US can significantly increase soy exports. Under the most extreme *LimFishm* scenario, the additional soybean cultivation area in these regions is 4.6 million ha. The land required for this expanded production is taken from maize, wheat, various other crops, and pasture land, and we observe a corresponding rise in staple crop prices. In particular, in the Americas and China, regional effects on land-use change and price reactions are likely.

The results also reveal the linkages and trade-offs between SDG 14 (*life below water*), SDG 15 (*life on land*), and SDG 2 (*zero hunger*). The results from the *SDG14* and *LimFishm* scenarios show that policies designed to achieve SDG 14 can lead to land-use change, and trade-offs with regard to achieving SDG 15. However, improving the availability of fish-based protein foods to support SDG 2, as assumed in scenarios *FGrow* and *LimFishm*, has implications for achieving SDGs 15 and 14 via feed production for aquaculture cultivation. Furthermore, we show that fishing policies and aquaculture production affect staple food and consumer prices at the regional level. Achieving SDG Target 14.4 bears trade-offs for achieving SDG 2, as it could cause fish and crop prices to rise and limit access to food, particularly in Sub-Saharan Africa and Southeast Asia, where capture fish is key to food security in coastal regions (FAO, 2020). Nevertheless, according to the World Bank, rebuilding sustainable fish stocks leads to sustainable and higher catch levels in the long term than those currently in force (World Bank, 2017). Hence, time dimensions must be considered. As the SDGs have 2030 as their target, rebuilding sustainable fish stocks would create additional restraints in this period and conflict with SDG 2 but provide benefits later on (World Bank, 2017). This study's results demonstrate that regions whose food security depends on marine fishing activities need support in the transition period until sustainable fish stocks are achieved, as they will suffer the most on the path to reaching SDG 14.

As discussed in terms of land use, dietary patterns and the substitution of animal products in the human diet play a crucial role in this analyses; however, our approach could be improved by adding sectoral detail to the food and livestock sectors. In addition to land use, consumption preferences are important in analyzing the impacts of aquaculture production on food security. If aquaculture fish consumption substantially replaces meat consumption, food prices may fall due to a lower demand for animal feed. However, prices may rise if aquaculture fish consumption replaces plant-based diets. Our analysis uses the income price elasticities provided in the GTAP database based on historical data, which might be restrictive with respect to potential future preference changes. Additionally, possible future synergies between aquatic and terrestrial food production, such as the use of manure as feed (Brown et al., 2014), require further evaluation. An in-depth analysis of the interactions between the meat and fish sectors, consequences for food security, and the role of biofuel policies are promising topics for future research.

CRediT authorship contribution statement

Tobias Heimann: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Ruth Delzeit:** Conceptualization, Data curation, Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix

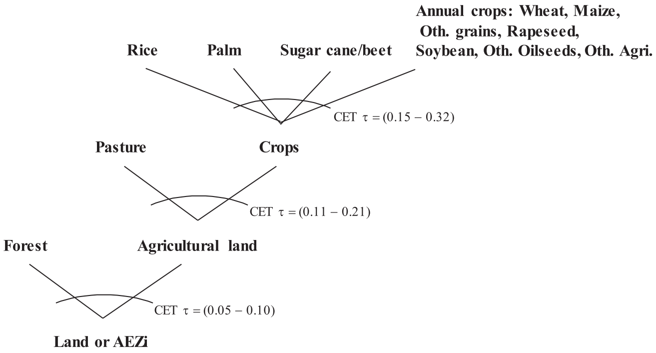

Fig. A.1. Nesting of constant elasticity of transformation function in the DART-BIOFISH model.

Table A.1
Elasticities of transformation.

	BRA	PAC	LAM	MEA	AFR	CHN	IND	EAS	MAI	ROA	RUS	FSU	CEU	DEU	MED	MEE	NWE	RNE	CAN	USA	ANZ
CET1	0.05	0.05	0.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.05
CET2	0.21	0.21	0.11	0.15	0.21	0.21	0.21	0.11	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.11	0.14	0.15	0.17
CET3	0.22	0.22	0.3	0.24	0.4	0.22	0.22	0.15	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.15	0.32	0.32	0.3

Source
Abler (2000) and Salhofer (2000). As used in the OECD's Public Employment and Management Model. As the OECD Model only covers developed countries plus Mexico, Turkey, and South Korea, we assume certain similarities for several countries. Constant Elasticity of Transformation (CET)1 denotes the nest between forest and agricultural land, CET2 the nest between cropland and pasture land, and CET3 the nest between land for different perennial and annual crops.

