Enhanced modelling of sustainable food and nutrition security: food supply and use of scarce resources

Deliverable No. 9.3

SUSFANS DELIVERABLES

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This deliverable reports on Task 9.3 and describes the enhanced modelling of food supply and the use of scarce resources. The enhancements improve the analysis of sustainable food and nutrition security in response to (policy) shocks with regard to coverage and accuracy of sustainability metrics provided by long-run modelling tools in SUSFANS.

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Deliverable short summary for use in media

It is the vision of SUSFANS to contribute to a better understanding of the European food system and to provide tools for policy makers to advance with respect to Sustainable Food and Nutrition Security (SFNS) in Europe. All three dimensions of sustainability – social, environmental and economic – are addressed in the project in a holistic, integrative approach building upon metrics, models and foresight tools. In order to explore the impacts of interventions on the food system, SUSFANS employs a set of well-established long-run models (CAPRI, GLOBIOM and MAGNET). To further enhance their ability to assess impacts of policy and other shocks on SFNS and to provide the relevant metrics identified in the project for appropriately measuring state and changes of SFNS, the long run models are further developed in the course of SUSFANS.

This deliverable specifically reports on the long-term models' enhancements for modelling impacts on SFNS regarding food supply and the use of scarce resources. It describes model changes and extensions promised in the description of work and additional ones decided upon in the course of the project. Specifically, the developments for the models CAPRI and GLOBIOM are covered as these are the two models with a comparative advantage in representing the food supply and resource use. The deliverable reports on model-specific enhancements related to CAPRI and GLOBIOM and on newly developed fish modules for both modelling systems. Model enhancements in other areas are covered in report D9.2 (Food consumption and nutrition of households) and report D9.4 (Commodity and nutrient flows, supply chains).

CAPRI-specific developments target a more realistic representation of the regional heterogeneities with respect to fertilizer responses. Statistical analyses of yield gaps in European regions provided earlier by work package 4 are exploited to develop more appropriate, region-specific potentials for yield increases under intensification scenarios. A successful implementation improves upon nutrient-related sustainability assessments on the supply side. Closer to the diet side of the food system is another CAPRI development introducing micronutrients to the product-based accounting system. Previously, the model only covered calorie, fat, and protein contents. The micronutrient accounting offers a significant step in making CAPRI model results relevant not only for food security, but also for nutrition security.

GLOBIOM-specific developments target to improve model behavior with respect to crop intensification and crop expansion responses. By employing new comprehensive crop-modelling results and new empirical estimates of crop supply elasticities, the knowledge base underlying the model's processes determining cropping levels and intensities is thoroughly revised. Moreover, a demanding calibration methodology is implemented to appropriately reconcile the new knowledge on model parameters with observed farmer's decisions. This substantial re-parameterization of GLOBIOM's crop supply specification leads to a more accurate quantification of a number of metrics related to production, resource use and environmental sustainability. For example, the level and spatial differentiation of nitrate leaching and irrigation management improves considerably.

An increased fish consumption substituting for meat-based protein sources is generally considered healthier and consequently relevant for the analysis of nutrition security. Observed recent expansions of this sector come from an expansion of aquaculture and not anymore from captures due to their natural constraints. Further future increases in fish consumption will inevitably continue to boost the share of aquaculture in overall fish production and raise questions regarding environmental sustainability but also with respect to competition for feed (and indirectly land). The developments of fish modules for CAPRI and GLOBIOM consequently contributes to the core of the SUSFANS objectives addressing food as well as nutrition security issues. Using available global databases, both models were able to develop and implement fish modules fitting to the specific structure of the modelling systems. Soon first scenario simulation incorporating the fish modules can be tested and the full-fledged application will be possible for the main body of foresight analysis foreseen in work package 10.

Teaser for social media

The CAPRI and GLOBIOM models are now capable of assessing the role of fish production, consumption and trade for the sustainability of food and nutrition security. Following health and climate change concerns, the expansion of fish consumption is often seen as one piece of the puzzle in solving future food system challenges. The interactions of fish with other food items are however complex and occur on the consumption as well as the production side. The developed modules are able to reflect important parts of these complexities and strongly enhance SUSFANS ability to develop relevant foresights for the food system.

Abstract

One enhancements of the CAPRI model improves upon yield responses to fertilizer application rates in the regional supply models. The basis for these are efficiency frontiers identifying yield gaps which were estimated for all European regions and main crops in the context of work package 4 (D4.5). The heterogeneity in yield gaps across regions are translated to adjusted technology definitions in the mathematical programming models determining intensity of crop production and land allocation to cropping activities. Another model improvement adds 21 micronutrient contents of products to allow deriving daily intake values per capita in post-model analysis beyond the previously included calorie, protein and fat contents. The list comprises fiber, sugar, calcium, iron, magnesium, potassium, sodium, zinc, selenium, vitamins (A, C, D, E, B1, B2, B6, B12), folate, saturated fatty acids, mono- and polyunsaturated fatty acids. The nutrient content coefficients were, with a few exceptions, mapped from the Food Composition Databases of the United States Department of Agriculture (USDA) using raw and unprocessed food items to achieve the best possible fit with CAPRI product items on the supply side.

The overarching objective for the enhancements of the GLOBIOM crop supply is to improve model behavior with respect to crop intensification and crop expansion responses. As a first step, a new set of EPIC (crop growth) simulations are implemented to better represent intensification gradients. In order to capture implied fertilizer response patterns, linearized quadratic costs were included in the linear programming models determining grid cell's supply behavior. Secondly, the crop supply elasticities governing crop expansion are renewed based on Bayesian Vector Autoregression, which is very flexible in handling a large set of variables, depicts relevant dynamics, and allows involving prior information. The econometric estimates employ historical yearly data on prices, yields, areas consumption and trade balances and are subjected to elasticity bounds derived from the literature. Finally, the GLOBIOM calibration procedure is revised to align GLOBIOM model outputs based on the new parameters with reported statistics on cropping patterns. A two-step procedure is introduced for adjusting model parameters, balancing the fit of model behavior to observed responses with the deviation of parameters from original values.

CAPRI and GLOBIOM both develop a new fish module expanding the product coverage and resolution of the models to address a crucial requirement for comprehensive SFNS modelling.

1 Introduction

It is the vision of SUSFANS to contribute to a better understanding of the European food system and to provide tools for policy makers to advance with respect to Sustainable Food and Nutrition Security (SFNS) in Europe. All three dimensions of sustainability – social, environmental and economic – are addressed in the project in a holistic, integrative approach building upon metrics, models and foresight tools (Rutten et al. 2016, Zurek et al. 2016, Zurek et al. 2017, Kuiper and Zurek 2017). In order to explore the impacts of interventions on the food system, SUSFANS employs a set of well-established long-run models (CAPRI, GLOBIOM and MAGNET). To further enhance their ability to assess impacts of policy and other shocks on SFNS and to provide the relevant metrics identified in the project (Zurek et al. 2017) for appropriately measuring state and changes of SFNS, the long run models are further developed in the course of SUSFANS.

This deliverable specifically reports on the long-term models' enhancements for modelling impacts on SFNS regarding food supply and the use of scarce resources. It describes model changes and extensions promised in the description of work and additional ones decided upon in the course of the project. Specifically, the developments for the models CAPRI and GLOBIOM are covered as these are the two models with a comparative advantage in representing the food supply and resource use. Other parallel model developments (including CAPRI, GLOBIOM MAGNET and SHARP), are covered in Kuiper et al. (2017) (Food consumption and nutrition of households, report D9.2) and Garmona-Garcia et al. (2017) (Commodity and nutrient flows, supply chains, report D9.4).

The structure is as follows: In the next section, specific CAPRI model developments regarding supply side parameterization and the newly introduced representation of micronutrients are presented. Section 3 then reports on developments of GLOBIOM with respect to the expansion of biophysical gradients as well as improvements of the database, crop supply elasticities and model calibration. As the addition of newly developed fish modules are undertaken for both CAPRI and GLOBIOM, a separate section 4 reports on the state of those to allow for better comparison and to also include a brief reference to fish-related improvements in MAGNET (Kuiper et al. (2017) providing details). A final section briefly assesses the relevance of the described model developments for an improved analysis of SFNS.

2 Enhanced CAPRI model specification

2.1 Ambition

The global agricultural sector model CAPRI is a suitable tool to analyze the effects of supply side drivers on agricultural production, land use, environmental externalities, farms and trade. Though global agricultural sectors and trade are represented, CAPRI focuses on the detailed representation of European agriculture both in terms of regional and product coverage. The activities foreseen for improving the supply side specification of CAPRI in task 9.3 of the DoA was to include biophysical information by linking CAPRI to the crop growth simulator EPIC on NUTS2 regional level in order to better analyze future agri-food sector developments, specifically climate shocks and other technological drivers.

In addition to the DoA, the objective of CAPRI supply side improvements was further extended in Rutten et al. (2016) where an approach to improve the explicit representation of biophysical parameters in the cost function is foreseen based on the estimation of production functions provided in Zimmermann and Latka (2017). More specifically, it is aimed to re-specify the supply setup of the CAPRI model in order to provide a (1) theoretically sounder and (2) more intuitive approach, which at the same time (3) significantly eases the integration with biophysical models. The estimates in WP4 will be used to refine supply model reactions at NUTS2 level in the EU.

Another improvement of CAPRI not foreseen in the DoA is the inclusion of micronutrient indicators tied to the product differentiation in CAPRI. It was considered important to go beyond the traditional energy oriented food security view and to additionally provide metrics that better capture the “nutrition” aspect of SFNS indicators. This (as well as the other developments described in this deliverable) is also in line with the metrics scheme developed for SUSFANS (Zurek et al. 2017).

Finally, with the stakeholder interaction in the early phase of the project, it became clear that a representation of the capture fish and aquaculture sector in the long term models, including CAPRI, should be given priority. Especially the already happening but likely further increasing interaction with the agricultural sector through the feed use in aquaculture and the ongoing and potentially intensified substitution of land-based animal protein by fish prompted the partner UBO in agreement with the project coordination to shift resources and to develop a fish and aquaculture module for CAPRI. The state and remaining challenges of this activity is not reported on in this section but instead in 4.2 for easier comparison with fish and aquaculture related modelling activities in GLOBIOM (section 4.1) and Magnet (only summary in 4.3, details reported in Kuiper et al. (2017)).

2.2 Implemented enhancements

Given the shift of resources to the fish and aquaculture module development, it was decided to not pursue the work on the connection to EPIC at this point. If resources allow, the development of an operational link between EPIC output on yield changes and NUTS2 will be pursued at a later stage of the project.

2.2.1 Yield responses

CAPRI EU supply models simulate changes in crop yields based on yield elasticities synthetically set based on information from the literature on general orders of magnitude. The current implementation features yield elasticities for cereals chosen as 0.3, and for oilseeds and potatoes chosen as 0.2. These estimates might be somewhat conservative when compared, for example, with Keeney and Hertel (2008). However, in CAPRI they relate to small scale regional units and single crops, and to European conditions which might be characterized by a combination of higher incentives for extensive management practises and dominance of rainfed agriculture where water is often the yield limiting factor. The changes in inputs corresponding with yield changes are derived from a weighted combination of two predefined high and low yield technology variants. The high yield technology assumes that 20% more yield can be reached by increasing inputs by 25%. The low yield technology assumes analogous that 20% less yield can be reached by saving 25% inputs. The choice of the optimal combination of the technology variants determines regional average intensity. The substitution is governed by Positive Mathematical Programming parameters implying certain yield elasticities.

So far, the model parameters driving yield elasticities and input/output relations were uniform across all EU supply model regions. However, it can be argued that these model parameters should be heterogeneous depending on the yield gaps observed in a supply model region. The yield gap is the difference between the potential yield under the given bio-physical conditions with optimal management for crop growth and the observed yield. Consequently, a yield gap is the consequence of limitations regarding the availability of crop nutrients and of pests and diseases. Following, a high yield gap would indicate that the inputs by the farmer (fertilizer, pesticides) are comparatively low and no oversupply of fertilizer is expected. When the actual yield comes close to the (water limited) yield potential, there will be no limitation of nutrients and oversupply is more likely. The explanatory variables considered for determining the frontier yields are a trend (YEAR), precipitation (PREC), radiation (RAD) and temperature (TEMP). For each of them the sums over the crop specific growing periods were considered.

Zimmermann and Latka (2017) analysed the dependencies of yield and input use. The actual yields (y) were regressed against the climate and management variables for each crop (j) per year (t) and region (r). The management variables considered were economic farm size (ESU), fertilizer expenditure per ha (FERT) and plant protection expenditure per ha (PROTEC).

Using results from Zimmermann and Latka (2017) the percentage change in expenditures for fertilizer and yield are calculated for an increase of fertilizer expenditures by 1 Euro. The percentage change in expenditures for fertilizers should be equivalent to the percentage change in applied quantity. As the requirements for nutrients are proportional to the yield, the percentage changes in yield and fertilizer expenditures should be identical under ideal conditions. However, in practice probably not all fertilizer applied by the farmer is finally taken up by the plant. Hence we define the ratio of percentage change in expenditures and percentage change of yield as the “efficiency” of additional applied fertilizer.

Conceptually this efficiency should not be below 0% or above 100%. As the calculation is based on a regression analysis, a few outliers are not in this range and were removed. The average over all regions the marginal efficiency of additional fertilizer is about 40% at the currently observed realized yield. It should be noted, that this is not the overall efficiency of fertilizer applications.

Figure 2.1 Efficiency of additional fertilizer (y axis) compared to realized yield (x axis) – own calculation

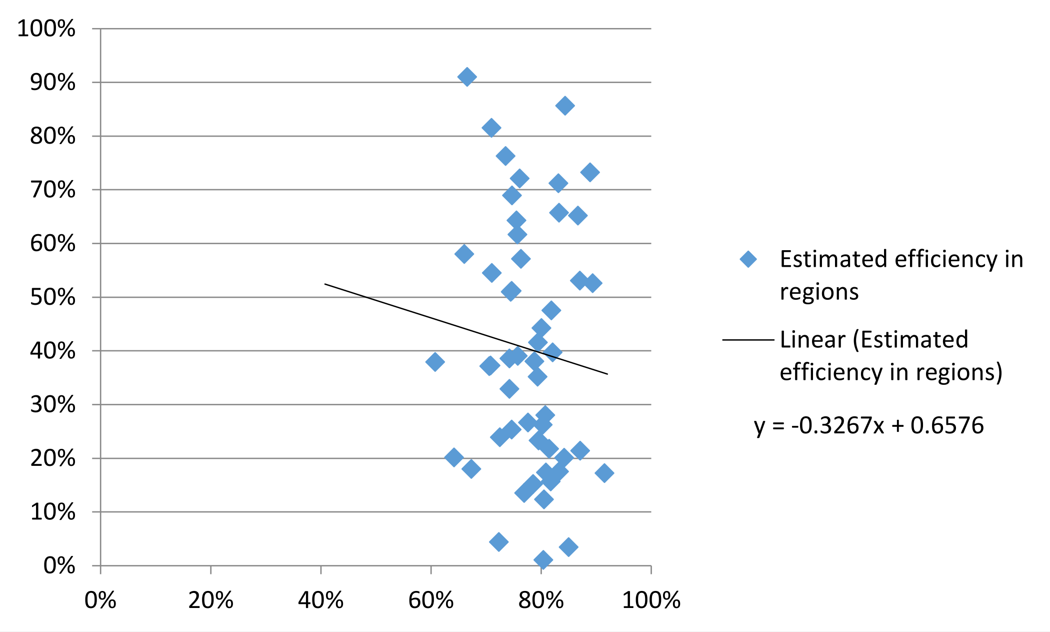


Figure 2.1 shows the efficiency of additional fertilizer compared to the realized yield in selected European regions. A linear trend suggests that the efficiency of additional fertilizer decreases with increasing yield. The calculations based on empirical analysis are in line with our theoretical considerations on the relation between yield gap and fertilizer application. Consequently, the specification of high and low yield technologies used in the CAPRI supply models is to be revised depending on the actual yield gap.

