Agricultural production and emissions in GreenREFORM*

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Abstract

The Danish agricultural sector emits over 20% of Danish greenhouse gases. It is therefore important that the GreenREFORM model describes agricultural production well. Modelling agriculture as an integrated part of a CGE model presents several challenges. First, the agricultural production function is not well captured by standard production functions better suited for production of industrial or service goods. Second, emissions arise at several different steps in the production process and most emissions are (in contrast to most other greenhouse gas emissions) not related to energy consumption. Third, the input-output table from Danish National Accounts system is not sufficiently disaggregated for our purposes, as we wish to model different types of agricultural production and consumption. Fourth, several key intra-farm flows are not captured by the national accounts. This document describes how these issues are dealt with in order to construct a module of agricultural production and emissions that can be integrated into GreenREFORM.

The development of the modules as well as of GreenREFORM is work-in-progress. Therefore, there are aspects of the modelling that can be improved. We provide a brief discussion of these remaining modeling challenges.

*Part of the material in this memo originates from Jørgensen and Christiansen (2020). The current memo expands on Jørgensen and Christiansen (2020) by outlining how the authors' agricultural production framework is integrated into the GreenREFORM model.

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1 Introduction

As part of the GreenREFORM project, we develop modules that aim to model those parts of the Danish economy that are of particular importance for environmental and climate-related policy questions. An agricultural module is important for at least four reasons. First, agriculture gives rise to a substantial share - over 20% - of Danish greenhouse gas (GHG) emissions. Second, the standard production function of GreenREFORM does not adequately capture those steps in the production process that gives rise to GHG emissions in agriculture. Third, the national accounts data that GreenREFORM is built on is not sufficiently detailed to capture key environmental and climate differences between different types of agricultural production. Fourth, several key flows between different types of agricultural production are not at all captured by the national accounts, as they typically take place within farms who conduct joint production of several agricultural outputs. The purpose of the agricultural module is to be able to model the economic decisions as well as the corresponding emissions of the Danish agricultural sector.

The agricultural module will be integrated into the larger CGE model of GreenREFORM. We refer to other working papers and model documentation available on www.greenreform.dk for an introduction to the GreenREFORM model framework. What is described here is therefore a partial equilibrium model of the agricultural sector that can fit into that framework, as well as a discussion of how the model is integrated into the larger GreenREFORM model framework. In terms of emissions, the focus of the module is a modelling of non-energy related GHG emissions, but we also explicitly model emissions of other types, including ammonia and fine particles, from agriculture. Energy-related GHG emissions from agriculture are handled by the general GreenREFORM framework for emissons accountings. Or ambition is to be able to include a detailed modelling of other pollutants at a later stage, including emissions of nitrogen to water bodies. We also note that while agriculture employs land as a key input in production, emissions related to land use and land use change (i.e., LULUCF emisisons) are handled in a separate module and is not covered in this paper.

The GreenREFORM agricultural module is a result of an attempt to balance several, sometimes opposite, demands on the model. These include a demand for a detailed model of the agricultural production system as well as a model that fits within the overall GreenREFORM model. To fit within the GreenREFORM model, the agricultural moduel must be relatively low-dimensional in order to improve computing time and it must be solvable within a computable general equilibrium framework. Finally, the available data puts constraints on what is possible. Nevertheless, we believe that the GreenREFORM agricultural module includes several key features that makes it well-suited for evaluation of economic and environmental-economic policies related to agriculture. These include:

- It is an inherently dynamic model. This implies that adjustment costs are explicitly modelled and that the path towards a new equilibrium can be inspected.

- The model is built to be consistent with the Danish National Accounts system. This means, for instance, that the agricultural contribution to, e.g., GDP and tax revenues, are consistent with the national accounts.
- Production factors, including labor, can move between sectors. This means that regulation that impacts some parts of agricultural production more than others will result in an adjustment between agricultural sectors. It also means that regulation that impacts agriculture will result in an adjustment between agriculture and the rest of the economy.
- The model includes a land market. This means that it is possible to model the implications on agricultural production and land prices of taking land out of agricultural production.
- The model has a detailed modeling of agricultural non-energy GHG emissions consistent with the UNFCCC emissions inventory.
- We include an explicit framework for modeling technologies that can reduce emissions. We include data on some technologies, and more can be added if sufficient data becomes available.

This document is structured as follows: In section 2, we describe the agricultural production functions. In section 3, we describe additSome technologies ional data used for the agricultural model, namely emissions data, data on non-market resource flows and data on land use. We continue by outlining how we model emissions abatement technologies in section 4. In section 5, we discuss how the module can be integrated into the larger GreenREFORM model. Finally, in section 6, we conclude and discuss a series of potential future additions to the agricultural module.

2 The agricultural module

We model agricultural production as 13 separete production sectors. These are conventionally and organically producing sectors for pigs, cattle (meat), cattle (milk), poultry and non-horticultural plants (10 sectors) as well as a fur sector, a sector for horticulture and an agricultural contractor, cf. table 1.[1] The agricultural sectors use bespoke production functions with the exception of agricultural contractor, which uses the default GreenREFORM production function. All sectors produce a generic output, which is used as an input in production in other sectors as well as for final consumption. However, we also model additional outputs where necessary in order to capture key flows between different agricultural sectors.main

We believe this sectoral split is well-suited for capturing the heterogeneous nature of GHG emissions from agricultural production. The main source of GHG emissions from plant production

[1]The agricultural contractor models what is termed “maskinstation” in the Danish agricultural accounts. The main purpose of this sector is to account for intra-agricultural flows of machinery in production.