Table A.2
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
		MED	Mediterranean with Cyprus, Greece, Italy, Malta, Portugal, Spain
Middle East and Northern Africa		MEE	Eastern European Union with Austria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Romania, Bulgaria, Croatia
MEA	Middle East and Northern Africa	NWE	North-Western European Union with Denmark, Finland, Ireland, Sweden, United Kingdom
AFR	Sub-Saharan Africa	RNE	Other Northern European Countries: 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	Other Asian Countries	ANC	Australia, New Zealand, Rest of Oceania
RUS	Russia		

Table A.3
Sectors in DART-BIOFISH.

Agricultural related products (28)		**Energy products (14)**	
Crops		COL	Coal
PDR	Paddy rice	CRU	Oil
WHT	Wheat	GAS	Gas
*MZE**	*Maize*	*MGAS**	*Motor gasoline*
*PLM**	*Oil Palm fruit*	*MDIE**	*Motor diesel*
*RSD**	*Rapeseed*	OIL	Petroleum and coal products
*SOY**	*Soy bean*	ELY	Electricity
OSDN	Other oil seeds	*ETHW**	*Bioethanol from wheat*
C_B	Sugar cane and sugar beet	*ETHM**	*Bioethanol from maize*
AGR	Rest of crops	*ETHG**	*Bioethanol from other grains*
Processed agricultural products		*ETHS**	*Bioethanol from sugar cane*
VOLN	Other vegetable oils	*ETHL**	*Bioethanol from lignocellulosic biomass*
FOD	Rest of food		
*PLMoil**	*Palm oil*	**Biofuels**	
*RSDoil**	*Rapeseed oil*	*BETH**	*Bioethanol*
*SOYoil**	*Soy bean oil*	*BDIE**	*Biodiesel*
*OSDNoil**	*Oil from other oil seeds*		
*SOYmeal**	*Soy bean meal*	**Non-energy products (2)**	
*OSDNmeal**	*Meal from other oil seeds*	SERV	Services
*PLMmeal**	*Palm meal*	OTH	Other goods
*RSDmeal**	*Rapeseed meal*		
*DDGSw**	*DDGS from wheat*		
*DDGSm**	*DDGS from maize*	**Forest and forest products (1)**	
*DDGSg**	*DDGS from other cereal grains*	FRS	Forest
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*		

Table A.4
Income elasticities for animal protein sectors.

Sector	BRA	PAC	LAM	MEA	AFR	CHN	IND	EAS	MAI	ROA	RUS	FSU	CEU	DEU	MED	MEE	NWE	RNE	CAN	USA	ANZ
OLVS	0.741	0.750	0.736	0.780	0.917	0.712	0.785	0.893	0.705	0.870	0.743	0.768	0.896	0.904	0.882	0.816	0.905	0.962	0.906	0.917	0.830
ILVS	0.742	0.756	0.735	0.760	0.877	0.704	0.785	0.862	0.707	0.792	0.743	0.769	0.898	0.904	0.886	0.820	0.899	0.973	0.906	0.917	0.913
PCM	0.742	0.756	0.739	0.782	0.906	0.703	0.785	0.867	0.706	0.759	0.743	0.760	0.897	0.904	0.882	0.811	0.906	0.972	0.906	0.917	0.871
AQUF	0.742	0.787	0.749	0.760	0.965	0.705	0.785	0.855	0.705	0.794	0.743	0.751	0.896	0.904	0.874	0.825	0.900	0.994	0.909	0.917	0.931
CAPF	0.742	0.787	0.749	0.760	0.965	0.705	0.785	0.855	0.705	0.794	0.743	0.751	0.896	0.904	0.874	0.825	0.900	0.994	0.909	0.917	0.931

Source: Aguiar et al. (2016).