2.2.2 New indicators for Micronutrients

Nutrients are differentiated into macro- and micronutrients. Macronutrients consist of proteins, carbohydrates and fats, whereas micronutrients are composed of vitamins and minerals (Whitney and Rolfes 2007 p.7). The human body requires certain amounts of different nutrients. Arising deficiencies or oversupplies of some nutrients however are regarded to be harmful to a person's health (Mann and Truswell 2017). Nutrition security is composed of the relations between the nutritional status and various other factors including food intake and health (Gross et al. 2000). The adequacy of the average nutritional status may indicate whether nutrition security is reached or how it changes over time and under different assumptions.

The nutrient inventory in CAPRI has been updated and enlarged. Previously, daily intake values per head for calories, protein and fat have been processed in the post-model analysis. This list has now been enlarged by 21 further nutrients (fiber, sugar, calcium, iron, magnesium, potassium, sodium, zinc, selenium, vitamins (A, C, D, E, B1, B2, B6, B12), folate, saturated fatty acids, mono- and polyunsaturated fatty acids).

The nutrient data is taken from the Food Composition Databases of the United States Department of Agriculture[1] (USDA). The most similar products are identified. Including their respective nutrient values, these are mapped to the existing commodities in CAPRI. For a few products micronutrient values are missing in this database. In these cases, the respective values for similar products in the USDA database are taken or nutrient values from Heseker and Heseker (1993) are included to fill the gaps.

The most suitable commodities are chosen from the extensive USDA database containing more than 220,000 food commodities. To reach the best possible fit with the CAPRI items, the chosen commodities are raw and unprocessed when possible. The intake of processed products is covered by the respective primary product consumption (Britz and Witzke 2014 p.189). Some food categories in CAPRI consist of several products of one food group with comparably small market shares each. To find the best fitting USDA items for creating similar aggregates, different approaches are referred to. In some cases (e.g. for "other cereals") the products included in one food category are listed in the CAPRI sets and the analogue USDA items are chosen. For other categories (e.g. pulses) the USDA selection is derived from FAOSTAT food categories, as also consumption data from FAOSTAT is underlying in CAPRI (FAO 2017a). In case the FAOSTAT category lists a large number of products, those with the highest global production quantity in 2014 are selected (FAO 2017c). Some difficulties have occurred in the mapping procedure due to missing products (e.g. rapeseed) and in the selection of animal products. Poultry meat is a heterogeneous aggregate. Nutrient values of chicken, goose, turkey and duck meat are diverging. To account for the relatively higher consumption amounts of chicken meat, weighing factors derived from global production quantities are used to create weighted averages of the nutrient values for this group (FAO 2017c). As the commodities in CAPRI are handled on a carcass weight basis including bones, the nutrient values for all boneless meat products are divided by a conversion factor of 1.3 (European Commission 2017). Due to a lack of proper nutrient data for sheep and goat meat,

[1] https://ndb.nal.usda.gov/ndb/nutrients/index

here the values for beef are taken as a temporary solution. Furthermore, nutrients in sugar beet are derived from the nutrient values for sugar based on a conversion rate of 15 % (FAO 1994). Comprising nutrient data for coffee and tea could only be found for the brewed beverages but not for coffee beans or tea leaves. Assuming a remaining water content of 10 g/ 100 g tea or coffee, the USDA nutrition information is converted for these commodities (Baggenstoss et al. 2008; DTU National Food Institute 2017).

Variability in nutrient contents influenced by production methods or food preparation is not accounted for in the nutrient values. Since daily food consumption in CAPRI is derived as the average per person food intake in a population, also the nutrient intake is not differentiated by gender or age but provided for the average consumer. These limitations need to be kept in mind when interpreting the CAPRI nutrient output.

The mapping of CAPRI items to commodities from the USDA Food Composition database is listed in Table 2.1.

Table 2.1 Mapping of CAPRI items to commodities from the USDA Food Composition database

CAPRI Group	CAPRI Item	USDA Item
Cereals	Soft wheat	Wheat soft, white
	Durum wheat	Wheat, durum
	Rye and Meslin	Rye grain
	Barley	Barley, hulled
	Oats	Oats
	Paddy rice	Rice, brown, long-grain, raw
	Maize	Corn grain, yellow
	Other cereals	Average of triticale, sorghum, buckwheat[1]
Oilseeds	Rape	Spices, mustard seed, ground
	Sunflower	Sunflower seed kernels, dried
	Soya	Soybeans, mature seeds, raw
	Olives for oil	Olives ripe, condensed
	Other oilseeds	Average of safflower, poppy, watermelon, and flax seeds[2]
Other annual crops	Pulses	Average of lupins, cowpeas, broadbeans, lentils, peas, chickpeas, and blackbeans[2]
	Potatoes	Potatoes, raw, with skin
	Sugar beet	Average of sugar, brown and granulated[3]
Vegetables	Tomatoes	Tomatoes, red, ripe, year-round average
	Other vegetables	Average of watermelon, onions, cucumbers, cabbages, eggplants, and carrots[4]
Fruits	Apples, pear & peaches	Average of apples, pears, peaches
	Citrus fruits	Average of oranges, clementines, and tangerines[2]
	Other fruits	Average of bananas, mangos, plantains, pineapples, papayas, and plums[4]
Other perennials	Table grapes	Average of grapes muscadine and Euro type
	Table olives	Olives ripe, condensed
	Table wine	Alcoholic beverage, wine, table, all
Marketable products from animal production	Milk from cows	Milk, whole, 3.25% milkfat, without added vitamin A & D
	Beef	Beef, carcass, lean & fat, selected and choice, raw[5]
	Pork meat	Pork, fresh, carcass, lean & fat, raw[5]
	Sheep and goat meat	Beef, carcass, lean & fat, selected and choice, raw[6]
	Sheep and goat milk	Average of milk sheep and goat, fluid
	Poultry meat	Weighted average of duck, chicken, goose, and turkey[5,7]

(Table 2.1 continued)

CAPRI Group	CAPRI Item	USDA Item
Processed products	Rice milled	Average of rice flour, white and brown
	Molasse	Molasses
	Starch	Cornstarch
	Sugar	Average of sugar, brown and granulated
	Rape seed oil	Oil, canola
	Sunflower seed oil	Average of oil, sunflower, linoleic and high oleic
	Soya oil	Average of oil, soybean, not and partially hydrogenated
	Olive oil	Oil, olive, salad or cooking
	Other oil	Average of oil, poppyseed, safflower, and flaxseed[2]
	Palm oil	Average of oil, palm and palm kernel
	Butter	Butter, without salt
	Skimmed milk powder	Milk, dry, nonfat, regular, without added vitamin A & D
	Cheese	Average of cheese, blue, brie, camembert, cheddar, edam, feta, gouda, and mozzarella[1]
	Fresh milk products	Average of milk whole, producer, yogurts
	Creams	Cream, fluid, light
	Concentrated milk	Milk, canned, concentrate, sweetened
	Whole milk powder	Milk, dry, whole, without added vitamin D
	Whey powder	Average of whey, acid and sweet
New products	Coffee	Average of coffee, from grounds and espresso[8]
	Tea	Average of tea, black and herb[8]
	Cocoa	Cocoa, dry, powder, unsweetened
	Freshwater fish	Average of carp and tilapia
	Saltwater fish	Average of cod, tuna, and salmon
	Other aquatic products	Average of crab, lobster, shrimp, mussel, octopus, and oyster
Water	Water	Average of water, tap and bottled

[1] Based on CAPRI group
[2] Based on FAOSTAT category
[3] Multiplied with the assumed conversion rate of sugar beet to sugar of 0.15
[4] Based on FAOSTAT, selection of items with highest global production quantity in 2014
[5] Divided by 1.3 as conversion factor to account for missing bones in USDA values
[6] The values for beef are taken as the data situation is insufficient for sheep and goat meat
[7] Poultry meat is weighted based on 2014 global production quantities (chicken 0.89, turkey 0.05, duck 0.04, goose 0.02)
[8] Brewed beverages are converted into products with a remaining water content of only 10 mg/ 100 mg of product

2.3 Future work

The results taken from Zimmermann and Latka (2017) show that the efficiency of inputs declines when the actual yield comes closer to the potential yield. Following the marginal cost for producing additional output should increase when the yield gap is closing. One might assume that this also affects the yield elasticity, i.e. the closer the actual yield is to the potential yield, the lower the yield elasticity should be. However, so far no clear evidence in the literature is found in this respect. Further research and discussion will be targeted towards deriving generic rules on how yield elasticities should be made dependent on the yield gap. Once satisfactory results with respect to literature findings and observed variations in regional cropping intensities are derived, the new crop supply specification will be implemented in the regional non-linear programming models in CAPRI. This requires adjustments in the definition of technology variants and the calibrating PMP parameters.

Current FAO statistics on daily calorie and nutrient intake are in parts deviating substantially from other nutritional databases and contradict knowledge on body mass distributions in the population. The general tendency is an overestimation of daily intakes indicating at underestimated waste coefficients or other deficiencies in the supply-utilization accounts of agricultural products. Targeting these issues is an ongoing research activity which will ultimately lead to adjustments in the macro- and micro-nutrient data structure in CAPRI.

3 Enhanced GLOBIOM model specification

3.1 Ambition

To improve the representation of sustainable food supply on the production side, the following changes were planned in the current GLOBIOM representation of food supply in the European and global partial equilibrium economic model GLOBIOM and in the biophysical model EPIC:

- The improvement of the linkage between GLOBIOM and EPIC by developing intensification gradients along the nitrogen, phosphorus and irrigation water in EPIC.
- Implementing the developed intensification gradients to GLOBIOM by using them jointly with estimated crop specific supply, area and production elasticities to calibrate crop specific expansion parameters.

This would allow for a better representation of farmers' decisions in terms of intensification versus area expansion and would improve environmental assessments.

3.2 Implemented enhancements

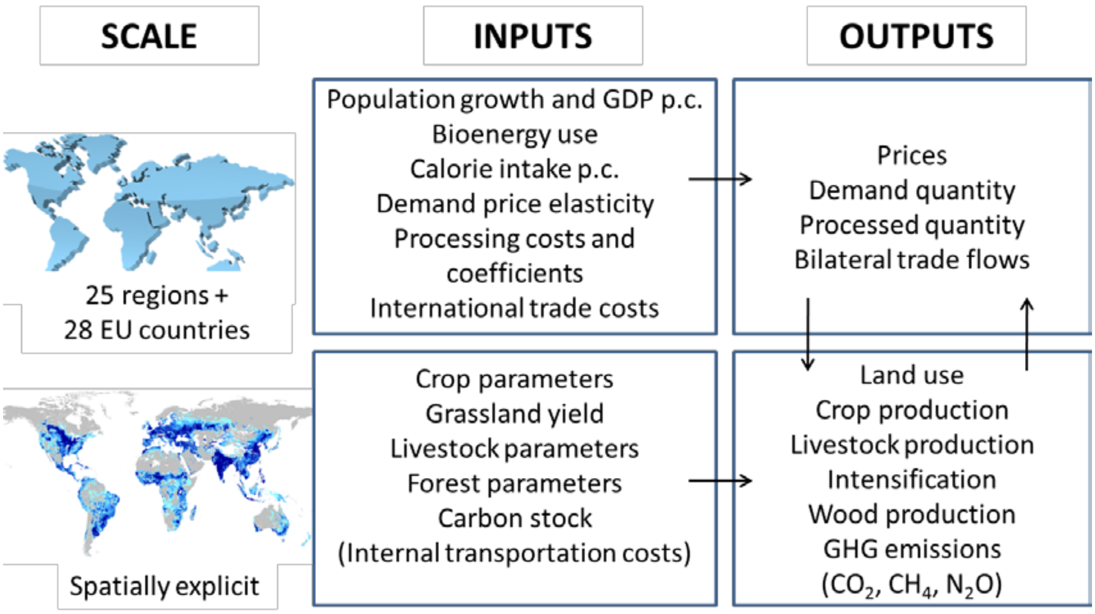
3.2.1 Intensification and expansion gradients in GLOBIOM (current version)

GLOBIOM is a partial equilibrium model of the agriculture, forestry and bioenergy sectors. It takes as input data parameters related to current and alternative production, processing, trade activities (cost, productivity, inputs, population growth, diet preferences, trade tariffs, bioenergy policies, etc.) for these sectors (see *Figure* 2.2), and endogenously simulates from the year 2000 onwards (at a ten year time-step) the price, production, processing, trade and consumption levels of related commodities, as well as the required use of resources (land, water) using multiple production technologies (e.g., rainfed or irrigated) and their environmental impacts (e.g., GHG production, biodiversity loss) at a high spatial resolution.

Within one time step, at regional scale, the demand for a crop for food, feed or biofuel products, the domestic supply of such crop (via cropland use) and the trade flows are all linked through a market balance equation, and are solved for an equilibrium solution. The solution depends on variables on a grid cell level and regional level.

GLOBIOM maximizes the sum of the consumer and producer surplus in a given region, with one time step. An increase in demand for a crop can be met either via increased imports/reduced exports, and/or an increase in the domestic supply. Increasing the domestic supply can only be done through *cropland expansion* and/or *cropland intensification*.

Figure 3.1 A simple representation of GLOBIOM inputs and outputs



Cropland expansion happens at grid cell level through land cover change from the land covers grassland, other natural vegetation, or forest to cropland. The amount of land converted to cropland for each land cover is limited by three main factors:

- First, by the initial level of cropland in the base year 2000. These values are based on the initial land cover data from the GEOBENE database (GLC2000 remote sensing land cover product harmonized to SPAM cropland use data).
- Second, the cost related to land cover change. This cost consists of two components, the *land resource scarcity cost* (a constant elasticity function) and the *land cover conversion cost* (a quadratic cost function).
- Third, the cost of crop production: each crop and production system type is associated with specific costs.

The economic value of the production generated by the newly converted cropland has thus not only to cover the costs of cropland expansion (conversion and increased scarcity cost), but also be competitive compared to the cropland already in use, which can potentially be intensified.

Cropland intensification happens when for a given total quantity of cropland used in a region, its allocation changes for a more productive use. This can happen through three processes:

- By reallocating to grid cells of higher crop yield (*spatial reallocation*), holding the regional total acreage per crop and system constant.
- Through replacing one crop for another crop (*crop substitution*), holding cropland repartition across grid cells and system constant.
- Finally, by replacing one production system for another (*system substitution*, i.e., more of highly fertilized cropland, or more irrigated cropland), holding cropland repetition across pixels and crops constant.

All three processes are simultaneous, and are controlled in the model by three mechanisms:

- The *relative marginal profitability* of cropland use is calculated for each specific combination of grid cell, crop type and crop production system. The profitability itself depends i) on the crop yields as derived from the EPIC model (specific to each system, crop and grid cell), ii) the endogenous crop prices, iii) the costs of the inputs (fertilizer and water, also derived from the EPIC data), and iv) on additional assumptions on production costs, and a spatial calibration cost (for each grid cell, crop and crop production system). The latter costs represent unobserved costs, and equal the values necessary to prevent cropland use to deviate from its initial value in the first time step (year 2000).
- The *scarcity of water resource* is accounted for. Similarly to the land cover change, the total use of water at regional level is physically limited to available resource for irrigation (derived from the KLUM data). In addition, water use is part of operating costs, and irrigation is limited by a scarcity cost. The latter (used in operating cost estimation) is estimated as a constant elasticity of substitution function of the total water use at regional level.
- The total area changing cropland use is limited by *inertia constraints*, representing the maximal rate at which producers can change their use of cropland:
    - In each grid cell, for each crop the acreage under subsistence farming system cannot deviate from its initial value;
    - In each grid cell, the total acreage allocated to one crop cannot be higher than a fraction of the previous time step's area allocated to

the same crop. This fraction is governed by a crop specific parameter;
- o In each grid cell, the total acreage allocated to a production system cannot be higher than a fraction of the previous time step's area allocated to the same production system. This fraction is governed by a production system specific parameter;
- o At regional level, the ratio of total acreage of rainfed high fertilization non-subsistence system over the total acreage of non-subsistence rainfed systems cannot be higher than the previous time step's value by more than 5%.

The model features related to cropland expansion and intensification presented above occur at each time step. However, from one time-step to another, additional features need to be considered and mostly involves changes in key parameters of the features described above.