Table 1: Green Reform agricultural sectors

Sector	Conventional/organic	Production function	Additional outputs
Vegetables	Conventional	Plant CES	Litter, Energy straw, Coarse feed
Vegetables	Organic	Plant CES	Litter, Energy straw, Coarse feed
Horticulture	Both	Plant CES	-
Cattle (milk)	Conventional	Animal CES	Manure
Cattle (milk)	Organic	Animal CES	Manure
Cattle (meat)	Conventional	Animal CES	Manure
Cattle (meat)	Organic	Animal CES	Manure
Pigs	Conventional	Animal CES	Manure
Pigs	Organic	Animal CES	Manure
Poultry	Conventional	Animal CES	Manure
Poultry	Organic	Animal CES	Manure
Fur	Both	Animal CES	Manure
Agricultural contractor	-	GreenREFORM CES	-

Source: Own definitions.
Note: Litter is "Strøelse" in Danish. Coarse feed is is "grovfoder" in Danish.

is use of fertiliser. We therefore model a composite plant sector rather than different types of plant production. We do not distinguish between soil types, as the GHG emissions from plant production on loamy and sandy land are almost identical (e.g., Beck et al., 2018). Since production of milk is inherently joint with production of meat from former dairy cattle, the output of the milk-cattle sector includes both. The meat-cattle sectors only cover cattle raised for the exoress purpose of meat production. The majority of produced cattle meat in Denmark is in fact former dairy cattle. Fur production and horticulture are separate sectors not only because of idiosyncratic GHG emission structures, but because their cost structure is quite different from the rest of agriculture. In particular, the fur sector features high returns and the horticultural sector is more energy-intensive than conventional plant production. Finally, we note that while the sector split is adequate for capturing differences in greenhouse gas emissions, it may not be ideal for capturing differences in nitrogen emissions. We discuss this in section 6.1.

The production module is calibrated to fit a tailor-made version of the Danish National accounts, that is being tailor-made to the demands of the GreenREFORM project. This dataset includes a split of the single national accounts agricultural sector into the 13 agricultural sectors used in this module. The tailor-made national accounts data is constructed by Statistics Denmark and a description of the dataset is forthcoming in a separate memo. The input-output table includes flows of all marketed goods and services from the rest of the economy into each of the 13 agricultural subsectors as well as flows of marketed agricultural outputs that are used as inputs in other production sectors, exports or as final consumption. However, we also model non-market based interactions between the agricultural sectors. In order to do this, we construct a dataset that contains the relevant flows. This dataset is described in more detail in section 3.

In the Danish context, the so-called ESMERALDA model has often been used to simulate the effects of agricultural economic policy. The ESMERALDA model is a partial equilibrium model of the Danish agricultural sector. ESMARALDA models links between different agricultural production types and the production function consists of nested CES functions. ESMERALDA uses a slightly different approach to the decomposition of Danish agriculture into sectors. Whereas the Green Reform model separates sectors using an activity criteria (in Danish: produktionsgren), ESMERALDA instead employs a firm unit criteria (in Danish: bedriftstyper). That means that where all vegetable production in Green REFORM will be placed in the vegetable sectors, the animal producing sectors of ESMERALDA will also produce vegetables, since animal and vegetable production to some degree takes place within the same farms. With this caveat in mind, it is still of interest to compare the Green REFORM production function with the ESMERALDA production function. Figure 1 shows the production function of ESMERALDA and table 2 shows average elasticites used in ESMERALDA.[2]

In the remainder of this section, we describe the production functions of the agricultural module of GreenREFORM. We do attempt to compare the production function structure of ESMERALDA to the specifications outlined in the current memo, but it is a difficult exercise for at least two reasons. First, differences in structures make it difficult to compare elasticities between models directly, Second, the CES shares also affect the attributes of the models. It is somewhat easier to compare effects on the margin of e.g. introducing a tax on GHG emissions. We plan on doing such a comparison, but this work remains to be done.

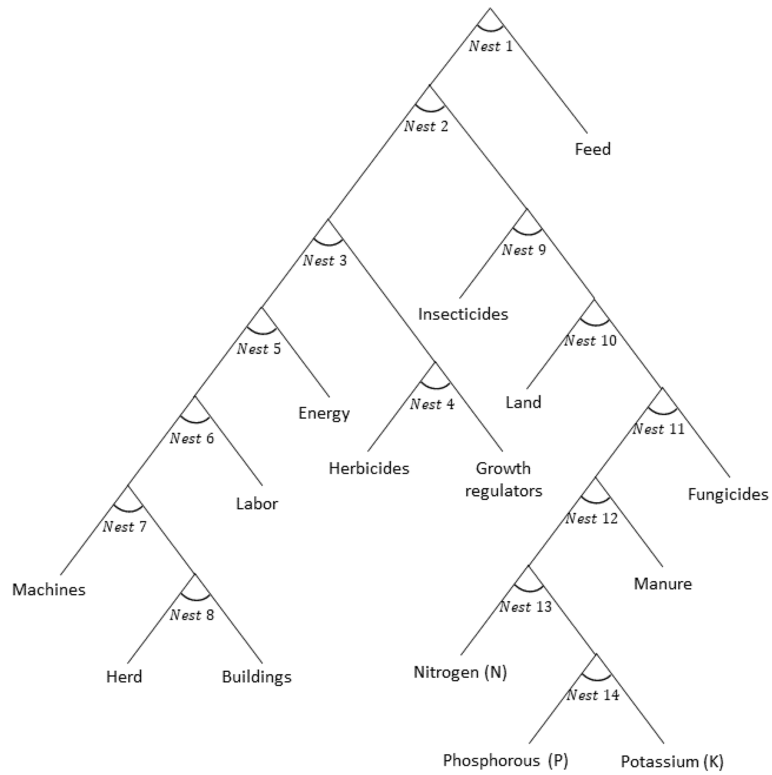
Table 2: Average ESMERALDA elasticities

	Sector type		
	Vegetable	**Animal**	**Other**
Nest 1	0.01	0.06	0.01
Nest 2	0.07	0.00	0.03
Nest 3	0.16	0.01	0.12
Nest 4	0.16	0.01	0.12
Nest 5	1.44	0.19	0.32
Nest 6	0.32	0.15	0.40
Nest 7	0.41	0.17	0.60
Nest 8	0.01	0.05	0.01
Nest 9	0.11	0.01	0.15
Nest 10	0.09	0.00	0.06
Nest 11	0.46	0.06	0.59
Nest 12	0.30	0.02	0.30
Nest 13	0.16	0.02	0.14
Nest 14	0.11	0.01	0.17

Note: "Other sectors" are nonfood vegetable production as well as grass. Elasticities are unweighted averages of sector-specific elasticities.
Source: Own calculations based on personal correspondence with Jørgen Dejgård, Institute of Food and Resource Economics, University of Copenhagen.