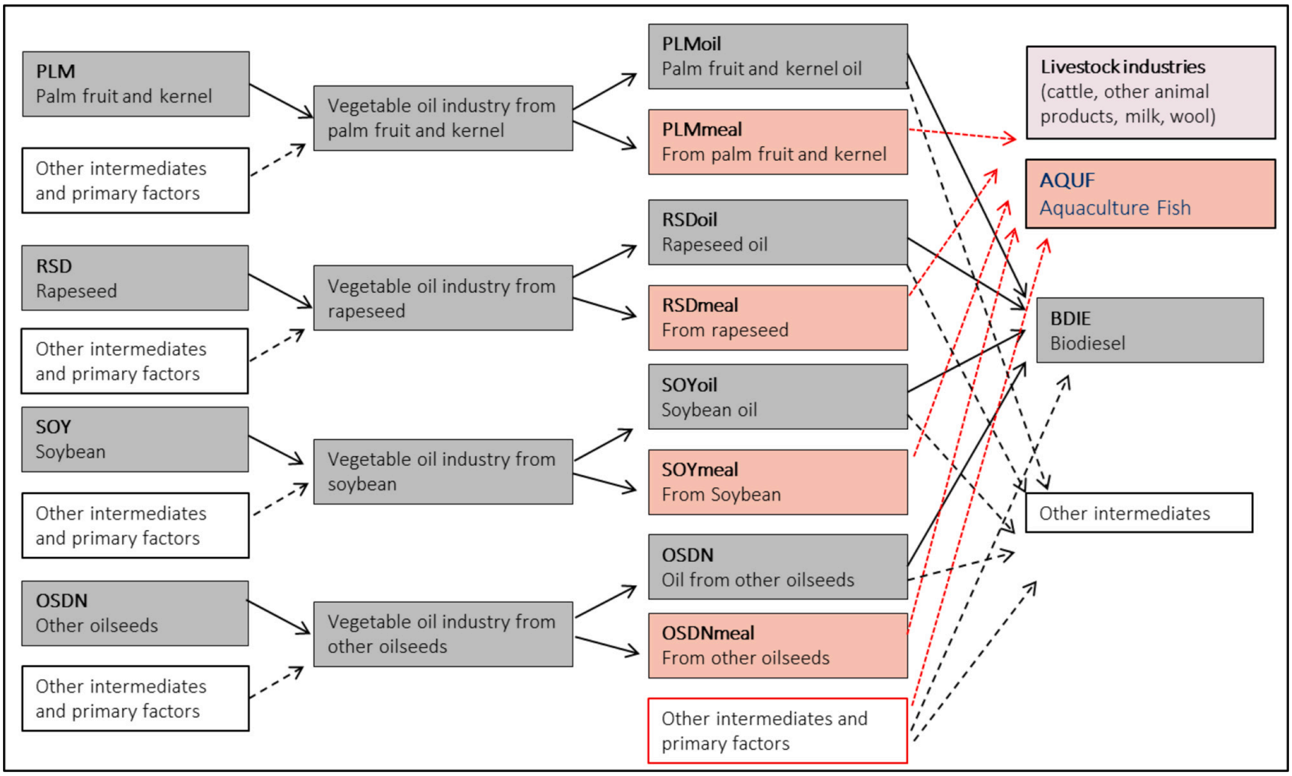

Fig. A.2. Oilseed oil and meal coproduction in the DART-BIO model.

Table A.5
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%

Table A.6
Sensitivity analysis: Global production with varying elasticity of substitution. Differences to *Baseline* scenario 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 nest; σ^{os} = elasticity within oilseed meals nest.

Sector	**Baseline Output 2030 (in bill. USD)**			**Output**								
	σ = 1	$\sigma^{fm} = 1; \sigma^{os} = 2$	σ = 4	σ = 1			$\sigma^{fm} = 1; \sigma^{os} = 2$			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 A.7
Sensitivity analysis: Global production with varying elasticity of substitution. Differences to *Baseline* scenario 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 nest; σ^{os} = elasticity within oilseed meals nest.

Sector	**Baseline Prices 2030 (const. USD)**			**Prices**								
	σ = 1	$\sigma^{fm} = 1; \sigma^{os} = 2$	σ = 4	σ = 1			$\sigma^{fm} = 1; \sigma^{os} = 2$			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%

(*continued on next page*)

Table A.7 (*continued*)

Sector	Baseline Prices 2030 (const. USD)			Prices								
	$\sigma = 1$	$\sigma^{fm} = 1; \sigma^{os} = 2$	$\sigma = 4$	$\sigma = 1$			$\sigma^{fm} = 1; \sigma^{os} = 2$			$\sigma = 4$		
				Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
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%