To account for **long-term technological progress** (e.g., genetic progress, adoption of more efficient cropping practices), the parameters describing the yield and inputs of crops at high spatial resolution (originally derived from EPIC simulations) are increased at each future time steps. This creates an automatic cropland intensification process that depends solely on scenario assumptions, on top the endogenous features described in previous section. This crop yield multiplier is a crop-specific function of future region-, time- and scenario-specific GDP growth, the relationship between GDP and crop yield being estimated from historical data. For each time step, the crop yield multiplier is applied to all crop, crop production system and gravels, and its value varies across crops, regions, time horizons and scenarios, depending on GDP trajectories. In addition to the crop yield parameters, crop input needs are also modified following the same approach, with further assumptions based on historical data on the one hand, and scenario-specific assumptions on changes in nutrient and water use efficiency on the other hand (Valin et al. 2013).

3.2.2 The hypercube dataset and updates to the representation of crop management

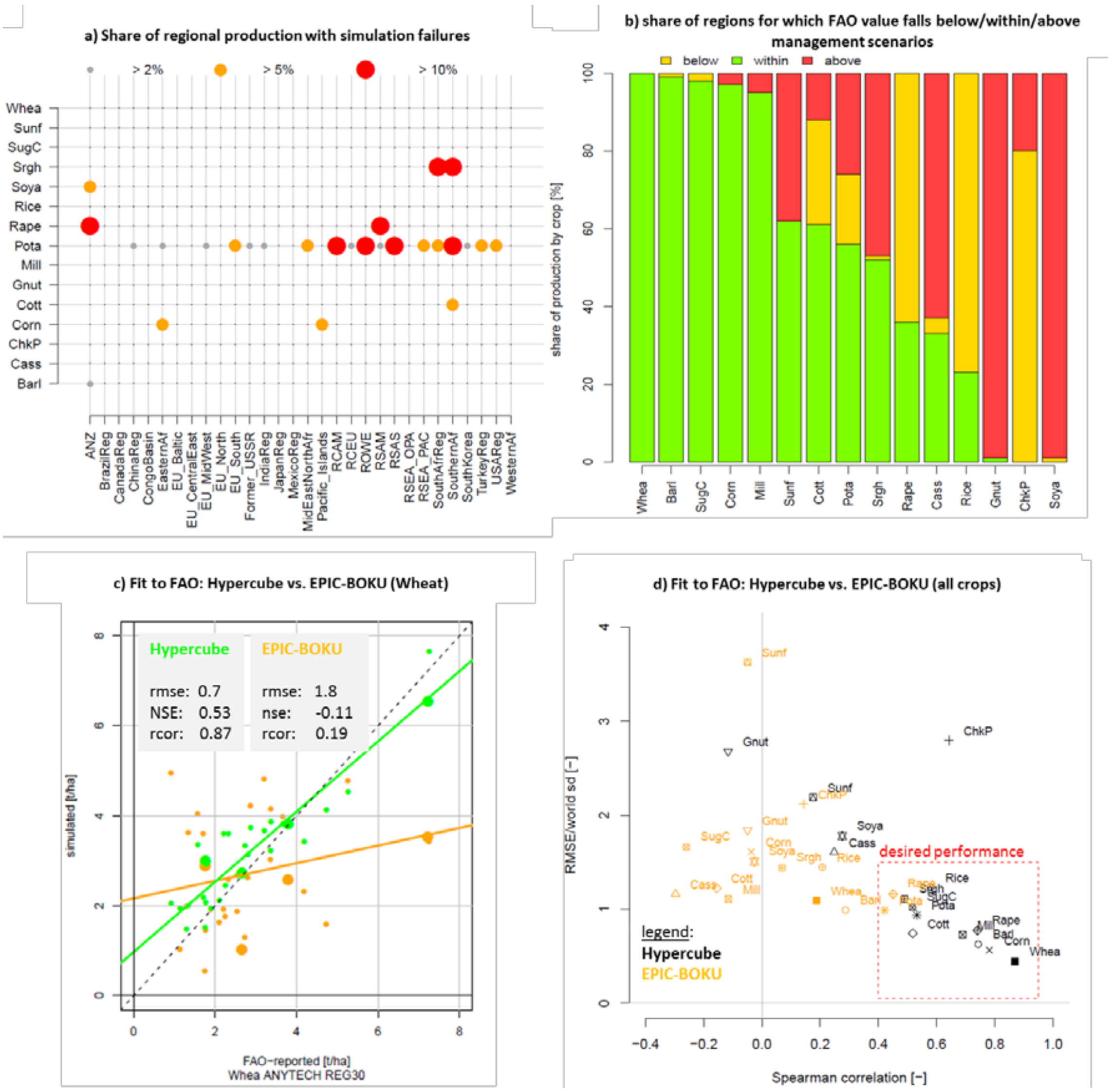
As described above, the possibility for intensification strongly rely on the pixel-level information on the relative profitability of possible alternative uses of cropland, between up to 18 possible crops and for up to 4 different crop management systems (subsistence, rainfed low fertilization, rainfed high fertilization and irrigated high fertilization). The underpinning data relies on simulation outputs of the EPIC crop model to include information at pixel-level on the harvested productivity and input needs (N and P fertilizers, irrigation water) of the various crop activities and crop management systems considered in the model. In the current version of the model, the EPIC dataset used relies on simulations done by Erwin Schmid at the BOKU University of Vienna, and will be hereafter referred to as EPIC-BOKU. Within this project, we implemented in GLOBIOM a new set of EPIC simulations (hereafter referred to as the Hypercube), simulated internally at IIASA.

As depicted for wheat in (Balkovič et al. 2014), the goal of the Hypercube is to better depict the gradient in fertilization and irrigation intensity of crop management. The dataset includes EPIC (v. 0810) simulation outputs for 17 major crops (barley, cassava, corn, cotton, chick pea, groundnut, millet, potato, rapeseed, rice, soya, sorghum, sugarcane, sunflower, wheat, sugarbeet and rye) at global scale with high spatial resolution (212707 spatial units homogeneous with respect to EPIC soil, altitude and slope inputs, delineated at 5 arcmin and of maximum 0.5° x 0.5° lat-lon size) around year 2000. The dataset includes values of yield (harvested biomass in tons of dry matter per hectare - tDM), mineral fertilizer input (nitrogen in kgN/ha and phosphorus in kgP/ha) and irrigation water input (mm/year). For each pixel and crop, simulations are run for a combination of 5 N-application rates x 3 water input rate, leading to 15 crop management-specific scenarios. In these simulations, fertilization and irrigation operations are done using the automatic setup of EPIC: on a daily basis, input is supplied to the soil-plant system whenever a stress to biomass accumulation occurs (up to a daily maximum value), up to maximum quantity allowed during the entire crop season. Maximal application rate for phosphorous application is unbounded, while the scenarios vary according to the maximal yearly nitrogen application rate: 0.1, 25, 100, 200 and 400 kgN/ha for nitrogen fertilization (5 scenarios), and 0, 300 and 2000 mm/yr for irrigation water (3 scenarios). Further details can be found in (Balkovič et al. 2014).

In the project, we used the hypercube data in order to i) update the data underpinning the economic rationale for alternative land uses in GLOBIOM, and ii) refine the economic modelling for moving along the fertilization intensity gradient. To do so, we first processed the hyper cube dataset to the GLOBIOM pixels: averaging in time to yearly average, detecting and filtering out pixels with erroneous simulations and interpolating missing GLOBIOM crops (dry beans and sweet potato). As illustrated in Figure 3.2, we then performed an intensive evaluation of the difference to the previous EPIC dataset (in the ability reproduce FAO reported yields at the scale of GLOBIOM regions, accounting for the uncertainties in required additional information like the map of current spatial distribution of crops and crop management systems). We then harmonized the compiled hypercube dataset so that the regionally averaged values of yield and nitrogen fertilizer application matches reported statistics, before further evaluating the resulting harmonized dataset in terms of spatial patterns in current yield and yield gaps as compared to available datasets such as the M3 dataset (Mueller et al 2012) and the GYGA initiative.

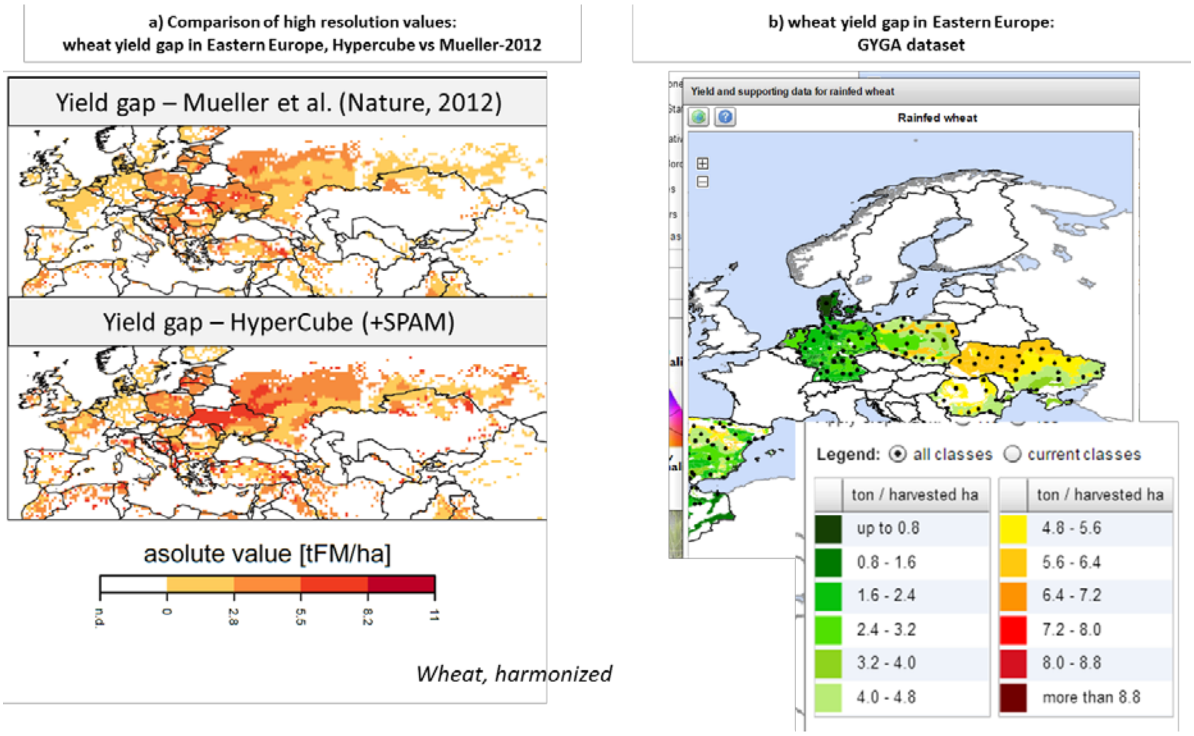
Finally, we analysed ways to summarize at pixel level the information on yield responses to nitrogen fertilizer application in reduced forms, in accordance to potential improvements in the economic modelling of fertilization intensity. The analysis established the estimated relationship between yield and fertilization is non-linear and sometimes non-monotonous across the fertilization gradient. Such type of relationship is difficult to deal with in mathematical programing, and quickly increases computation time. Such a relationship could be made continuous only in an interpolated stylized monotonous form - which given the number of points per gridcell, could only be derived with statistical robustness over larger areas. Such a solution could be considered, however at the cost of losing the link between particular systems and a precise set of EPIC simulations. In addition, the GLOBIOM model is formulated as a *linear programming* type of model. Such type of model cannot deal with strictly non-linear relationship (even monotonous). Although it is possible to linearize monotonous non-linear relationship, another feature of linear programing models is that they must be *separable*, i.e., that the equations are additive with respect to the variables to be optimized. For the market balance equation (a key equation in the model), this is the case as long as the production systems are described only the acreage variable (multiplied by the yield parameter). Considering the yield as a function of a variable related of intensity would break the separability assumption via the market balance equation (in which acreage and yield variable would enter multiplicatively). Some model reformulation could be considered to transform such a problem into a separable one, but this would imply two quadratic terms to be linearized for each crop and production system. The current computation time cost makes such a solution not viable.

Figure 3.2 - Illustrations of Hypercube evaluation at aggregated level



a) Share of GLOBIOM gridcells for which value is missing doe to simulation failures for each (crop x region) combination. b) for each crop, share of global production covered by regions for which FAO reported yield falls below/with/above the range of hypercube simulated yield values across management scenarios (before overlay with crop production system information). c) Illustration of the fit to FAO regional aggregated values for wheat yield, for the initialized hypercube and the previous EPIC dataset (after overlay with cropland use information), as well as metrics summarizing the fit. d) Graphical overview of statistical metrics characterizing fit to FAO between the Hypercube and the previous dataset, for all GLOBIOM crops (the dotted red rectangle delineating desirable values).

Figure 3.3 Illustration of Hypercube evaluation at high spatial resolution



The figure compares the spatial patterns of yield gap estimates for wheat in Eastern Europe, between the harmonized hypercube and independent data sources: global-scale M3 product (left panel, N. D. Mueller et al. 2012) and local to national-scale yield gap analysis from the GYGA initiative (right panel).

Following previous considerations, we retained the following formulation of crop production systems in GLOBIOM (and their linkage to the Hypercube & SPAM datasets):

- We define 3 'crop production systems': subsistence farming (SF), rainfed commercial systems (CR), and irrigated commercial systems (CI)
- Each production system is modeled by 1 or 2 acreage variables & set of EPIC parameters:
    - **Subsistence farming (SF)** crop production systems have 1 acreage variable, associated to 1 management scenario of Hypercube parameters (rainfed, lowest level of fertilizer application). The initial area is delineated after SPAM SS systems distribution. Conceptually, the subsistence farming system does not change compared to the initial version of the model.
    - **Rainfed commercial (CR)** crop production system is modeled with 1 or 2 acreage variables depending on the gridcell and crop considered:

        - For leguminous crops (in all gridcells, for Soya, Dry beans and Chik Peas) or for non-leguminous crops (in pixels where fertilization has little impact), the Hypercube does not support an effect from varying N-fertilizer application on yield. Therefore, only one acreage variable (CR_neutral) & Hypercube dataset (rainfed, second level of fertilization) are used. The initial spatial distribution of (crop x CR_neutral system) acreage taken from adding SPAM LI and HI areas for in relevant (crop x gridcell combinations).
        - For non-leguminous crops in the remaining gridcells, the Hypercube data supports a linear effect of N-fertilizer rate on yield, and we associate two different acreage variable (CR_low & CR_high) each associated to a different Hypercube dataset (respectively rainfed N01 and rainfed Nhighest). The initial spatial distribution of (crop x CR system) acreage taken from adding SPAM LI and HI areas for in relevant (crop x gridcell combinations), while the split between CR_low and CR_high is determined at the harmonization step (cf. next section).
    - Irrigated commercial (CI) crop production system is modeled with 1 or 2 acreage variables (depending on the gridcell & crop considered, same procedure as for CR, and spatial initialization taken from SPAM IR system - the split between CI_high and CI_low being done at the harmonization procedure).

The two commercial can have flexible fertilization rate at the gridcell level (if the hypercube datasets is sensitive enough to fertilization input), which is modelled by having two variables for each system (e.g., CR_high and CR_low; CI_low and CI_high), each associated to the highest and lowest fertilization level possible in the harmonized hypercube dataset. To better control the endogenous intensification response via fertilization (i.e., changes in the acreage of high and low fertilization), we added to the objective function for each crop a linearized quadratic cost associated with the increase in the regionally aggregated acreage dedicated to high fertilization systems. We in addition keep pixel level inertia constraints that cap the pixel level increase in the acreage of any crop system. The calibration of the parameters of this new crop system formulation is detailed in section 3.2.4.

3.2.3 Crop supply elasticities

For the calibration of cropland expansion and intensification in GLOBIOM correct crop yield, acreage and production elasticities with respect to prices are needed. The goal would be to use exogenous elasticity values, based on the available literature and estimated from historical data as targets in calibrating GLOBIOM's expansion and intensification. The crop elasticity with regard to price would inform us, whether GLOBIOM exhibits the correct response to a corresponding price shock or not. For this purpose we need to assemble as set of supply elasticity per GLOBIOM region and GLOBIOM crop. In this sense, we define the elasticity of the crop acreage, quantity or yield as the increase in these values in ratio to an increase in price.

The primary source of crop supply elasticities would be values estimated in the literature. Based on a literature review, it became clear that the literature values do not agree on the specific elasticities (due to the differing methods, data and scopes of the studies) and do not cover all needed GLOBIOM crops. For this purpose, an econometric estimation method was utilized to obtain a harmonized set of crop yield, acreage and production elasticities.