[2] We thank Jørgen Dejgård Jensen, University of Copenhagen, Institute of Food and Resource Economics for supplying us with this data.

Figure 1: ESMERALDA's production function



Note: All sectors in ESMERALDA employ the same production function; however, elasticities as well as CES shares differ across sectors.
Source: Own illustration based on personal correspondence with Jørgen Dejgård, Institute of Food and Resource Economics, University of Copenhagen.

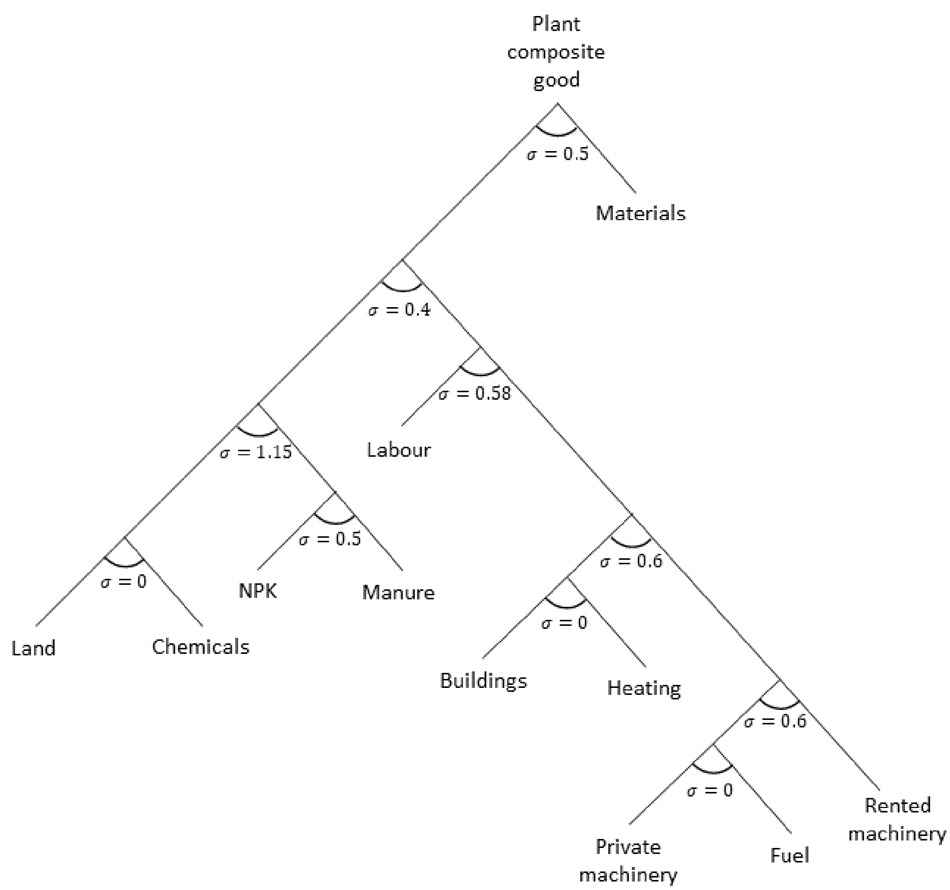
2.1 Plant production

The production functions of plants in the agricultural module of GreenREFORM take the following inputs: chemicals, land, inorganic fertiliser (NPK)[3], manure, labour, buildings, electricity, machines, and fuel to the machines as well as an input of other materials, which covers all other inputs to the agricultural plant sectors observed in the national accounts. The nested CES production function outlined in Figure 2 converts these inputs into a composite plant good. This composite good is split out into several sepate goods. A description of split of the composite plant good is postponed to subsection 2.3.

The production functions are, with minor adjustments, identical to those of Jørgensen and Christiansen (2020). These functions are in turn inspired by the agrucultural module of the MAGNET-model (Woltjer et al. (2014)).[4] The following differences exist: In our specification intermediate

[3]Organic farmers are prohibited from the use of NPK.
[4]MAGNET, Modular Applied GeNeral Equilibrium Tool, is a modular global trade model, which also includes an agricultural module.

Figure 2: Production of plant products



Source: Own illustration.

goods such as chemicals, electricity, and fuel are proportional to their relevant inputs rather than to output as in MAGNET. We choose this specification as these inputs are of special importance for the climate effects which is our focus. We also model the use of fertiliser separately from land, as fertilizer use is an important source of greenhouse gas emissions (Nielsen et al. (2017)). In MAGNET, fertilised land is an aggregate input and hence it is not possible to substitute between fertiliser and land. The elasticity between land and fertiliser is set to 1.15, which is taken from Hertel et al. (1996). Finally, we split capital into buildings and machines as depreciation rates and adjustment costs of these two inputs are separately identified in the GreenREFORM data.

In order to fit the model within an input-output framework, all inputs in the production functions are mapped to output from specific GreenREFORM sectors. Thus, fuel and heating covers the energy use of the sectors, rented machinery is the output from the agricultural contractor, chemicals and NPK-fertilizer is are inputs from the chemical sector and manure is produced by the animal sectors. Those inputs that we do not explicitly account for, are contained in the "materials" nest in the same manner as the materials nest in the standard GreenREFORM production function (Kirk, 2020). We also use the elasticity for the top nest from the nest between KELB and M from the standard GreenREFORM production function.

