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Aligning agricultural production and environmental regulation: An integrated assessment of the Netherlands

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ABSTRACT[1]

Climate change mitigation requires a transition towards a more sustainable system which eventually achieves circularity and climate-neutrality in all sectors, including agriculture. Despite the consensus about this ultimate goal, there is no unique way forward to achieve it. In this regard, usual questions that policy-makers face without having a clear answer relate to the potential deployment of new technology, the possibility of limiting certain economic activities, the externalities that will emanate from their interventions, etc. The aim of this study is to support the policy debate by exploring the potential impacts of several pathways that Dutch agriculture could follow for this transition. This paper presents a methodological approach on how to translate policy objectives into sustainability requirements using a linear programming (LP) model. This model which delivers insights on the optimal size of several agricultural activities has been used for facilitating stakeholder participation in scenario design. By using the Netherlands as a case study, an integrated assessment of several pathways that the Dutch agricultural sector could follow was carried out to contribute to the design of the future development strategy. The outcomes of the multidisciplinary assessment shows that it is feasible to meet long-term (2050) climate and environmental objectives for Dutch agriculture along different pathways. More specifically, limiting the size of the livestock sectors turned out to be necessary to achieve the intended emissions reductions. As a result the land use changed, with an increase in (agro-)forestry being unavoidable when strict climate neutrality would be required.

1. Introduction

It is unquestionable that addressing the challenges that climate change is imposing to modern society results in a 'titanic' task. This is even more so when a more generic set of sustainability objectives are specified in order to move to a circular agriculture, accounting for an efficient and sparse use of resources (e.g. LNV, 2018). When dealing with it, policy-makers should not look at this issue as they have traditionally done with some other economic problems, i.e. designing policy interventions by following a 'top-down' approach with limited participation of economic agents considered in a broad sense. On the contrary, climate change and circularity require societal interventions in a multi-dimensional manner as well as collaborative efforts from various actors in the food system (Hoes et al., 2019). In this context, policy-makers might wonder how to articulate the process of designing public interventions when involving various stakeholders with conflicting interests in the consultation. An answer can be found in economic models which contribute to create a common 'ground' for all stakeholders and bring some structure to the discussion.

The added value that economic models can deliver in order to

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facilitate the communication among different stakeholders such as experts, planners, policy-makers, private sector and civil society organisations was already advocated by Tinbergen (1969) during his speech for the Nobel Prize in Economics.[2] This 'communication' purpose of economic models also relates to the need for a 'multi-level planning', in which a set of models should be somehow connected. This is so to deliver insights that are relevant for the decisions which affect the different stakeholders represented at each level. One step further in this multi-stakeholder decision process is the concept of optimisation, especially relevant if understood à la Tinbergen (1969): 'The true unknowns of the problem are not SC much the quantities of consumption and productive effort to be made and a few more traditional unknowns, but rather the set of institutions which taken as a set are able to approach the welfare economic optimum as well as possible'. Building on Tinbergen's work, which focuses on exploring trade-offs of different macro-economic objectives, this contribution goes beyond the economic realm and interlinks the economic aspects of agriculture with its environmental and ecological components. Drawing attention to the agricultural economic literature, Gouttenoire et al. (2011) provide a literature review and additional discussion on how modelling tools can be used for informing the decision-making process associated with the redesign of livestock farming. Looking at the use of cropland, Li et al. (2020) use an optimisation model to identify sustainable land-use patterns that contributes to achieving a multi-dimensional objective, including: water use efficiency, net economic benefit, land resource allocation equity and greenhouse gas emissions.