The econometric model is based on jointly modeling the movements of historical time-series of crop prices, yields, production and a wide sample of other agricultural, economic and environmental variables for each region. This modeling approach is based on a strain of literature from time-series modelling, termed as vector autoregressions (VAR), which has become popular in capturing the dynamic and inter-related nature of macro econometric time series (Blake and Mumtaz, 2012; Del Negro 2012). Recent Bayesian VAR approaches – pioneered by Christopher Sims (Sims and Zha 1997) – allow for estimating VARs involving a large set of variables with reasonable accuracy.

We can express our model in a more formal fashion by denoting with Y_{ct} the $n \times 1$ vector of variables in the model at time t for crop c (where n is the number of variable in the model). We can write our VAR as:

$$Y_{ct} = a + B_1 Y_{ct-1} + B_2 Y_{ct-2} + C_1 Z_{t-1} + C_2 Z_{t-2} + v_t \qquad \text{[Equ. 1]}$$

$$E(v_t, v_s) = \Sigma, \qquad t = s$$
$$(v_t, v_s) = 0, \qquad t \neq s$$
$$E(v_t) = 0$$

where Y_{ct-1} and Y_{ct-2} are time lagged counterparts of Y_{ct}. B_1 and B_2 are $n \times n$ parameter matrices, a is a constant and v_t is an $n \times 1$ vector of error terms. Note, that while the disturbances are not correlated over time (that is we assume a constant variance-covariance matrix), the $n \times n$ matrix Σ ensures the contemporuous influences of variables on each other. The $k \times 1$ vectors Z_{t-1} and Z_{t-2} contain exogenous variables, that is climate related variables. The main assumption being that (at least in the short to medium term) cropping decisions do not influence the weather, while weather related variables do have a strong influence on the crop output. The $n \times k$ matrices in [Equ. 1], C_1 and C_2 are the corresponding parameter vectors. We use the average maximum and minimum temperatures, as well as the average temperature and precipitation in the region for Z_t.

Table 3.1 Prior on the implied elasticities from the literature review

Region		Area								
		Barl	Corn	Gnut	Rape	Rice	Soya	SugC	Sunf	Whea
EU_Baltic	min	0	0.08	0.1	0		0		0	0.1
	max	2.65	0.72	1.74	1.46		1.27		2.12	0.85
EU_CentralEast	min	0	0.08	0.1	0		0		0	0.1
	max	2.65	0.72	1.74	1.46		1.27		2.12	0.85
EU_MIdWest	min	0	0.08	0.1	0		0		0	0.1
	max	2.65	0.72	1.74	1.46		1.27		2.12	0.85
EU_North	min	0	0.08	0.1	0		0		0	0.05
	max	2.65	0.72	1.74	1.46		1.27		2.12	0.85
EU_South	min	0	0.08	0.1	0		0		0	0.1
	max	2.65	0.72	1.74	1.46		1.27		2.12	0.85
Region		**Yield**								
		Barl	**Corn**	**Gnut**	**Rape**	**Rice**	**Soya**	**SugC**	**Sunf**	**Whea**
EU_Baltic	min		0				0			0
	max		0.15				0.17			0.09
EU_CentralEast	min		0				0			0
	max		0.15				0.17			0.09
EU_MIdWest	min		0				0			0
	max		0.15				0.17			0.09
EU_North	min		0				0			0
	max		0.15				0.17			0.09
EU_South	min		0				0			0
	max		0.15				0.17			0.09

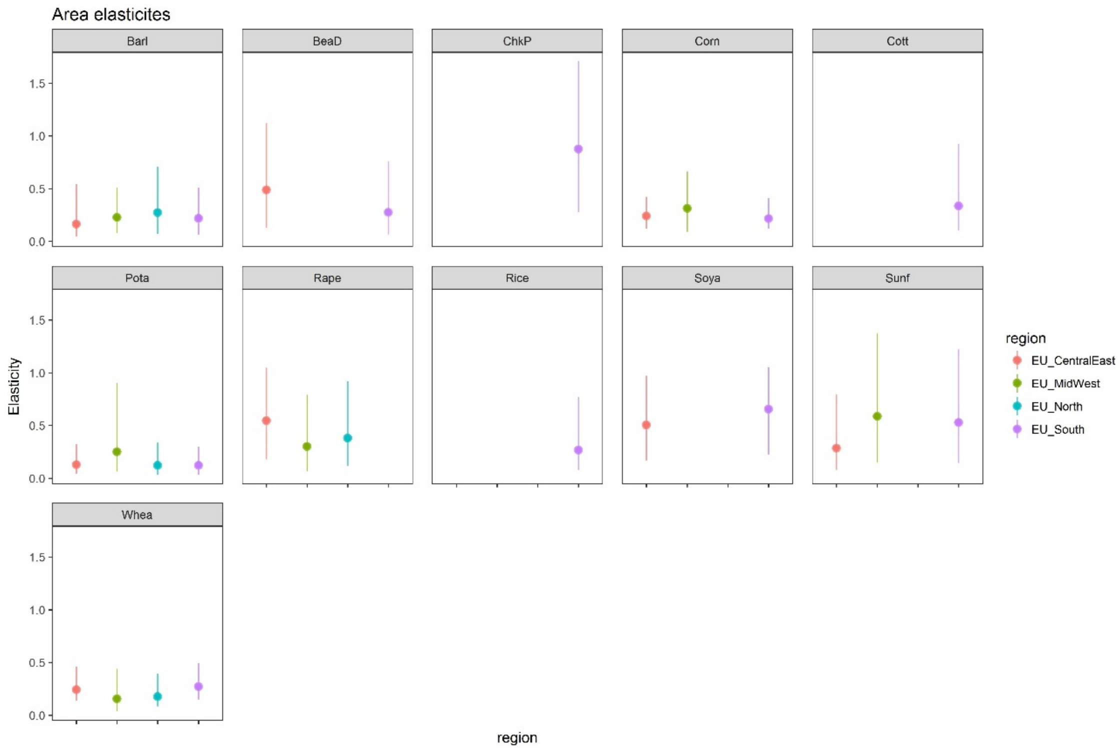
The model is estimated based on historical yearly data stemming from FAO, covering 1966 to 2012. The producer prices were obtained from FAO and have been converted to 2010 US dollars, using the World Bank's conversion tables. To arrive at regional prices, the prices have been averaged using a weighted average by the output and consumption of each crop per region. Since there is a structural break in the FAO prices in 1990, where they changed the data collection methodology, the time-series were smoothed using a cubic spline approach to eliminate sudden breaks. The yields, areas, consumption and trade balances, as well as total cropland area stem from FAO. The GDP data were obtained from the Penn World Tables. Data on fertilization and irrigation was obtained from IFA, where the yearly irrigation was obtained using the cubic spline approach outlined in the previous sections. Historic data on regional weather was obtained from the World Bank's development indicators.

For the purposes of estimating the long-term elasticities using the model in [Equ. 1], we are interested in the resulting increase in the area, yield and output of crop c as a response to one (or multiple) standard deviation shock to the price of the crop. Once the parameters have been estimated, so-called impulse response functions can be used to assess the model's response to shocks. We can simulate shocks on prices and observe the response of acreage, yield and production in the system. We use the structural VAR approach from (Hamilton 1994) to calculate such IRFs and thus impose sign restrictions on the responses. These values provide us with an estimate of the crop specific elasticities.

In order to incorporate elasticity values from literature (which were the primary source of data), we follow (Kilian and Murphy 2014) and restrict the implied elasticities to lie within specific ranges from the literature. The detailed values for the elasticity restrictions are depicted in Table 3.1. For region and crop combinations where no elasticity values were available, we assumed a prior elasticity bound, based on the ratio of the crops' elasticity over the total area of cropland in the regions. If the crop's area is more than 10% of the region's total crop area, then an elasticity value below 1 was assumed, with the assumption being that crops with such a large production would be fairly inelastic to sudden price fluctuations. If the crop area is between 10% and 1% of the total crop areas in the region, then elasticities up to 2 were allowed. And finally, if the crops area is less than 1% on average than the sum of all the crop areas in the region, then an elasticity up to 2.5 was allowed in the impulse response functions.

The results for the elasticity of crop area production with regard to prices are illustrated in *Figure* 3.4. The error bars correspond to the 16th and the 84th percentile.

Figure 3.4 - Price elasticities of crop areas for European GLOBIOM regions

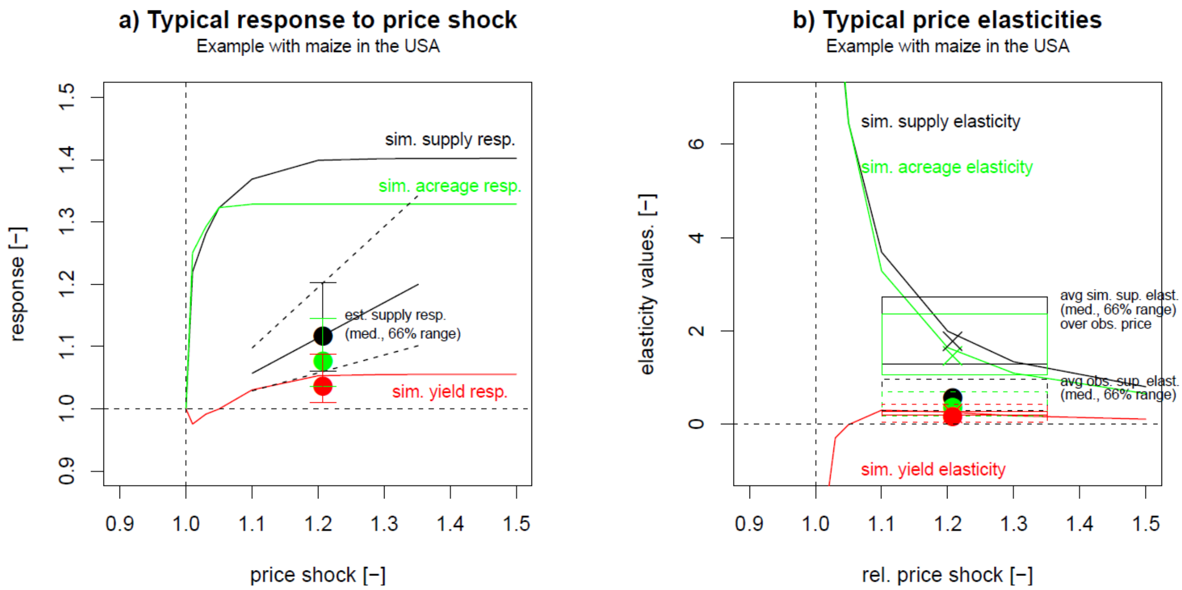


Note: The error bars correspond to the 16th and 84th percentile.

3.2.4 GLOBIOM calibration

In this project we set ourselves as a goal to improve the GLOBIOM model behavior with respect to cropland intensification and expansion responses. As detailed in section 3.2.2, a first pillar of the required work involved improving the dataset of biophysical parameters that informs the economic rationale for cropland use decisions within the model (i.e., the hypercube), with a revision of the governing equations. A second pillar was the acquisition of estimates of the responses of supply, acreage and yield responses to price signals based on statistics reported at country level (i.e., crop elasticities, see section 3.2.3). At last, it was necessary to identify and calibrate the relevant model parameters so that the model behavior matches estimates based on reported statistics.

Figure 3.5 - Measuring elasticities in GLOBIOM and comparing to external estimates



Panels illustrates from an example (Maize in the USA) how a) simulated model response (lines) and b) underlying elasticities (lines and cross points) for increasing price shocks can be compared to independent estimates of elasticities (big dots in both panels, with error bar / dotted rectangle indicating uncertainty range).

Prior considerations. Before model calibration, a few steps were needed to characterize the model performance (i.e., estimate elasticities implied by the model behaviour), compare it to the estimates described in 3.2.3, elicit the most important model parameters underpinning this behaviour and systematically test their influence.

We first ran multiple scenarios prices shocks for the year 2000 in order to evaluate the crop yield, acreage and supply elasticities implied by the model response to these price shocks. As illustrated in *Figure* 3.5 a) for the case of maize in the USA the model simulates increases in supply under increased prices that i) saturates to a maximum supply increase and ii) relies strongly on acreage response. This translates into elasticity values (*Figure* b)) that depends on the price level but decreases with the amplitude of the price shock. The supply, acreage and yield responses (and their implied elasticities) can be compared to the estimates based on country statistics (by assumption, constant elasticity and linear response), once averaged over a certain range of price shocks, as displayed in *Figure* . Over all crops and regions in GLOBIOM, the analysed model behaviour (prior to calibration) showed three important features: a) the supply elasticity is in general in GLOBIOM as compared to estimates based on country statistics, b) this bias is much higher for low levels of price shock (the model is too responsive for low price shock) and c) this bias owes primarily to an overestimated crop-specific acreage response (expansion over other crops rather than of cropland, indicating to high degree of substitution across crops).

We then investigated the parameters controlling the model's implied elasticities (by scanning all relevant equations and parameters), and run multiple sensitivity tests to diagnose the impact of their values on implied elasticities. The analysis highlighted that two parameters involved in the inertia constraints (the maximum rate of change in the acreage of a crop at pixel-level within one time step, and the maximum rate of change in the acreage of a crop management system at pixel-level within one time step) have an important role in controlling the saturation acreage and supply response as well as the ratio of acreage over yield response. The analysis also showed no model parameter seemed to affect the bias of high acreage response at low levels prices shocks, suggesting that additional features are needed to avoid this bias. We then developed a reduced version of the model (focused on the representation of high-resolution land use dynamics for a particular region and commodity) in order to test additional modeling features and parameterizations. We finally decided to add an additional linearized quadratic cost associated to the expansion of the harvested area at regional for each crop (e.g., similar to the new equation associated to fertilization). To summarize, after inclusion of new data and equations, the model features needing calibration for each crop C and region R are the following:

- The parameter setting at pixel-level the maximal rate of acreage change for a particular crop and region (*MCC(C,R)*).
- The two parameters of the new quadratic cost related to the expansion of regionally aggregated harvested area per crop and region (slope *slope_HAexp(R,C)* and intercept *int_HAexp(R,C)* of the marginal cost curve).
- The two parameters of the new quadratic cost related to the expansion of regionally aggregated highly fertilized area across all highly fertilized crop management systems per crop and region (slope *slope_HIexp(R,C)* and intercept *int_HIexp(R,C)* of the marginal cost curve).

Model calibration procedure. To calibrate the values of these 5 parameters per crop c and region R, we developed a formal procedure in 2 steps:

- (step 1) Simulate model response to price shocks with the original model version under varying levels of MCC(R,c) parameter value (from 1.1 to 1.5 by steps of 0.05) to select the value allowing reaching a correct acreage elasticity value for high price shocks.

- (step 2) Using MCC value selected in step 1, run multiple simulations of response to price shocks with the small model and the final set of equations to set the value of the 4 other parameters. This procedure is further split in two steps:
    - (a) scan a wide range of values for the 4 parameters in 1296 combinations. The intercept coefficients of both functions vary within 6 values from 1e-6 to 0.1 by multiplicative steps of 10. The slope coefficients vary so that the marginal cost of one additional unit at +50% in expansion equals the marginal cost for the first expansion unit multiplied by a factor f varying within 6 values (from 1 to 1E6 by multiplicative steps of 10). Then select the subset of parameters combinations for which i) 80% maximum supply response is not obtained for a price shock lower than +10% (eliminates too flat curves), and ii) for each variable (supply, acreage and yield), the correlation to the price shock value (along all price shock values) is higher than a threshold (by default 0.75, but can be lower depending on the crop and region) to isolate the set of parameter values being closest to a linear response. From this subset we isolate the value of intercept parameters having the lowest sum over the three variables of ranks in terms of quadratic distance between obtained elasticities and observations for each variable and the minimal value of f parameter multiplied by the intercept parameters (for lower values, the responses will be too strong, and for higher values the response will progressively get flatter).
    - (b) Using the minimal values for the intercept and intercept x f detected in the previous step, we scan again for 1296 combinations of f and int values (for each cost curve – total crop harvested area expansion, and high fertilizer input harvested acreage), but with a narrower range: 6 intercept values are tested from the minimum to the maximum across crops of the value selected in step a) in regular steps, and 6 f values are tested for each intercept values, corresponding to 0.1 to 10 times the value of intercept x f identified in step a). Candidates for the final set of 4 parameters are then determined by selecting the parameter sets with 80% of the maximum simulated supply response obtained for at least +10% level of price shock, and ranking them according to the sum of response correlations to price shocks across all 3 variables (yield,

acreage and supply) The final parameter set is then selected manually selected the 5 best candidates.