There are several differences between the production functions of GreenREFORM and ESMERALDA. The ESMERALDA production function has a more finely disaggregated input structure of chemicals and fertilizers. With available data, Green REFORM could be similarly expanded. In GreenREFORM we distinguish between privately owned machinery, which requires fuel, and rented machinery, which is a service delivered by the agricultural contractor, which includes fuel. There are also differences in the production function structure of the two models: Whereas we nest land closely with all types of chemicals and fertilizers, ESMERALDA has herbicides and growth regulators closer to capital, labor and energy. Another difference is that in ESMERALDA, capital and labor are nested together before energy, whereas in the agricultural module of Green REFORM, capital and energy are nested together before labor, which is consistent with the nesting structure in the default production function of the Green REFORM model. Finally, the Green REFORM model is part of a framework that is consistent with the input-output system of the Danish National accounts, and it therefore takes a range of "materials" inputs as the topmost nest.

The differences in nesting structures makes it difficult to compare the chosen elasticities directly. However, there are some similarities: For instance, in ESMERALDA, the average elasticity beween fertilizer-, fungicides- and insicticides-enhanced land and the remaining inputs (nest 9) is 0.09, whereas the closest comparable elasticity between input-enhanced land and remaining inputs in Green REFORM is of a similar magnitude (0.1).

2.2 Animal production

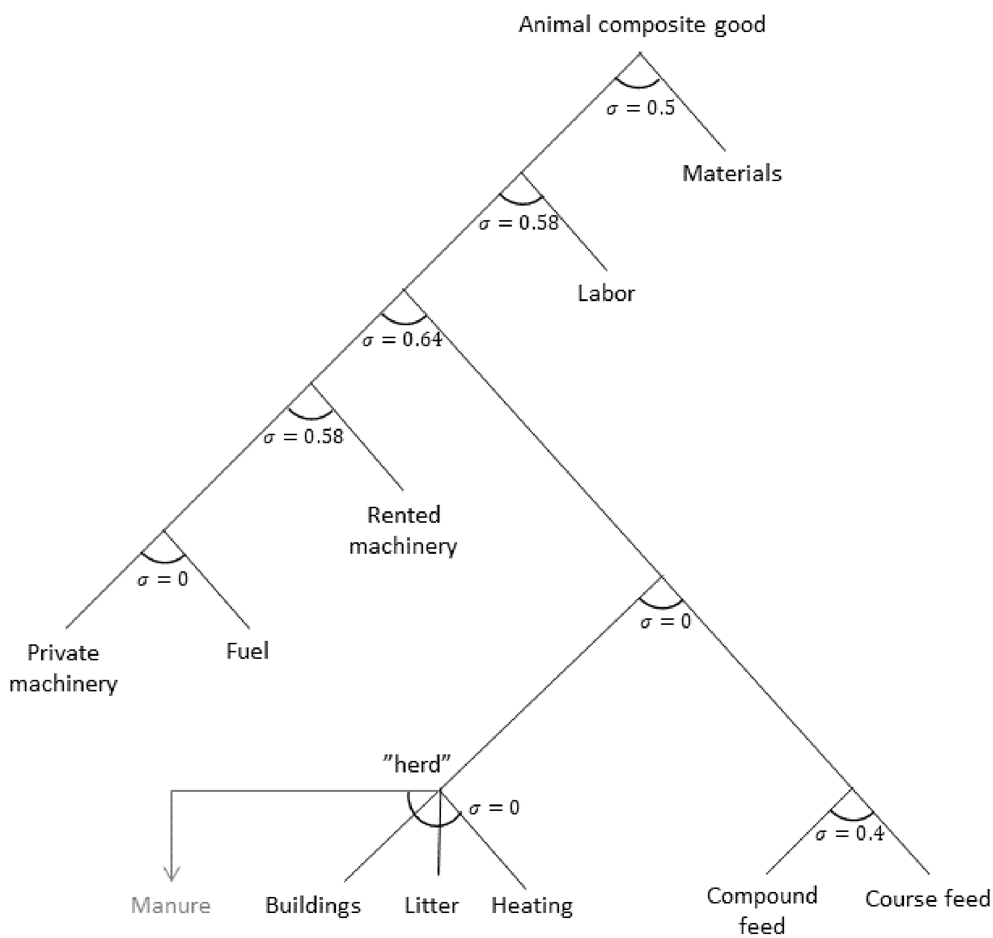
The animal production structure of the agricultural module of Green REFORM is, like plant production, almost identical to the production structure of Jørgensen and Christiansen (2020). The specification draws on that of the MAgPIE model (Lotze-Campen et al. (2008)).[5] Each branch takes machines, electricity, buildings, herd, compound feed (Danish: “kraftfoder”), coarse feed, litter, materials and labor as inputs. The production function outlined in Figure 3 transforms these input into the animal composite good. The nesting structure is somewhat different from the ENVISAGE and MAGNET models (Woltjer et al. (2014); van der Mensbrugghe (2008)). As in ENVISAGE and MAGNET, labour is nested together with the remainder in the top nest of the production of livestock (Woltjer et al. (2014); van der Mensbrugghe (2008)).

We only model the stock of animals implicitly, as we assume that it is proportional to the building stock. This is a reasonable modelling, since most animals live inside stables in industrialised countries (Nielsen et al. (2017), Annex 3D-1). We can therefore think of the subnest that consists of buildings, litter and heating as representing the animal stock, i.e. the “herd”. The dynamic adjustment of the capital stock is sluggish, and we assume that adjustment of the herd stock does not place additional constraints on this adjustment proces. We model manure production as proportional to the animal stock. As manure is actually an output of the animal producers, we model it here as a production input with a negative price. Finally, the animal stock requires litter and animal food. Animal food is a mix of compound feed and coarse feed. The mix depends on the type of animal, e.g., cattle mostly consume coarse feed whereas chickens mostly consume compound feed. Litter and coarse feed are sourced from the plant producers. These inputs (as well as manure) are often not traded on the market, but is instead part of joint farm production. As we separate activities into different sectors, we model these flows explicitly.