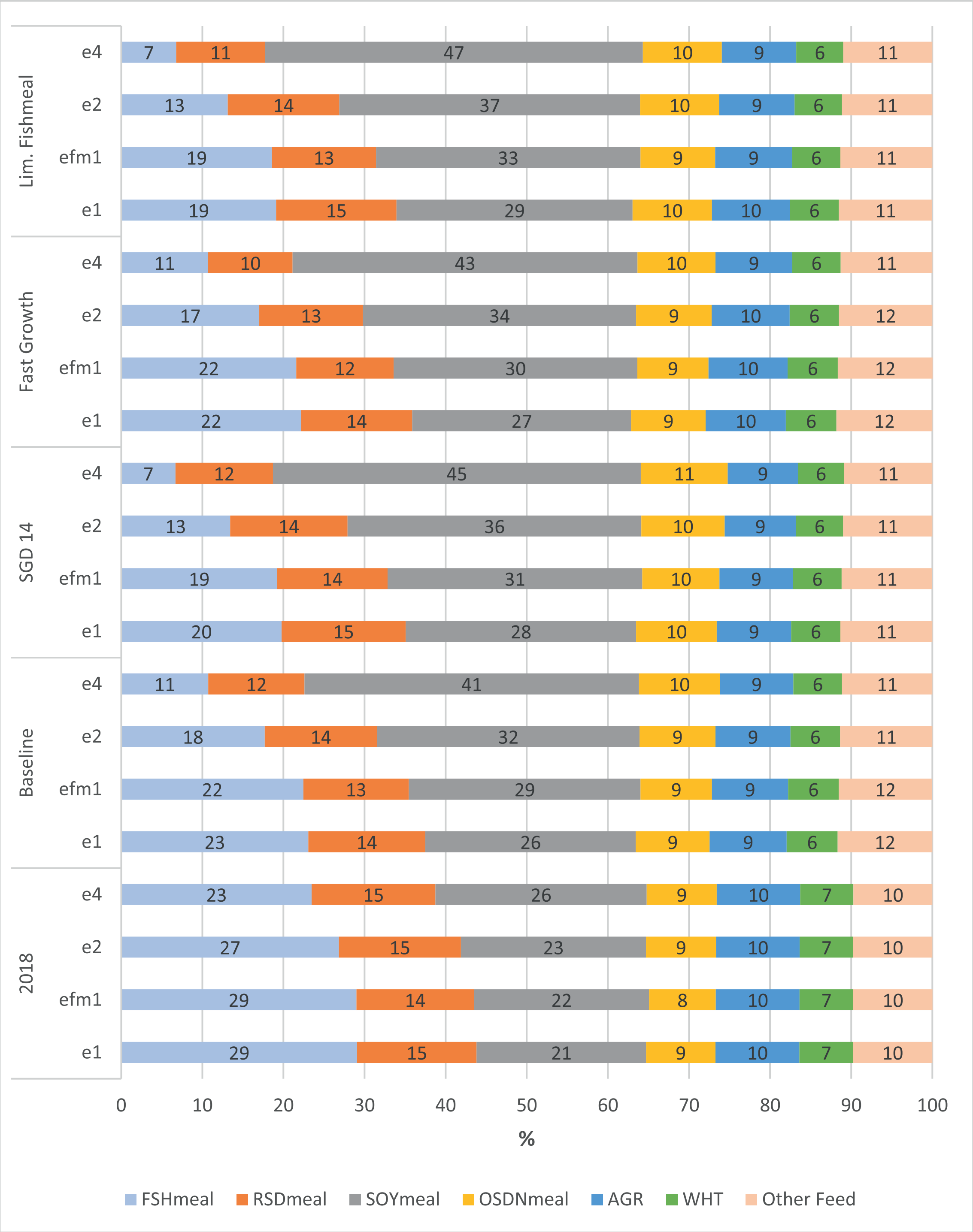

Fig. A.3. Results of the sensitivity analysis on fish feed composition; volume shares in 2018 and 2030 in percent. Note: e1: $\sigma = 1$; e2: $\sigma = 2$; e4: $\sigma = 4$; efm1: split nesting for fishmeal and oilseed meals: Elasticity between fishmeal and oilseed meals nest σ^{fm};=1, Elasticity within oilseed meals nest $\sigma^{os} = 2$.

Table A.8
Feed prices in 2011.

Feed Item	Price in USD/mt*	Source	Detail
Fish Meal	1442	World Bank	World Bank Commodity Price Data (The Pink Sheet)
Fish Oil	1533	FAO	FAO Commodity Statistics Update March 2016; http://www.fao.org/3/a-bl391e.pdf
Soybean Meal	409	World Bank	World Bank Commodity Price Data (The Pink Sheet)
Soybean Oil	1297	World Bank	World Bank Commodity Price Data (The Pink Sheet)
Rapeseed Meal	243	Canola Council	https://www.canolacouncil.org/markets-stats/statistics/historic-canola-oil,-meal,-and-seed-prices/)
Rapeed Oil	1368	IMF	IMF Primary Commodity Price System
Wheat	301	CMO; World Bank	CMO Historical Data; World Bank Commodity Price Data (The Pink Sheet)
Rice bran	154	USDA	USDA Yearbook: U.S. Rough and Milled Rice Prices, monthly and marketing year
Groundnut	1883	CMO; World Bank	CMO Historical Data; World Bank Commodity Price Data (The Pink Sheet)
Meat and Bone Meal	369	Feedstuffs.com	https://www.feedstuffs.com/search/node/Grain%20%26%20ingredient%20cash%20market?sort=field_penton_published_datetime&order=asc
Corn Gluten Meal	536	Feedstuffs.com	https://www.feedstuffs.com/search/node/Grain%20%26%20ingredient%20cash%20market?sort=field_penton_published_datetime&order=asc
Other feedstuff	279	Feedstuffs.com	https://www.feedstuffs.com/search/node/Grain%20%26%20ingredient%20cash%20market?sort=field_penton_published_datetime&order=asc

* Prices are calculated as 3 year averages from 2010 to 2012.

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