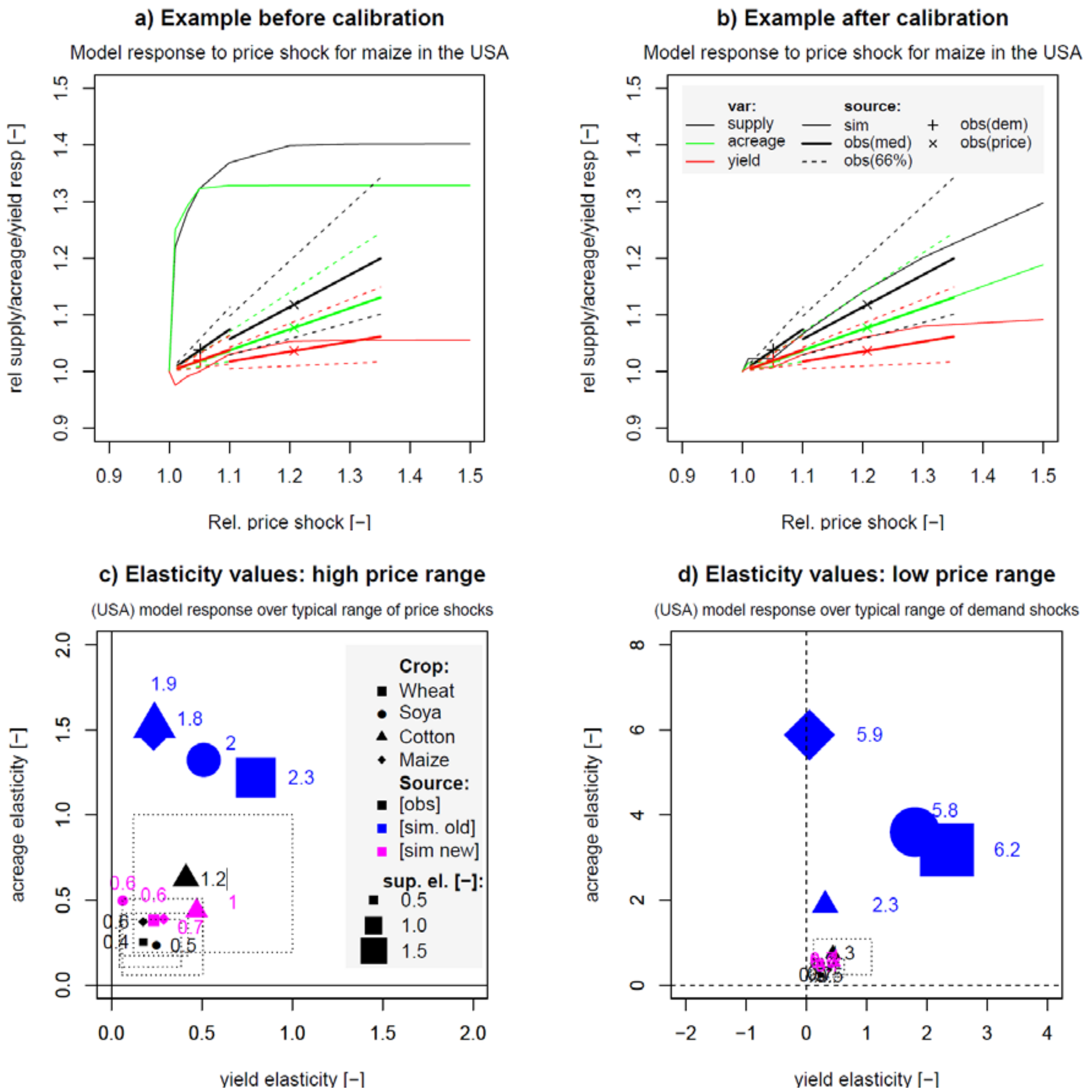
Illustration with case of the USA. While the calibration of all crops and regions is in process with the above procedure, we can illustrate the results for the four main crops of the USA (Maize, Cotton, Wheat and Soya). As illustrated in *Figure* a), the original version of the model overestimates acreage elasticity. After following the calibration procedure exposed in the previous section, the 5 calibrated parameters are given the values summarized in *Table* .3. As it can be seen on *Figure* b) for the case of maize, the model bias are corrected and the model response is much closer to the observed elasticities, as well as more linear along the different price levels. The idea is the same for the other 3 crops (Cotton, Soya and Wheat) as displayed in *Figure* c) and d).

Table 3.2 Results from calibration in the USA. Final value of the 5 calibrated parameters for the four major crops of the USA, using the procedure.

Parameter		**Corn**	**Cott**	**Soya**	**Whea**
MCC		1.45	1.45	1.45	1.45
Harvested Acreage expansion cost function	*INTERCEPT*	1.0E-03	1.0E-03	1.0E-03	1.0E-03
	SLOPE	1.4E-05	8.1E-05	2.8E-05	2.0E-05
High fertilizer input systems acreage expansion	*INTERCEPT*	2.1E-02	2.1E-02	-	2.1E-02
	SLOPE	3.0E-05	1.3E-04	-	4.6E-05

As illustrated by the case of maize in *Figure* b), the calibrated model does not necessarily has implied elasticities exactly fitting the median estimate (e.g., it is the case for acreage but not for yield and thus not for supply). This also for example illustrated with the case of Soya in *Figure* c), for which the yield elasticity is lower than the observed elasticity. As depicted in *Table* 3.2, there is no quadratic cost related to the expansion of high fertilizer input systems for soybean, since it is a leguminous crop, for which the EPIC model do not simulate a high sensitivity for N fertilizer input. However, in reality, Soya can remain sensitive to fertilization, and in particular to Phosphorus input. It can also be sensitive to other inputs not directly modelled by EPIC, such as pesticide application, which might also be significantly contributing to the observed yield elasticity. However, the implied elasticities are usually within the error range of observed elasticities.

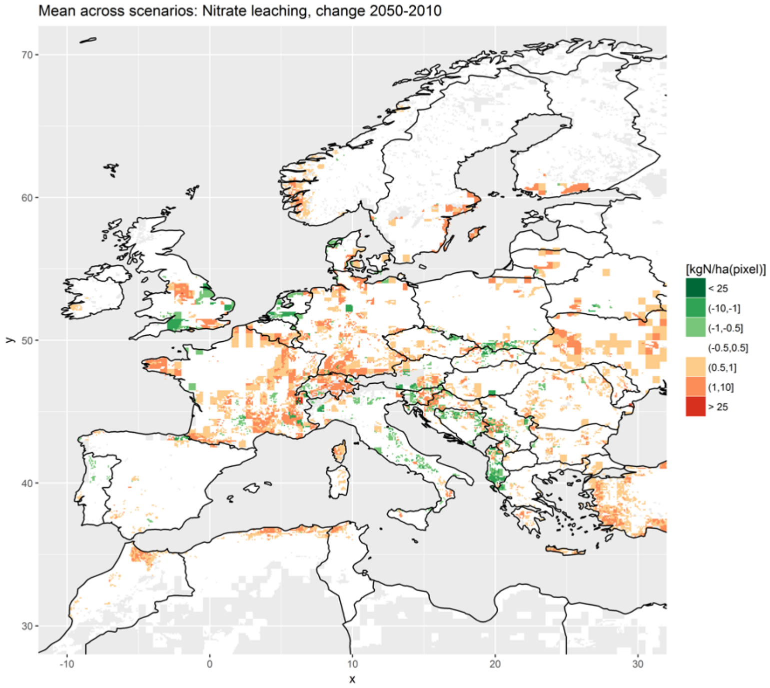
Figure 3.6 Illustration of calibration results for the case of USA



Panels a) and b) display the simulated maize supply (thin solid black lines), acreage (thin solid green lines) and yield (thin solid red lines) responses to price shocks for respectively the original model and for the improved model after calibration, as well as expected behaviour derived from estimated elasticises (thick solid or thin dashed lines). Panels c) and d) display the implied elasticities for respectively high and low price shocks for all four crops (varying symbols) for the original model (blue symbols), observations (black symbols) and the improved calibrated model (magenta symbols).

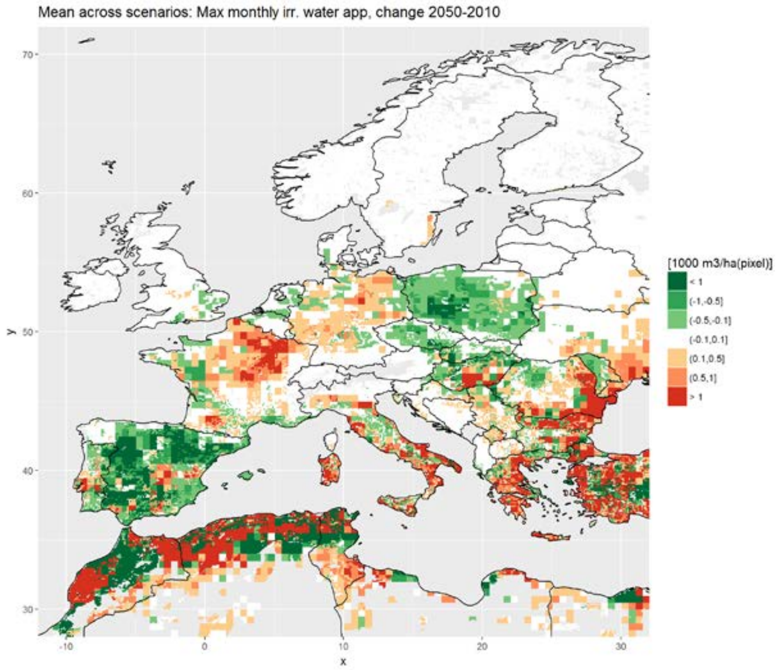
The implemented changes to GLOBIOM provide further advantages beyond the immediate target of better representing farmers' decisions in terms of intensification versus area expansion in the partial equilibrium model. It additionally improves the assessment of environmental impacts in terms of nitrate, phosphorous and irrigation related issues. Figures 3.7 and 3.8 give two examples for quantified metrics of nitrate leaching and water use for irrigation.

Figure 3.7 - High spatial resolution trends in nitrate leaching from 2010 to 2050



Notes: The panel presents the absolute change in cropland leaching (in kgN/ha_pixel, i.e., normalized by the total area of the pixel) between 2010 and 2050, averaged over the 3 SSP scenarios considered.

Figure 3.8 High resolution trends in max. monthly irrigation water use for cropland 2010 to 2050



Notes: The panel presents the absolute change in cropland maximum monthly irrigation water use (in 1000 m3/ha_pixel, i.e., normalized by the total area of the pixel) between 2010 and 2050, averaged over the 3 SSP scenarios considered.

3.3 Future work

A literature review and the newly estimated elasticities helped to characterize the behaviour of the current version of GLOBIOM with respect to land expansion and intensification, and the effect of various core parameters and model features. While the model lies in the central range when it comes to the long-term projected evolution of agricultural demand, supply and prices, it seems slightly optimistic in terms of future cropland development. This seems to be related to a relatively high acreage elasticity of crops, especially for low price shocks. This generates an underestimation of the costs of small production increases. While implementing the new EPIC dataset and the other newly generated datasets, we introduced further equations into the model to better control, and developed a procedure to calibrate the core model parameters the newly generated dataset of crop elasticities.

In terms of future work, two main issues should be explored: first, we use relatively short-term elasticities, which might evolve over time. Such a question should be investigated, and translated into the model to improve long-term dynamics. Moreover, the econometric model could be improved to take into account jointly all regions and crops under consideration.

A second potential improvement is based on the fact that the split between crop substitutions and cropland expansion is a key uncertainty for projecting cropland: while investigating such a question was not a priority in this project given the uncertainty in observations, this should be a natural follow-up.

Third, while the calibration of GLOBIOM on exogenous elasticities undoubtedly works, such a procedure is a time consuming process, especially when cross-crop elasticities would be taken into account. Therefore, exploring the internal representation of elasticities, for example over an explicit substitution function would be worth exploring, as this would free up computationally expensive calibration time.

4 Modelling of fisheries and aquaculture

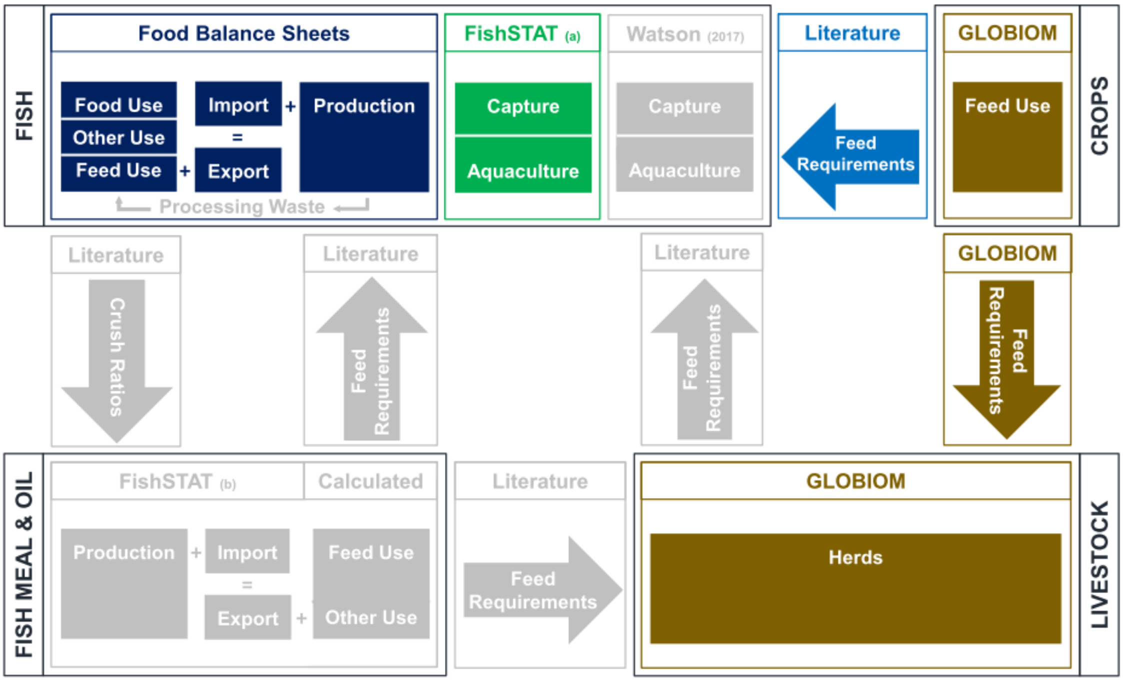
4.1 Fisheries and aquaculture in GLOBIOM

4.1.1 Ambition

The plan for expanding the coverage of the GLOBIOM model to fish called for the construction of a global, country-level model of the production, trade, and consumption of fish and seafood, with explicit differentiation between capture and aquaculture production systems. The plan further called for the linkage of the fish and seafood sector with the existing crop and livestock sectors of GLOBIOM. This linkage operates via the feed markets and the flow of feeds from the crop sector into fish farming on the one hand, and the provision and use of fishmeal and fish oil in livestock feeds on the other.

Figure 4.1. below shows the four sectors modeled, their linkages, and the data sources used in the construction of the modeling system. The sections in grey have not been implemented to date.

Figure 4.1. Schematic Representation of the GLOBIOM Fish Model and the Data Sources Used



Prior to this project, fish and seafood was the largest food group not yet explicitly represented in the GLOBIOM model. With this new development, the model is able to account for the calories, macro-, and micronutrients supplied by seafood, which constitutes a major component in diets of many countries, in the EU and elsewhere. Given the benefits of seafood consumption to human health and wellbeing, seafood is a critical part of a healthy diet. But due to the variety of seafood and the variation in seafood production systems, questions remain about the sustainability of seafood production, despite some clear advantages and efficiencies that seafood production has compared to other terrestrial meat sectors.