Compared to ESMERALDA, which nests capital with labor before energy, the Green REFORM model again nests capital with energy before labor. We choose an elasticity between capital and labour of 0.58 according to Kemfert and Welsch (2000). Whereas ESMERALDA has an explicit herd input, we only model the herd size implicitly as proportional to buildings. This is identical to a zero elasticity between herd and buildings. ESMERALDA has an average elasticity of 0.05 in the herd-buildings nest (nest 8). The Green REFORM model nests animal feed next to the animal-building aggregate, whereas ESMERALDA puts animal feed in the very top nest. Like with vegetable production, it is difficult to directly compare other parts of the production function structure.

[5] MAgPIE is a detailed global land allocation model, which also models regional agricultural production.

Figure 3: Production of animal products

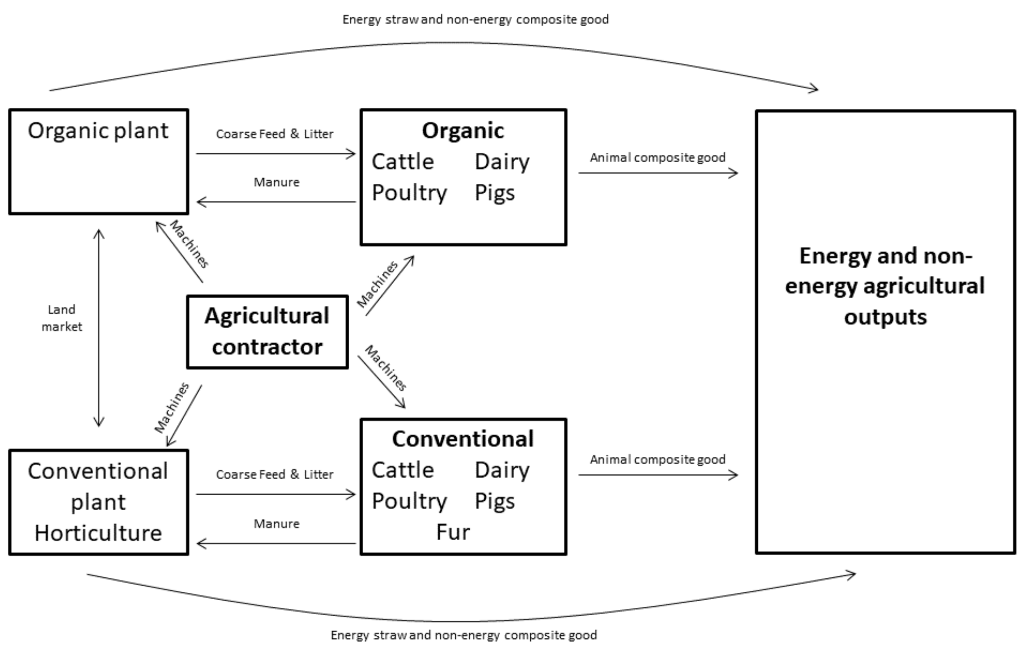


Source: Own illustration.

2.3 Outputs and sector links

As mentioned above, we model key flows between sectors. The animal sectors get coarse feed and litter from the plant producers and deliver manure to the plant sectors, which is used as fertilizer. The plant sectors compete for the available land and the agricultural contractor rents out machinery to all other sectors. The intra-agricultural flows of goods and production factors are illustrated in figure 4.

Figure 4: Intra-agricultural flows

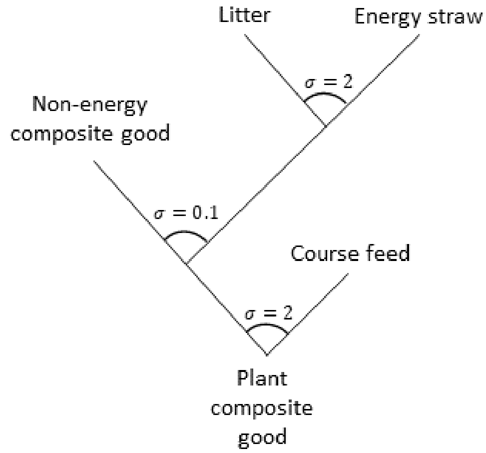


Source: Own illustration.

Plant output is split into coarse feed, litter, energy straw as well as other outputs using a CET-split of aggregate plant output (figure 5). There are two reasons for making such a split: First, a split between energy and non-energy goods are important in order for the agricultural module to be consistent with the rest of the GreenREFORM model. Second, we wish to be able to track market and non-market outputs seperately. Our chosen split accomplishes this, as energy straw covers the energy good output of agriculture, and coarse feed and litter are the two non-market outputs produced by the plant sectors.

The transformation elasticities of the CET split are highly uncertain, as the literature provides little guidance. The chosen elasticities are based on a stylized description of the choices a farmer has on what to do with her production output. First, the farmer has a choice on whether the entire plant should be used for coarse feed or not. Since most types of plant production can be used

Figure 5: CET split of plant production



Source: Own illustration.

to feed both animals and humans, a high transformation elasticity is chosen. Of the output that is not used for coarse feed, only a share is in fact edible by humans. Using time and resources, it is possible, but not easy, to increase how much of the plant that can be used for human food. Therefore, a low transformation elasticity is chosen. The parts of the plants that are not used for human food can then be used for either litter or energy straw. It is fairly easy to use energy straw for litter instead, or vice versa. Therefore, a high transformation elasticity is chosen.

We note that the composite output of the animal sectors is not split into different outputs. This is because the two reasons for doing so for plant production are absent for animal production: There is no non-market output as part of the animal sector composite good, and the animal sectors do not produce an energy good. However, since we have several animal production sectors, it is possible to distinguish between output of conventional and organic cattle, pigs, poultry and fur.

3 Additional data sources

In this section we describe additional data sources used in the calibration of the production functions, namely emissions data, data on non-market flows and land data.

3.1 Non-energy emissions

This section describes our approach to a detailed modelling of non-energy emissions in agriculture. The basic idea is to link emissions to those inputs in the agricultural production functions that give rise to the emissions. We focus on non-energy emissions, as the modeling of energy-related emissions from e.g. diesel used in agricultural machinery is unproblematic to model using the standard emission accounting approach of GreenREFORM (memo is forthcoming).

3.1.1 GHG Emissions

We split the non-energy GHG emissions into four main categories. The categories follow the categories of agricultural emissions from Danish National Inventory report (Nielsen et al., 2019). We model all agricultural emissions of the CRF tables (CRF category 3). We divide these into four main categories:

1. Methane (CH_4) emissions from enteric fermentation
2. Methane and nitrous oxide emissions (N_2O) from manure
3. Nitrous oxide emissions from fertiliser use
4. Other sources including liming and urea application[6]

The main idea is to tie emissions to the relevant production function nest.[7] For instance, if emissions are proportional to the stock of animals, they will be linked to the herd nest. This has two advantages. First, it means that we can calibrate the model directly to projections of e.g., cattle stocks and emissions related to cattle stocks, as these, are tightly linked.[8] Second, it captures that farmers can substitute production inputs in order to e.g. mitigate the effects of a tax on GHG emissions.

Enteric fermentation is a naturally occurring digestive process in ruminant animals where food is decomposed producing methane as a byproduct. The emissions are modelled as proportional to the number of animals, and will therefore be linked to the herd subnest, cf. figure 3.

Manure is a mixture of animal excrement as well as bedding and straw. Emissions stem from a biological process, which produces CH_4. Emissions related to manure management are modelled as proportional to manure production.

Fertilizers used in plant production containing nitrogen gives rise to emissions of nitrous oxide. N-fertilizers include animal manure and inorganic (i.e. chemically produced) fertilizer. Emissions from fertilizer use are tied to the relevant fertilizer subnests, i.e N and animal manure.[9]

Other sources account for less than 10% of total non-energy related agricultural emissions. These emissions are linked to the closest proxy to the emitting source. For instance, emissions from urine and dung deposited by grazing animals, liming and field burning are assumed to be proportional to land use. We extract historic emissions levels for all emission sources from the so-called CRF-tables of the Danish National Emissions Inventory (DNEI, Nielsen et al., 2020b). We classify the line items of the inventory in two dimensions, namely the relevant sectors and the

[6] Emission from field burning are not relevant in Denmark as it has been prohibited since 1990 (Nielsen et al., 2019).

[7] This is consistent with the method used in the Esmeralda model.

[8] One way this link can be modified is through the use of new technologies that directly or indirectly reduce GHG emissions. We include a framework for modelling such technologies explicitly, cf. section 4.

[9] Sewage sludge is also used as a fertilizer, although of a smaller magnitude than manure and inorganic fertilizer. We do not explicitly model the flow of sewage sludge, but we link emissions from sewage sludge used as manure to the manure-NPK aggregate.

production function input or aggregate that they are most closely correlated with. Using this as well as economic information on production function input quantities, we calibrate implicit emissions coefficients. Table 3 contains an exhaustive list of emission sources of the module. The table presents an overview, but we use a finer sector classification where possible; for instance it is possible to distingush between emissions from manure management and enteric fermentation from dairy and non-dairy cattle, sheep and pigs.

Table 3: Non-energy emissions categories

Sectors	Category	Proportional to	*Notes*
Animal	Manure Management	Herd	
Animal	Enteric Fermentation	Herd	
Vegetable	Land related	Land	*Includes field burning, liming, urea application, crop residues and deposits by grazing animals*
Vegetable	Fertilizer	Total fertilizer	*Includes sewage sludge, and indirect N2O emissions from managed soils*
Vegetable	Organic fertilizer	Manure	
Vegetable	Inorganic fertilizer	NPK	

Note: We classify each Danish National Emissions Inventory line item into the following sectors: Vegetable, cattle, poultry, swine and all animal sectors. We then distribute emissions between the relevant agricultural sectors in Green REFORM using the quantity of the relevant production input as key.

We note that the totals of non-energy GHG emissions in the Green REFORM model are based on the “Green National Accounts”, published by Statistics Denmark. The Green National Accounts emissions use a different emissions accounting scheme (see Beck and Dahl (2020) for a detailed comparison). However, the total of CRF emissions included here is almost perfectly identical to the non-energy emissions total for agriculture in the Green National accounts. To ensure full consistency with the Green National Accounts emissions, we scale all CRF emissions by gas-specific factors. As emissions totals are almost identical, the required scaling is minimal. For instance, for CO_2 emissions in 2017, we must scale emissions by a factor of 1.005 to ensure consistency.

3.1.2 Other air pollutants

As with GHG emissions, agricultural production also gives rise to a series of non-energy related air pollutants, including NH_3,NO_X, SO_X, CO, $PM_{2.5}$ and PM_{10}. Disaggregated information on these emissions come from the Danish Informative Inventory (DNII), submitted to UNECE under the Long-range Transboundary Air Pollution convention (Nielsen et al., 2020a). As with the CRF-tables we link the line items of the DNII tables to the relevant production function inputs. Again, we ensure that the totals of non-energy related air pollutants of the Green National accounts are unchanged by calibrating scaling parameters. These scaling parameters are, like with the GHG scaling parameters, quite small. For instance, for NH_3 emissions in 2017, DNII levels must be scaled by a factor of 0.9892.

3.2 Non-market data

The non-market data covers the intra-farm flow of non-market goods mentioned in subsection 2.3. These flows do not represent actual market transactions.[10] However, they are crucial for understanding the joint production of several types of agricultural outputs that take place on a single farm. As the sectors of GreenREFORM are separated according to activities (Danish: Produktionsgrene), it is necessary to model these flows explicitly.

The dataset is compiled by aggregating and modifying the disaggregated accounting data on Danish farms published by Statistics Denmark.[11] The input data includes imputed values of inputs and outputs of the non-market flows that we include in the model (manure, coarse feed and litter). We use this data to construct an input-output tableof non-market flows within agriculture. The identifying assumption that enables a transformation to an actual input-output table is that the conventional agricultural sectors produce to other conventional sectors and similarly for organic sectors.