An explicit, and sufficiently detailed fish model allows for the analysis of the seafood markets, and a fish model linked to the crop and livestock sectors slows for a better analysis of the interactions and tradeoffs of the entire food system.

4.1.2 Implemented enhancements

The first major component of the GLOBIOM fish model is the Food Balance Sheets 1961-2013 (FishstatJ) dataset created by the Food and Agriculture Organisation of the United Nations (FAO, 2016). This dataset provides a global account of production, imports for human consumption, exports for human consumption, non-food use, and apparent food use of fish and aquatic products at the country level for the past several decades and most recently for the year 2013. Non-food use in the dataset has been disaggregated further into feed use and other use (including ornamental, seed, cosmetic, etc.). The dataset has been vetted and adjusted as necessary to enforce the physical balance of supply and demand within each country, and the global trade balance of the sum of global exports and imports.

The Food Balance Sheets (FBS) dataset aggregates fish and aquatic products into 11 so-called FAOSTAT groups (freshwater fish, demersal fish, pelagic fish, other marine fish, crustaceans, cephalopods, other mollusks, meat of aquatic mammals, other aquatic animals, aquatic plants, and other aquatic products). The GLOBIOM model considers the first 7 of these groups, which combined constitute over 90% of global seafood.

Other commercially important fish and crustacean species groups (salmon and trout, tuna, shrimp) were disaggregated using additional data sources as far as publicly available data allowed (World Bank, 2013).

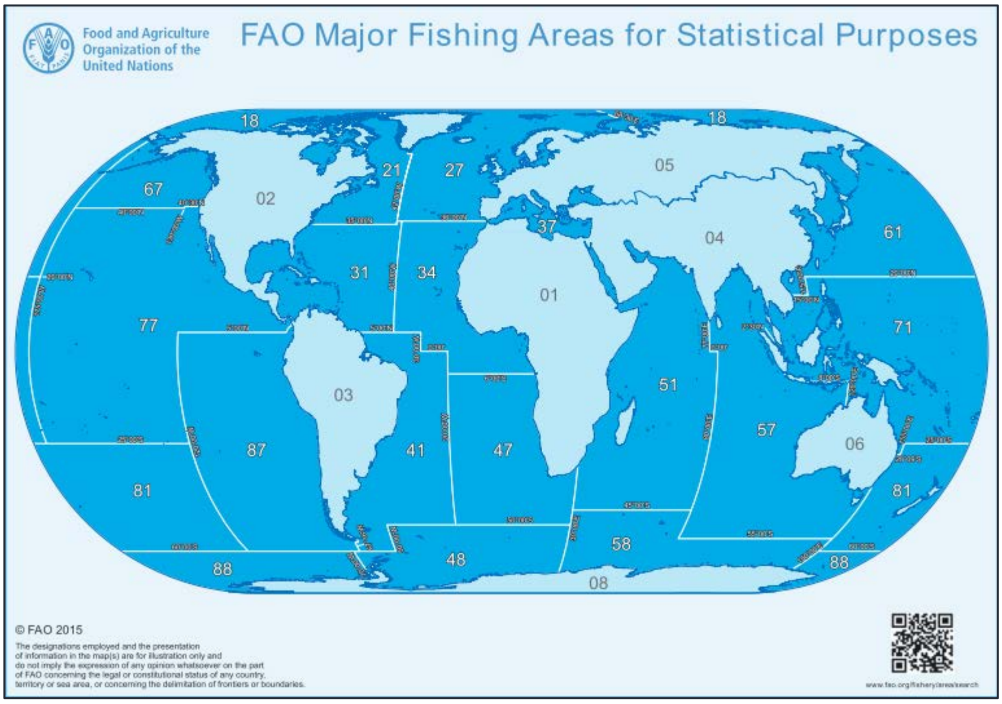
The second major data component of the model is the Global production by production source 1950-2015 (FishstatJ) dataset (FAO, 2017). It includes information on production at individual species level and allowed for the creation of an additional species group for filter feeding carps, bringing the total number of GLOBIOM fish commodities to 10, as shown in Table 4.1. below.

Table 4.1 Fish Species Groups in the GLOBIOM Model

GLOBIOM Model Species Groups
Filter Carps
Salmon
Other Freshwater and Diadromous
Demersal
Tuna
Other Pelagic
Other Marine
Shrimp
Other Crustaceans
Molluscs

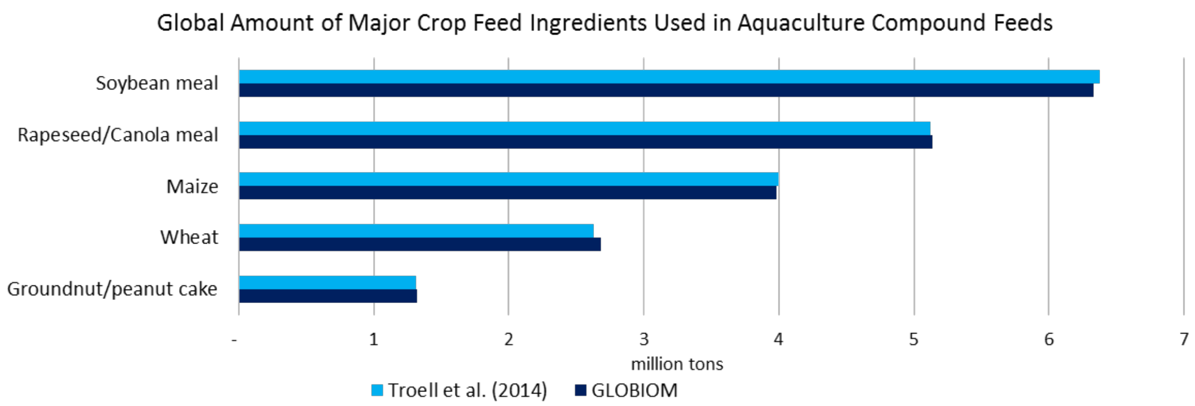
Crucially, the production dataset also distinguishes between capture and aquaculture production, which we have harmonized with the production values in FBS. It also provides spatial detail on the source of fish production at the level of 27 FAO Major Fishing Regions for Statistical Purposes. Figure 4.2. below shows the delineation of these areas across the globe.

Figure 4.2. FAO Major Fishing Regions for Statistical Purposes



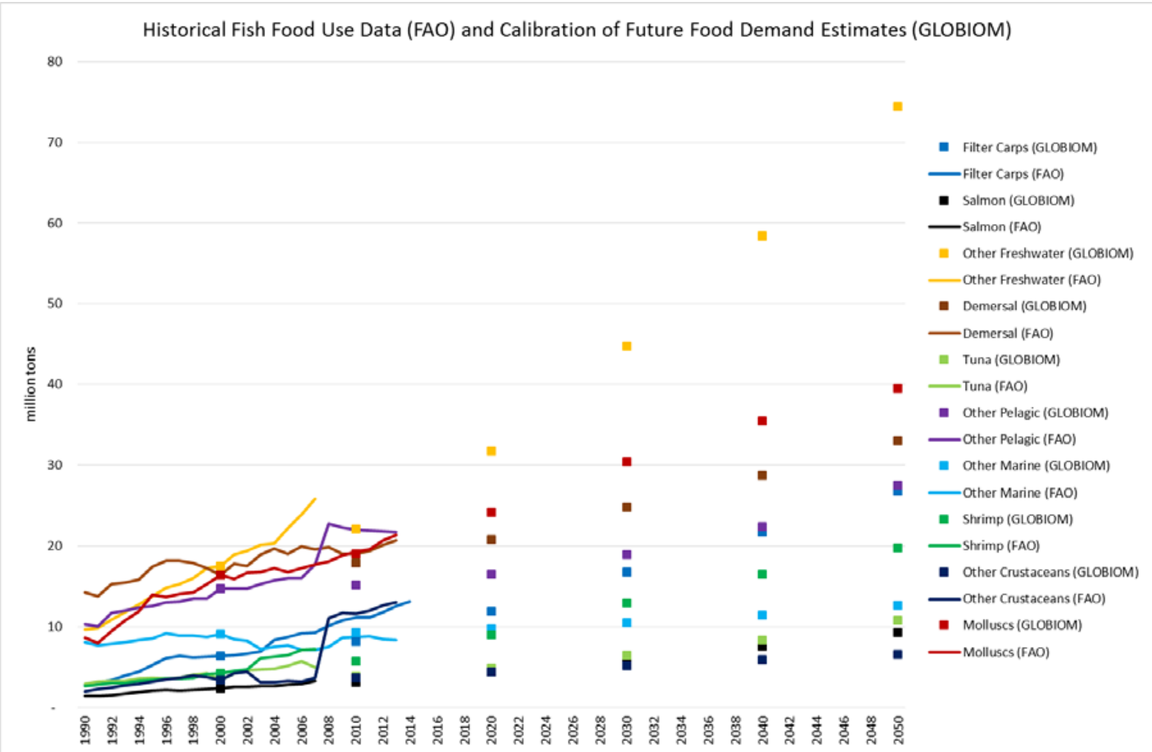
On the production side, the aquaculture production system of the 10 GLOBIOM species groups has been characterized at the country level by crop feed requirements for the 5 globally most commonly used crop ingredients in formulated aquafeeds (soybean meal, rapeseed meal, maize, wheat, groundnut cake). The global total use of crop ingredients in GLOBIOM has been calibrated to the most recent estimates found in the literature (Troell et al., 2014). Figure 4.3. below shows the fit of the calibration.

Figure 4.3. Calibration of the Use of Major Crop Feed Ingredients in Compound Aquafeeds



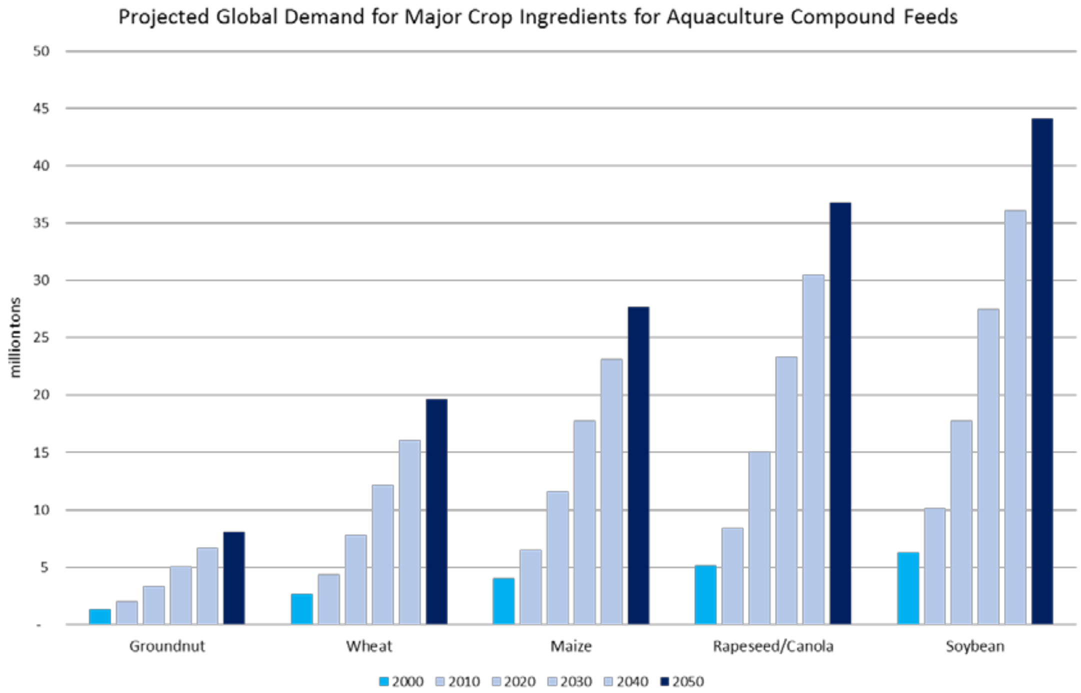
Based on the year 2000 food demand for fish, future demand through the year 2050 has been estimated using projected population growth, income growth, and a dataset of income elasticities for 144 countries (USDA, 2013). Income elasticities have been calibrated at the country level to the long-term trends apparent from the available historical data. Figure 4.4. below shows the fit of the calibrated demand growth with the historical food use data.

Figure 4.4. Calibration of Future Food Demand Estimates



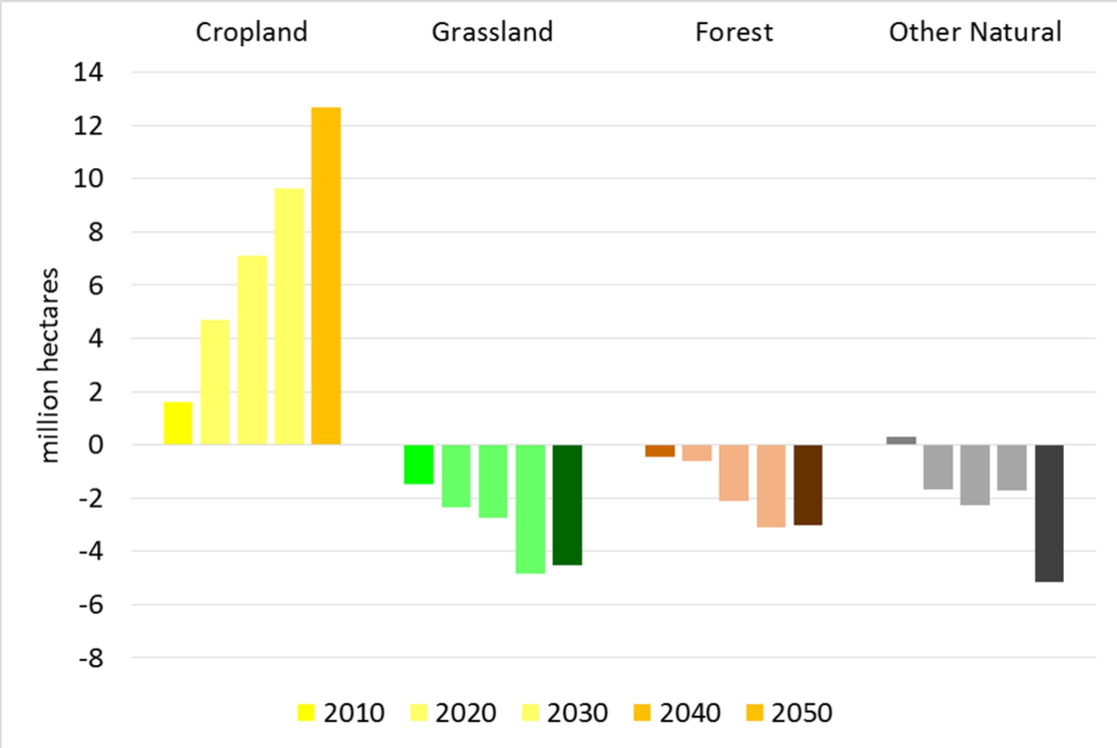
The combination of the production system characterization and the estimated future demand growth has allowed for the testing of an exogenous demand scenario. In this scenario, given the stagnation of global capture fish production in recent decades, it is assumed that aquaculture will be solely responsible for meeting all future fish demand increases. The resulting projected demand for crop feed ingredients necessary for this aquaculture production increase is calculated and shown in Figure 4.5. below.

Figure 4.5. Projected Demand for Major Crop Feed Ingredients



Capitalizing on the existing capabilities of the GLOBIOM model, the necessary cropland area corresponding to the additional crop production is shown below in Figure 4.6., along with the resulting projected differences in land uses in the major land use categories represented in the model.

Figure 4.6. Projected Demand for Major Crop Feed Ingredients



4.1.3 Future work

The next step necessary to complete the fish model is the calibration of international trade flows between countries. The GLOBIOM model represents trade bi-laterally, but unfortunately, a bilateral trade matrix dataset is not published by the FAO like it is done for many other food and agricultural commodities.

Furthermore, it is necessary for the model to represent the processing of food fish along with the resulting processing waste, which is a key source of fishmeal and fish oil globally.

With this in place, we will be able to include fishmeal and fish oil as two additional, fully separate, commodities in the model, representing the production, trade, and use of these materials at the country level and globally, and maintaining a complete physical material balance.