In general, the prices of non-market inputs are normalized to 1 in the base year. However, since several types of emissions are connected to the nitrogen content in fertilizer and manure use, it is of interest to model the N-content directly. We separate this out using information on total nitrogen use in the agricultural sector of The Danish Energy Agency (2020). From this report we know 1) the total amount of inorganic fertilizer used and 2) the total amount of fertilizer used per hectare. We complete the data with two identifying assumptions, namely that 1) organic plant production uses only manure-fertilizer and they use 170 kg per hectare (the maximum they are allowed to use under the current regulations); and 2) conventional plant production and horticulture use the remaining fertilizer in shares proportional to their land use. This implies that non-organic plant producers and horticultural producers use a total of 190 kg N per hectare per year. We do not account for the N-content from sewage sludge explicitly, and the N-quantities of sewage sludge is therefore implicitly part of the manure-N in these calculations. There is room for improvement of this modelling, if data availability permits.

3.3 Land

The total amount of land available for agriculture comes from Statistics Denmarks accounting data.[12] As a baseline for land rent, we use the price per hectare that farmers pay when they rent land from each other according to Statistics Denmarks accounting data.[13] This modelling ensures that the rents to land equal the rental price of land. In 2015, this rental price was 3.861

[10]For instance, the flow of coarse feed from vegetable production to animals does not correspond to an actual transaction in the real world. The farmer often produces coarse feed and uses it for their own animals.

[11]Tables REGNPRO1 and REGNPRO2 on Statistikbanken.dk

[12]Table JORD1 on statistikbanken.dk

[13]In danish: Forpagtningsafgift. Available on statistikbanken.dk, table LPRIS36. Note that this price includes EU-subsidies given to farmers for producing (“enkeltbetalingsordning”/”grundbetaling” & “grøn støtte”.

Danish kroner per hectare (around 520 EUR). Note that this price includes direct EU subsidies to farmland (basic payment and greening payments).

Every year, some agricultural land is taken out of production and used for other purposes, such as roads, settlements etc. We use the projection of agricultural land up until 2030 of Jensen (2019). This projection is also used by The Danish Energy Agency (2020) for their emissions projection. Jensen (2019) projects that agricultural land is reduced by about 12.000 hectares per year, which we adopt. adopt.[14] From 2030, we assume that available land is constant.

4 Abatement technologies

Agriculture has access to several technologies that can be used to reduce non-energy emissions. These technologies are of the "end-of-pipe" abatement type, in the sense that 1) emissions are proportional to some input or output in the production function, and 2) a share of these emissions can be removed at cost. The model includes a framework for modelling such technologies explicitly using the methodology described of Stephensen et al. (2020a).

We include some technologies in the current version of the model; however, it is relevant to include more technologies on e.g., changes in cattle feed and improved drainage of animal sheds, if data is available. It is quite easy to expand this list of technologies if the necessary data is available. Notably, a few NH_3-reducing technologies (air cleaning, heat exchangers, frequent removal of animal waste) described in the Energy and Climate Outlook are not currently included, as we lack cost information on these technologies.

Only a few data points are needed per technology, namely the unit cost of the technology, the implementation potential (how large a share of emissions can the technology be applied to) and the reduction share (how large a share of the emissions that the technology is applied to are removed). This allows us to calculate the total reduction potential, i.e. if a technology can reduce 20% of emissions and the technology can be used on 50% of some emisisons, the reduction potential is 20%*50% = 10% of emissions. We can also incorporate a baseline forecast of technology adoption use, but if this is not available, the model will produce one.

We currently include three technologies, namely manure acidification, slurry cooling and biogasification of manure. The data on emission reduction shares of these technologies as well as a baseline forecast of technology adoption stem from background material to Denmark's Energy and Climate Outlook ("Basisfremskrivningen", The Danish Energy Agency, 2020). We extract information on unit costs of these technologies from Dubgaard and Ståhl (2018). Dubgaard and Ståhl (2018) also detail implementation potentials and reduction shares.

Table 4 contains an overview of the technological data included in the model.

[14] Jensen (2019) reports a slightly higher agricultural area in historic years than Statistics Denmark. We use the levels of land of Statistics Denmark, as it is consistent with much of the rest of our data, which is also from Statistics Denmark.

Table 4: Technologial abatement data

Technology	Sector	Baseline implementation 2015	2040	CH4 Reduction potential	Implementation potential	Cost
Acidification	Cattle	2%	8%	60%	27%	1.827
Acidification	Pigs	1%	2%	60%	27%	1.827
Slurry cooling	Pigs	3%	9%	20%	18%	774
Biogasification	Cattle	10%	9%	41%	60%	1.374
Biogasification	Pigs	6%	6%	41%	66%	1.374

Source: Own calculations based on The Danish Energy Agency, 2020 and Dubgaard and Ståhl (2018).
Note: Costs are in 2018 constant prices and calculated as the cost in Danish kroner per ton reduced CO_2-equivalent. The costs do not include other environmental benefits of the technologies such as reduced nitrogen emissions or improved air quality. Reduction potentials are listed for methane, but technologies also reduce NH_3 (acidification slurry cooling) and N_2O (biogasification) emissions. Reduction potentials, implementation potentials and costs can vary over time, but this is not the case in the current dataset.

5 Integration

In this section we outline how the agricultural module is integrated into the larger GreenREFORM model.

The basic idea of integration is that the agricultural module "takes over" the production of the agricultural sectors from the GreenREFORM CGE model. This means that the standard production function structure is replaced with the production structure described in this note. T It is only the production structure that is replaced; the agricultural model therefore inherits other production features from the GreenREFORM CGE model, such as quadratic capital installation costs and capital user costs. We also modify the emissions accounting module of the model to take non-energy agricultural emissions from the module instead of the "generic" emissions modelling described in Beck and Dahl (2020).

We note that we do not entirely "turn off" the production functions of the CGE model for the agricultural sectors. Instead, we the CGE-model agricultural sectors adjust to the agricultural module via adjustment of appropriate parameters. This is similar to the basic idea used for integration of the energy module (Stephensen et al., 2020b, section 2). In particular, CES-shares in the production functions are adjusted to align input demand with the agricultural module, and the otherwise fixed markup premium adjusts to achieve matching output prices, and thus keep the balance between the value of inputs and outputs (of marketed goods) intact.

In general, it holds for both the CGE-model and the agricultural module that the value of outputs equals the value of inputs. The inputs can be divided into inputs of goods and services (including taxes), production taxes, labor costs and gross surplus and mixed income, the last of which is divided into usercost of capital and profits. In the CGE-model a markup price premium is calibrated to adjust profits in order to ensure that the value of output equals the value of inputs in years covered by data. - In forecasted years, the markup premium is forecasted at fixed value.

In forecasted years, the principles of integration between the two models are as follows. Input prices and demand for agricultural outputs of market-goods is determined by the CGE-model, whereas output prices and input demand of the agricultural sectors is determined by the agricultural module.

In the agricultural module the producers use two additional inputs not accounted for in the National Accounts (NA), which the CGE-model is based on. Those are land and intra-agricultural non-market goods (i.e. manure, coarse feed and litter), the last of which is traded between respective agricultural sectors. Non-markets goods are thus also an extra source of revenue, but one which net out across the agricultural sectors.

Land has a rental price (usercost). This is included in the agricultural model by calibrating a reduced sector-specific markup in years covered by data. This implies that the pure profits in the module in a given sector will be lower than in the corresponding sector in the CGE model, but the sum of land rents and profit of the agricultural module will equal the profits of the CGE model. Via the principles of integration, as explained above, changes in the usercost of land will carry over into changes in profits in the CGE-model.

Trade in intra-agricultural non-market goods nets out across agricultural sectors. This means that the inclusion of these non-market goods shifts profits between the respective agricultural sectors relative to the CGE-model in years covered by data as well as in forecasted years. But changes in the prices of non-market goods will be reflected in the prices of market output, which carries over in the CGE-model via the integration as explained above.

6 Concluding remarks

This memo has outlined the GreenREFORM approach to modeling agriculture. The agricultural module is, like the GreenREFORM model as a whole, work in progress. There are several aspects of the framework that we aim to expand on, and the model must also be calibrated to economic projections as well as emissions projections before economically meaningful simulations can be conducted. Below, we discuss a series of features that we would like to implement, but are missing from the current version of the model.

6.1 Emissions to water

When farmers use nitrogen fertilizers, a share of the nitrogen end up in water bodies (coastal waters, lakes etc.). The amount of nitrogen that ends up in the water depends on soil type and crop choice as well as how much of the nitrogen that is retained in the ground and groundwater (the retention rate). The EU requires that, by 2027, all coastal water bodies in Denmark must be in good ecological condition. The main challenge for achieving this is agricultural nitrogen leaching. Another challenge is nitrogen emissions to the groundwater, which can potentially pollute the Danish drinking water.

The current model setup does not capture the dynamics of nitrogen emissions in as much detail as one would perhaps like. There are two reasons for this. First, nitrogen emissions depend on soil type and crop choice. Since we have lumped all types of plant production into a single production sector, we do not capture these differences. This aggregation has been guided by a wish to keep the number of agricultural sectors at a managable level. Second, nitrogen emissions are local in nature: different plots have different retention rates and water bodies can absorb different amounts of nitrogen before it affects the ecological condition of the water. The current Danish regulation reflect this: Farmers in different parts of the country have different requirements in terms of which nitrogen abating measures they must use.[15] These issues are difficult to capture without a spatial model. However, a spatial model would the increase the dimensions of the model beyond what is feasible to integrate into the (already high-dimensional) GreenREFORM model.

We are in the proces of acquiring dataset from Statistics Denmark which contains the geographic distribution of the agricultural sectors in the model. Combining this with geographic information on nitrogen emissions, it is possible to simulate the geographically distributed effects of shocks to the GreenREFORM model. However, using this approach, it would still not be possible to conduct simulations on geographically differentiated regulation or taxes. One way to overcome this could be to construct an independent partial equilibrium model where each agricultural sector is represented by many firms, depending on where the production is located. Results from this could then be aggregated and fed into the GreenREFORM model. It would be possible to construct a first take on such a satellite model with the available data; however, we believe that this is outside the initial scope of the GreenREFORM project.

6.2 Organic soils and agricultural production

A share of the agricultural land is so-called organic soil, which has a higher carbon content. These soils emit more carbon than other soils. At the same time, these organic soil plots are often less productive than other plots (see, e.g., Dubgaard and Ståhl, 2018, p. 229). An important part of Danish agricultural climate policy is therefore to remove organic soils from agricultural production and convert them into wetlands or forests. Our current modeling would not capture the dynamics of such a policy very well. However, we are currently developing a land use module for the GreenREFORM model, which will include dynamics of emissions from organic soils.

6.3 Consumption of agricultural products and a beef tax

A concern for policy makers who want to regulate agricultural GHG's is leakage, i.e. the amount of emissions that appear in some other country in response to a reduction in Danish agricultural emissions and agricultural production. One way to reduce leakage is to put a tax on *consumption* of e.g. meat instead of on the production of meat. It is a challenge to do this in a realistic fashion

[15]The same is true for the Danish regulation of Phosphorus emissions, which is also geographically differentiated.

using the input-output structure of the national accounts. This is because most agricultural outputs are processed by an agricultural processing sector before they are sold to consumers. This means that if we put a tax on beef consumption, it will reduce the demand for all types of agricultural output, not just the cattle sector.

In an ideal world, we would solve this by disaggregating the food processing sector of the Green-REFORM model in the same way as we have disaggregated the agricultural sector. This increases the dimensionality of the model, however. How to do this in a realistic but tractable fashion is an area for future work.

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