This in turn will allow for the inclusion of fishmeal and fish oil as two additional feeds in the characterization of the aquaculture production system. Indeed, given the limited supply of these marine ingredients from capture fisheries, the utilization of these resources will be of strategic importance for the sustainability of future aquaculture growth and thereby also future diets.

A further benefit of this approach will be to be able to represent the use of fish oil for human consumption (for example in the form of oil capsules), which is potentially very interesting given the role that fish oil and fatty acids contained therein play in a healthy and nutritious diet.

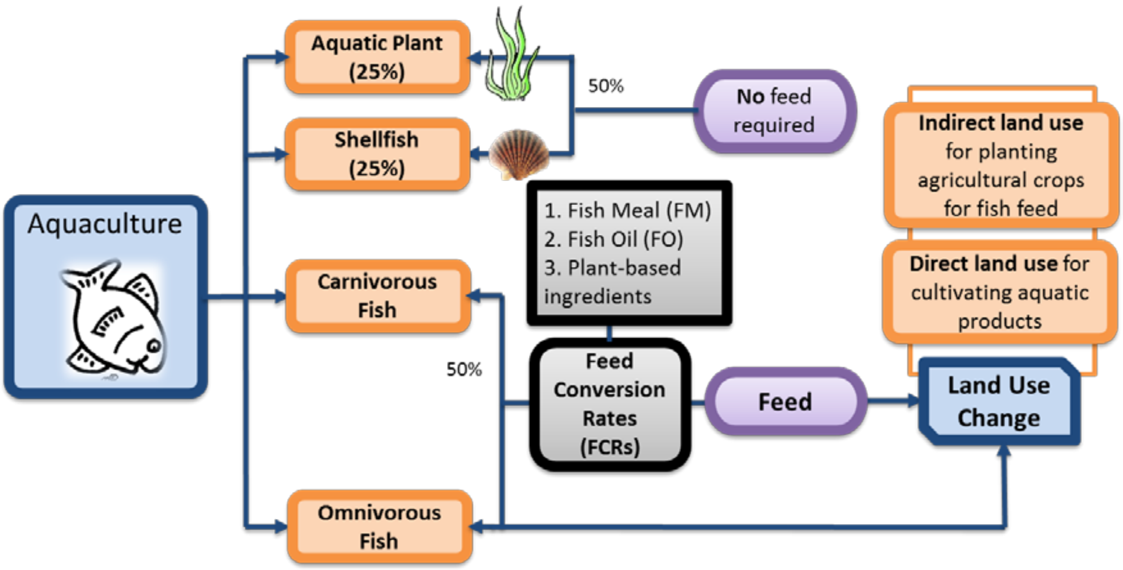
The data and information necessary for the construction of the fishmeal and fish oil section of the model has been identified, and will be based on datasets published by the FAO as well as the literature (e.g. Tacon and Metian, 2008).

4.2 Fisheries and aquaculture in CAPRI

4.2.1 Ambition

The objectives of this fish module are: i) to provide future perspectives on seafood markets; ii) to investigate the interaction between aquaculture and captured fisheries; iii) to provide insight into the links between aquaculture and agricultural markets and identify the impact of aquaculture growth on global land use through crop demand substituting fishmeal and fish oil feed (*Figure* 4.7).

Figure 4.7 The impact of aquaculture on land use through feed production



Source: Chang et al. (2016)

4.2.2 Data

A major effort of the study is to include aquaculture in the CAPRI database. The fish module contains 8 fish commodities (*Table 4*.2) including 6 species categories, fish meal (FIML) and fish oil (FIOL). Two main data sources are FAOSTAT (FAO FIPS CBS) and FAO FISHSTAT. FAOSTAT (FAO FIPS CBS) provides quantity data especially for the 6 fish species including total production, trade, human consumption, feed use, seed use, other use and stock change; however, the spilt of aquaculture from fisheries is not disclosed here. In order to investigate aquaculture activities and eliminate data inconsistency, we calculate the share of aquaculture and captured fisheries over the total production from FAO FISHSTAT and compute new quantities according to the production given by FAOSTAT (FAO FIPS FBS) as shown in Table 4.3. In terms of FIML and FIOL, their data from FAOSTAT (FAO FIPS FBS) only represent the amount processed from fish offals and wastes, which is not reasonable. Therefore, we use the production and trade quantity of FIML and FIOL from FAO FISHSTAT. For having a basic knowledge of how FIML and FIOL are distributed to feed use, other use and human consumption, we compute the share of each of the three demands over the given domestic use (DOMM) from FAOSTAT (FAO FIPS FBS) and multiply the domestic use (production + import – export) calculated in accordance with FAO FISHSTAT.

Table 4.2 Fish commodities in CAPRI fish module

#	FAOSTAT description	CAPRI abbreviation
1	Crustaceans	CRUS
2	Cephalopods & Molluscs	MOLS
3	Freshwater fish & diadromous fish	FFIS
4	Demersal fish	DFIS
5	Pelagic fish	PFIS
6	Marine fish, other	OFIS
7	Fish meal	FIML
8	Fish body oil & fish liver oil	FIOL

Source: summarized by author

Table 4.3 Fish commodities and corresponding data sources

	FAOSTAT (FAO FIPS FBS)	FAO FISHSTAT
6 species from FAO group	Total production (PROD), import, export, human consumption, feed use, seed use, other use, stock change, $Aquaculture = AQUAshare * PROD$, $Captured = CAPshare * PROD$	Total production Aquaculture, captured, $AQUAshare = \frac{aquaculture}{total\ production}$, $CAPshatre = \frac{captured}{total\ production}$
Fishmeal & Fish Oil	Total production (PROD), import (IMPT), export (EXPT), human consumption (HCOM), feed use (FEDM), seed use , other use (INDM), stock change (STCM), Domestic use (DOMM0) = PROD + IMPT – EXPT, $HCOMshare = \frac{HCOM}{DOMM}$ $FEDMshare = \frac{FEDM}{DOMM}$, $INDMshare = \frac{FEDM}{DOMM}$	Production (PROD), import (IMPT), export (EXPT), DOMM1 = PROD + IMPT – EXPT, $HCOM = HCOMshare * DOMM1$, $FEDM = FEDMshare * DOMM1$, $INDM = INDMshare * DOMM1$

Source: summarized by author

Fishmeal (FIML) and Fish Oil (FIOL)

FIML and FIOL are important inputs of aquaculture activities, particularly, at the stage of feed production. Feed accounts for nearly half of the total rearing cost (Rana et al., 2009). In 2012, the total feed used in aquaculture is estimated at 39.6 tons (Tacon and Metian, 2015). According to Tacon and Metian (2008), by weight, FIML and FIOL account for 9.5% and 2.2% of the total aquaculture feed in 2010, respectively. Aquaculture consumed 68% of FIML and 74% of FIOL of the total global consumption in 2012 (Tacon and Metian, 2015). FIML and FIOL are extracted mainly from small pelagic forage fish, in particular, anchoveta, mackerels and herrings. The FIML and FIOL industry highly relies on the reduction fisheries, which account for approximately 20% to 30% of the total captured landings (Péron et al., 2010). In addition, about 15% to 25% of FIML and FIOL production is contributed by fish processing waste (Msangi et al., 2013; Shepherd, 2012). Reduction Ratio (RR) and Waste Ratio (WR) are two important factors for computing FIML and FIOL production according to the landings of reduction fisheries and the amount fish processing waste. Generally speaking, a ton of fish can be processed to roughly 225kg FIML and 50kg FIOL (Tacon and Metian, 2008);

accordingly, the RR of FIML and FIOL are 0.225 and 0.05, respectively. The WR varies with fish species between 0.25 and 0.5 (Msangi et al., 2013). The issue has been raised in the debate over aquaculture net consuming wild fish stock through feed production. Consequently, the interaction between aquaculture and captured fisheries is planned to be tackled with the CAPRI model.

Feed conversion rate (FCR) and Feed formulation

FCR plays an essential role to reveal the feed demanded by each farmed species. *Table* indicates, on average, 1.4 tons of feed is required to produce 1 ton of crustaceans. As aforementioned, FIML and FIOL are two substantial ingredients in the feed, in particular, for carnivorous species such as crustaceans and finfish. However, the use of FIML and FIOL in fish feed is steadily replaced by crop meal and oil due to their raising prices. In the fish module, 13 of the CAPRI crop products are assumed to have the potential to replace FIML and FIOL included in the feed production such as soya cake (SOYC), soya oil (SOYO), corn (MAIZ), white wheat (SWHE), dark wheat (DWHE) rapeseed oil (RAPO), sunflower oil (SUNF), sunflower oil (SUNO), barley (BARL), paddy rice (RARI), rape seed (RAPE), rye and meslin (RYEM) and other animal waste use in fish feed (FIOT). Among which, soybean byproducts are the predominate alternatives to FIML and FIOL. Consequently, the combination of FIML, FIOL and the plant-based ingredients used in feed for various fish species is required for the investigation of how seafood markets interacts with agricultural markets. The initial value of the share of each ingredient is adjusted according to several literatures and shown in Appendix 7.1.

Table 4.4 Feed Conversion rate (FCR) of the CAPRI fish species

#	CAPRI species	FAOSTAT description	FCR (1995-1999)	FCR (2000-2004)	FCR (2005-2009)	FCR (2010-2014)
1	**CRUS**	Crustaceans	1.4	1.4	1.4	1.4
2	**MOLS**	Cephalopods & Molluscs	-	-	-	-
3	**FFIS**	Freshwater fish & diadromous fish	0.9	0.9	1	1
4	**DFIS**	Demersal fish	1.3	1.3	1.3	1.3
5	**PFIS**	Pelagic fish	1.3	1.3	1.3	1.3
6	**OFIS**	Marine fish, other	1.3	1.3	1.3	1.3

Source: Claude E. Boyd and Polioudakis (2006); Tacon and Metian (2008)

Feed formulation provides an overview of the crops used in feed production. In general, all the single species in the same CAPRI fish species category are assumed to have the same diet structure. The form of feed formulated for CRUS is referring to the shrimp feed. MOLS is a filter non-fed category therefore has no feed demand. PFIS, DFIS and OFIS are mostly cultured in the ocean and assumed to be fed with feed compounded in the same way.

Freshwater fish & diadromous fish (FFIS): an exception

FFIS is an important CAPRI fish category which accounts for the largest part (47%) of total aquaculture production. This category is composed of freshwater fish and diadromous fish, including herbivorous and omnivorous fish like carps, barbells and tilapias etc., and carnivorous fish such as sturgeons, eels, salmons, trouts, smelts and shads etc. According to Tacon and Metian (2015, 2008), the FCR of carps and tilapias ranges between 1.5 and 2 and of trouts and salmons between 1.3 and 1.5. However, considering that about 30% of aquaculture is filter-feeding species, this study assumes all FFIS species are fed and uses total FFIS production as denominator to estimate FCR. Hence, the FCR of FFIS shown in *Table* is smaller than the literature states.

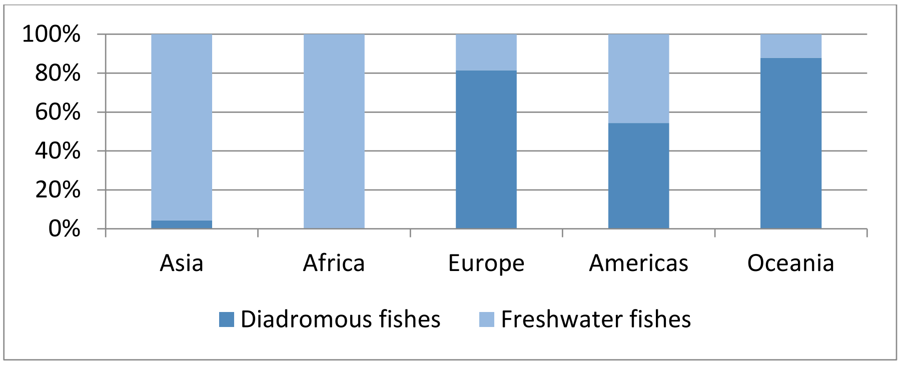
Due to the diverse diet habits of fishes in FFIS, the structure of feed for different fishes should also be taken into consideration. Generally, the major freshwater fish species, such as carps and tilapia, on average consume feed that contains plant-based ingredients up to 85% (Claude E. Boyd and Polioudakis, 2006); by contrast, the most well-known diadromous fishes like trout and salmon demand the feed, in which FIML and FIOL account for 35% and 15% to 20%, respectively (Tacon and Metian, 2008). ***Figure 4.8*** indicates the proportion of freshwater fish and diadromous fish production in the FFIS category at continental level in 2005. In order to project accurate demand of ingredients by feed for FFIS as well as to study its influence on the agricultural markets, this study classifies the CAPRI NUTS0 regions (country level) into three groups: Carnivores farming countries (group C), Vegetarians farming countries (Group V) or mixed farming regions (Group M) as shown in ***Figure 4.8.***

Figure 4.9 and ***Table 2.5.*** The classification is based on the fraction of the freshwater fish and carnivorous fish production in each country. In other words, a country that produces more than 70% of carnivorous fish is assigned to group C, less than 30% to group V, between 30% and 70% to group M. The three categories provide a better reference to project the future demand for FIML, FIOL and other crop ingredients by aquaculture.

As shown in ***Figure 4.8***, in America, the ratios of freshwater fish and diadromous fish cultures are half-and-half. Among the American countries, Brazil focuses on freshwater fish farming (98%) like carps which consume feed with low FIML and FIOL; In contrast to Brazil, Chile farms only carnivorous salmonids. In Asia, most of the Asian countries focus on freshwater fish farming.

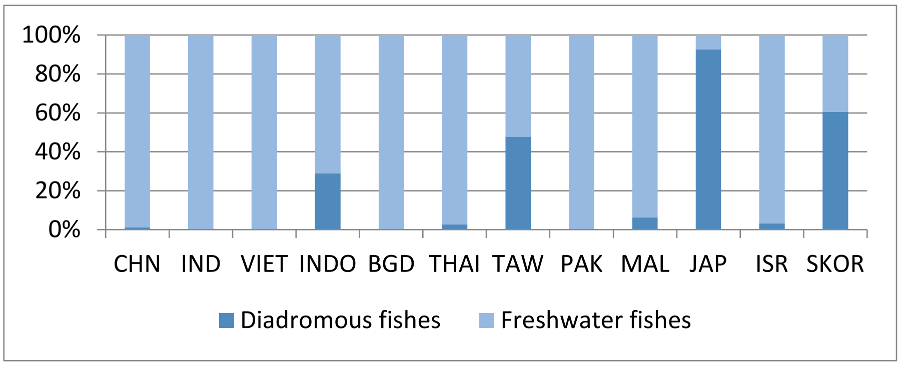
Figure 4.9 addresses the exceptions that Japan has a high diadromous fish production, and Taiwan and South Korea have an equivalent production of both.

Figure 4.8 Distribution of freshwater fish and diadromous fish at continental level (2005)



Source: FAO FISHSTAT

Figure 4.9 Distribution of freshwater fish and diadromous fish at country level in Asia (2005)



Source: FAO FISHSTAT

Table 2.5 Classification of countries by the diet habit of fish in FFIS

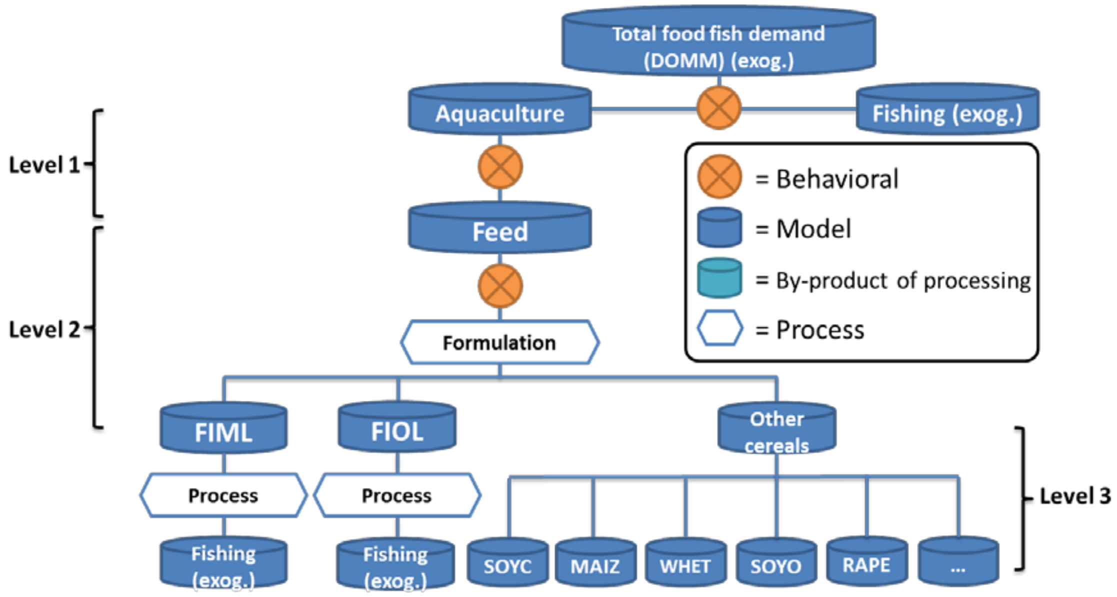
Group V (freshwater fish production is more than 70%)	Group C (diadromous fish production is more than 70%)	Group M (production of each group lays between 30 to 70%)
European countries		
Croatia, Hungry, Romania, Ukraine, Russian Federation, Czech Republic	Other European countries	Bulgaria, Poland, Netherlands, Germany
American countries		
Other American countries	Uruguay, Chile, Peru, Canada	Bolivia, Argentina

Source: summarized by author

4.2.3 Structure of the fish and aquaculture module

The CAPRI model is composed of two major modules, the supply and the market module (Britz and Witzke, 2014). The fish module is constructed under the market module at country level (NUTS-0 region). The total production of each 6 species is disaggregated to aquaculture and captured fisheries. FIML, FIOL and the 13 of CAPRI agricultural commodities listed in *Table* are treated as inputs to the feed industry.

Figure 1.10 Structure of fish module in CAPRI



Source: summarized by author

The structure of the CAPRI fish module shown in *Figure* ***1***.10 is described as follows. These 3 stages of decision making process and the commodities of each stage are listed in *Table* . In addition, the detailed equations are documented in the Appendix 7.2:

1. Disaggregation of fish production by species to aquaculture and captured fisheries, and captured production is considered exogenous.
2. Breakdown to 3 levels of distinguished decision-making process in terms of aquaculture.
3. In the 1st level, the producer behavior function of profit maximization is derived to investigate how fish farmers decide the supply quantity of cultured fish.
4. In the 2nd level, a relative small elasticity coefficient (between 0.5 and 1) within the 3 major inputs (fishmeal, fish oil and other cereals) with respect to the proportion of those ingredients used to the formulated feed is rather fixed. Cost minimization function is applied for a given aquaculture production and major input quantities and prices.
5. In the 3rd level, crops are taken in to account to highly substitute to each other, and a larger elasticity coefficient is assigned within all agricultural products.

Table 4.6 Commodities in each decision making stage

	Optimization	Commodities
Level 1	Profit Maximization	CRUS, MOLS, FFIS, DFIS, PFIS, OFIS
Level 2	Cost Minimization	FIML, FIOL, Aggregated crops
Level 3	Cost Minimization	SOYC, MAIZ, BARL, SWHE, DWHE, RARI, RAPE, RAPO, RYEM, SOYO, SUNF, SUNO, FIOT

Source: summarized by author

4.2.4 Future work

Due to the complexity of data consolidation, the fish module in CAPRI is currently under development and not yet fully applicable in scenario simulations. The structure of the CAPRI fish model is however fairly complete. The IMPACT model is so far one of the existing global agricultural economic models implemented on analyzing seafood market. The IMPACT modelers provided a complete model description and the published documentation (Chang et al., 2016; Delgado et al., 2003; Kobayashi et al., 2015; Msangi et al., 2013). The scenarios generated in the

IMPACT model are of interest being simulated in the CAPRI model as well for further comparison and improvement. The four scenarios with relevance to aquaculture are described as follows (Msangi et al., 2013):

Scenario 1: Faster technological progress at 50%. This scenario states the status where all aquaculture grows faster than in the baseline case by 50% by 2030.

Scenario 2: Increased use of fish processing waste in FIML and FIOL producing countries.

Scenario 3: Disease outbreak in shrimp farming industry in China and South and Southeast Asia with a drop of 35% in 2015.

Scenario 4: Consumers in China expand demand on crustaceans and salmon to three times higher than under the baseline scenario in 2030.

Tveterås et al. (2012) stressed that in 2009 39% of fish products are traded globally, and seafood is one of the most traded commodities in the world. However, the proper bilateral trade flows of CAPRI fish commodities are still lacking in the CAPRI database. In current CAPRI code, the trade matrix of seafood products is "invented" with the top importers and exporters. Consequently, the investigation of seafood trade and related policy issues is facing the challenge of having a qualified data source. Moreover, the data inconsistency of FIML and FIOL production from FAO FISHSTAT and its raw materials from captured fisheries from FAOSTAT (FAO FIPS FBS) multiplying RR creates obstacles to data generation. The rebooking between FIML and FIOL and fish landings processing for feed use might be required to prevent double counting currently happening in some parts of the CAPRI fish database.

4.3 Fish and aquaculture in GLOBIOM, CAPRI and MAGNET – a brief synopsis

The fish modelling activities in GLOBIOM and CAPRI both have the objective to explicitly include or differentiate out the fish sector in the supply and market structures of the models. The relevance of this sector as an important source of animal based protein and valuable micronutrients, its obvious potential to substitute land based nutrition under changing conditions, the likely increasing competition for land based feed, but also the already observed expansion of aquaculture in food production worldwide render these research activities crucial for SUSFANS.

For both models the FAOSTAT and FISHStatJ statistics are the main data sources supplying empirical information on production, consumption and trade of fish species categories. This will not only enable an easier comparison of modelling inputs and results in subsequent SUSFANS foresight activities, but also generate synergies in addressing remaining challenges of further model development and refinement. CAPRI chose a slightly more aggregate product definition but categories can be mapped between the models. The inclusion of separate fishmeal and fishoil categories is still to be implemented in GLOBIOM but this process may benefit from the experience in CAPRI. However, the empirical information on the processing of these product categories is weak for both models and requires careful and ideally consistent parametric assumptions. Generally, the model data ultimately derived through a set of data adjustment procedures to achieve consistency, avoid double counting, and delete will still be compared between the models giving likely rise to further steps towards consistency across the two models.

In terms of economic mechanisms implemented, both systems allow to simulate substitution behavior between fish and other food products following from changes relative prices and external shocks to the food system. Crucial for the connection to the rest of the agricultural sector are here model parameters such as feed conversion coefficients but also scenario assumptions regarding the extent of the land-based feed inputs to aquaculture. This requires careful attention when detailing stakeholder scenarios for SUSFANS simulations in WP10. A key challenge for the modelling of market outcomes is the lack of bilateral trade data, which currently leaves trade results somewhat questionable with respect to its empirical basis.

Apart from the development of supply side fish modules described in this report, the MAGNET model also changed the structure of the fish sectors' representation, which is reported in detail in Kuiper et al. 2017, D9.2). Consistent with the GLOBIOM and CAPRI developments, the database used by MAGNET has been extended to now include both wild catch fisheries and aquaculture as well as fish processing sectors using the same basic FAO data sources. Interactions between aquaculture and fisheries, for example fisheries providing fishmeal and fish seed to aquaculture has been taken into account. Feed is explicitly modelled and attention is given to the competition between aquaculture and cattle sectors for available feed. MAGNET distinguishes 4 groups, diadromous fish, fresh fish, crustaceans and marine fish and is thereby a little more aggregated than the fish modules in the partial equilibrium models. International fish trade in MAGNET is separated into aquaculture and capture fish products assuming that the aquaculture sectors follow the trade patterns from the GTAP database. Here, future communication between models before joint scenario simulation should consider a consistent set of underlying assumptions when creating the base year data on trade given that the empirical information is very limited.

5 Conclusion: key achievements for supply side modelling of SFNS

CAPRI-specific enhancements brought the model's capability to meaningfully assess SFNS in ex-ante simulation analysis one step further. The inclusion of micronutrients into the CAPRI accounting system and its post-model analysis will allow quantifying metrics related to the "nutrition security" part that were not available before. The general concept of making yield responses to fertilizer application rates dependent on the empirical assessment of yield gaps seems promising for a more realistic differentiation of crop production technologies between regions. If it can be successfully implemented, then this enhances the model's accuracy in representing sustainability metrics for EU regions related to agricultural intensity levels.

The implemented changes to GLOBIOM provide multiple advantages. First and foremost, it allows for a better representation of farmers' decisions in terms of intensification versus area expansion in the partial equilibrium model. Second, it improves the assessment of environmental impacts in terms of nitrate, phosphorous and irrigation impacts. Processes like nitrate leaching and management variables like irrigation obtained a more solid basis from crop growth models and observed response behaviour through these enhancements.

The enhancements representing both capture and aquaculture fish in GLOBIOM and CAPRI (and in MAGNET) will allow to develop and apply scenarios to analyze fish and seafood markets from several perspectives at once: production and production systems, consumer demand, feed technology and innovation, and environmental efficiency and carrying capacity. Specifically, the models are capable to (1) the explore the interactions of capture fish and aquaculture sectors, (2) to investigate the impact of pressures of global food markets on the entire fish production system, (3) to analyze the impact of aquaculture expansion on land use through the substitution of fishmeal and fish oil with crop-based feed.

6 References

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7 Annexes

7.1 Shares of feed ingredients for CAPRI fish species

Table 7.1 Shares of feed ingredient for 6 CAPRI fish species (Average 2005-2009)

CAPRI species	FIML	FIOL	SOYC	MAIZ	SWHE	DWHE	RYEM	BARL	OATS	PARI	RAPE	SUNF	RAPO	SUNO	SOYO	FIOT
CRUS	0,19	0,02	0,25	0,001	0,271	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,258
MOLS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FFIS Group V	0,13	0,01	0,45	0,36	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,011	0,001	0,001	0,029
FFIS Group M	0,07	0,03	0,39	0,36	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0.139
FFIS Group C	0,3	0,08	0,23	0,001	0.32	0,001	0,001	0,001	0,001	0,06	0,001	0,001	0,021	0,001	0,021	0,28
DFIS	0,3	0,08	0,23	0,001	0.32	0,001	0,001	0,001	0,001	0,06	0,001	0,001	0,021	0,001	0,021	0,28
PFIS	0,3	0,08	0,23	0,001	0.32	0,001	0,001	0,001	0,001	0,06	0,001	0,001	0,021	0,001	0,021	0,28
OFIS	0,3	0,08	0,23	0,001	0.32	0,001	0,001	0,001	0,001	0,06	0,001	0,001	0,021	0,001	0,021	0,28

Source: Author's estimates; Claude E. Boyd and Polioudakis (2006); Tacon and Metian (2015, 2008); SOYC: soya cake, SOYO: soya oil, MAINZ: corn, SWHE: white wheat, DWHE: dark wheat, RAPO: rapeseed oil, SUNF: sunflower oil, SUNO: sunflower oil, BARL: barley, RARI: paddy rice, RAPE: rape seed, RYEM: rye and meslin, FIOT: other animal waste use in fish feed

7.2 CAPRI fish module

1st level: Profit Maximization

$$max\,\pi = \sum_i f_i \cdot P_i - \sum_i fcr_i \cdot f_i \cdot W_i - qV$$

$$s.t.\,\alpha_0 + \sum_i \alpha_i \cdot f_i + \sum_i \sum_j \alpha_{ij} \cdot f_i \cdot f_j = V$$

i = CRUS(1), MOLS(2), FFIS(3), DFIS(4), PFIS(5), OFIS(6)

q: input price vector, V: input vector, f_i: production quantity of fish type i, P_i: producer price of fish type i,

fcr_i: feed conversion rates for fish type i, W_i: prices of formulated feed for fish type i, f_j: alias of f_i

$$max\,\pi = \sum_i f_i \cdot P_i - \sum_i fcr_i \cdot f_i \cdot W_i - q \cdot (\alpha_0 + \sum_i \alpha_i \cdot f_i + \sum_i \sum_j \alpha_{ij} \cdot f_i \cdot f_j)$$

F.O.C =>

$$\frac{\partial \pi(f_i)}{\partial f_i} = 0,$$

$$P_i - fcr_i \cdot W_i - q \cdot \left[\alpha_i + 2\alpha_{ii} \cdot f_i + \left(\sum_{i \neq j} (\alpha_{ij} + \alpha_{ji}) \cdot f_j\right)\right] = 0$$

$$f_i^* = \frac{P_i - fcr_i \cdot W_i - q \cdot \alpha_i - q \cdot \left(\sum_{i \neq j}(\alpha_{ij} + \alpha_{ji})\right) \cdot f_j}{2\alpha_{ii} \cdot q}$$

$$P_{F_i} = P_i - fcr_i \cdot W_i,\ n_i = \frac{P_i - fcr_i \cdot W_i}{q},\ b_{ii} = \frac{1}{\alpha_{ii}},\ b_i = \frac{\alpha_i}{\alpha_{ii}},\ b_{ij} = \frac{\alpha_{ij}}{\alpha_{ii}},\ b_{ji} = \frac{\alpha_{ji}}{\alpha_{ii}}$$

$$f_i^* = 0.5a_{ii}n_i - 0.5a_i - 0.5 \sum_{i \neq j} (b_{ij} + b_{ji})\, f_j$$

2nd level: Cost Minimization

Cost minimization for a given production level *X*, input quantities *x* and input prices *w*:

$$min\ C = \sum_j x_j w_j$$

$$s.t.\ \alpha\left(\sum_j \sigma_j^{\rho-1} x_j^{\rho}\right)^{\frac{1}{\rho}} \geq X \qquad \text{(CES)}$$

j: feed = FIML(1), FIOL(2), other crops(3) = SOYC, MAIZ, BARL, SWHE, DWHE, RARI, RAPE, RAPO, RYEM, SOYO, SUNF, SUNO and FIOT

X: aggregate feed quantity for fish type *i*, *q*: production level, *w*: input prices, *σ*: distributing parameter

Lagrange function: $L(x_1, \dots, x_5, \lambda) = \sum_j x_j w_j - \lambda\left(\alpha\left(\sum_j \sigma_j^{\rho-1} x_j^{\rho}\right)^{\frac{1}{\rho}} - X\right)$

F.O.C =>

$$\frac{\partial L}{\partial x_j} = 0,\ x_j = \alpha\left(\sum_j \sigma_j^{\rho-1} x_j^{\rho}\right)^{\frac{1}{\rho}}\left(\alpha^{\rho} \sigma_j^{\rho-1} \frac{\lambda}{w_j}\right)^{\frac{1}{1-\rho}}$$

$$\frac{\partial L}{\partial \lambda} = 0,\ X \leq \alpha\left(\sum_j \sigma_j^{\rho-1} x_j^{\rho}\right)^{\frac{1}{\rho}}$$

λ is defined as the shadow price of the constraint which will be the aggregate feed price W for a specific fish type output price, and here we rename λ to W. We add the zero profit condition for a constant return to scale composite feed industry (doubling all ingredients doubles the aggregate feed quantity) to obtain the following two behavioral model equations.

$$x_j^* = F\sigma_j\left(\alpha^{\rho} \frac{W}{w_j}\right)^{\frac{1}{1-\rho}} \qquad \text{for each } j = 1 \dots 5$$

$$PX = \sum_j x_j w_j$$

Here we can reparametrize the conditional demand equations using the elasticity of substitution, $\varepsilon = \frac{1}{1-\rho}$.

$$x_j^* = X\sigma_j \alpha^{\varepsilon-1}\left(\frac{P}{w_j}\right)^{\varepsilon}$$

On the second level, we assign a relative small elasticity coefficient (between 0.5 and 1) within the 3 major ingredient groups with respect to the proportion of those ingredients used to the formulated feed is rather fixed.

3rd level: Between other plant-based materials

In this stage, we neglect the energy contained in the different crops and its processed products that are used as feed ingredients and simply assume they substitute each other according to another elasticity of substitution.

other crops(5) = SOYC, MAIZ, BARL, SWHE, DWHE, RARI, RAPE, RAPO, RYEM, SOYO, SUNF, SUNO and FIOT

$$x_j^* = X\sigma_j\alpha^{\varepsilon-1}\left(\frac{P}{w_j}\right)^{\varepsilon}$$