The focus of this study is on Dutch agriculture in view of ongoing policy debate, with the Climate Act aiming at a 49% reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 levels.[3] In this context, there is a strong focus on making Dutch agriculture more circular and sustainable since together with Luxembourg the country is leading the ranking of MS categorised according to the severity of the challenge for agricultural sector emissions (Matthews, 2019). One important item in the context of the 'Climate Table for agriculture and land use' was the discussion of the environmental, social, ecological and economic consequences of potential pathways for the Dutch agricultural sector towards 2050.[4,5] Hereby, a key question is about the means that could be used when transiting towards a 'desired' pathway. For example, policy-makers could make use of regulation and buy-out schemes to limit the 'size' of economic activities in order to keep its negative effects below a certain ceiling (Hoste et al., 2019). However, imposing a 'cap' to the overall development of a sector might be controversial in those cases in which stakeholders with different interests are involved. A usual question in such a case would be to identify a fair criterion to distribute the reduction or allocate the ceiling. Should all the activities be reduced in a proportional way? Should the ceiling be imposed on those activities that have a higher contribution in terms of detrimental effects regardless the creation of value added that emanates from them? The attempt of responding to these questions provides a perfect example for revisiting Tinbergen's (1969) views regarding how to articulate multi-level planning and identify the socio-economic optimum.

Nevertheless, an additional challenge that emerged when estimating the optimum size for the livestock/crop production sector was how to incorporate technical change (Martin et al., 2013). In other words, there was a need for 'estimating' future technological advancements and innovations that would be available, as well as their potential costs. In the 'original' Tinbergen's framework (Tinbergen, 1969), technological change was included in the model, allowing this feature for the structure of the economy to adjust over time.[6] Since such an approach was not possible in our case, we proceed to run a set of alternative scenarios to explore potential paths for technological developments.

The aim of this study is to generate a methodological framework of existing agro-economic and agro-environmental models. Using this framework and expert knowledge, modelling exercises were performed in order to design an appropriate strategy for the future development of the Dutch agricultural sector. In order to translate policy objectives into sustainability requirements, a policy optimisation model solved by means linear programming (LP) was developed to identify the 'optimum size' in terms of the contribution to the economic value of the different agriculture activities, i.e. livestock numbers and crop areas, in the Netherlands (excluding horticulture) taking into account a set of overlapping environmental regulations (climate, P, N, ammonia). Secondly, the output of the policy optimisation model (optimised scenarios) was used to 'feed' two well-established partial equilibrium models for the agricultural sector, i.e. the agro-economic model AGMEMOD (Chantreuil et al., 2011) and the agro-environmental model INITIATOR (De Vries et al. 2003; Kros et al., 2015). This second step delivered additional insights in terms of the prospects for the agricultural sector for the period to 2050, including production, prices and emissions.[7] The results of the AGMEMOD model are further linked with an Input-Output (IO) model to understand how changes in prices are distributed through the supply chain.

The contribution of this paper is three-fold. Firstly, from the methodological point of view, the novelty of this paper is the presentation of the modelling system AGMEMOD-INITIATOR, as well as its linkage with the policy optimisation tool.[8] This modelling system combines the strength of AGMEMOD for modelling agricultural production, with the detailed coverage of emissions and environmental indicators that is provided by INITIATOR. Secondly, from an empirical point of view, it presents forward-looking insights on the consequences related to several paths that the agricultural sector in Netherlands could follow. This set of paths is defined in terms of alternative mitigation packages that could be implemented, as well as the interpretation of the environmental goals for the Netherlands.[9] Thirdly, it empirically demonstrates the value of using economic modelling as a 'tool' to create a common understanding among different stakeholders during the policy-making process, providing specific insights in terms of the formulation of agricultural policy that could be of inspiration for the implementation of regulation in other countries that face similar challenges.

The remainder of this paper is structured as follows. Section 2 presents the theoretical discussion on the suitability of using optimisation models in the policy-making process. Section 3 introduces the LP model and the scenarios that were developed to inform the discussion of the

[2] See, also Acocella et al. (2011) which present a 'theory of conflict' that acknowledges the role of strategic actors within the theory of economic policy developed by Tinbergen and Theil.

[3] Further information is available at: https://www.government.nl/topics/climate-change/national-measures.

[4] Further details on the Climate Agreement (*Klimaatakkoord*) for the Netherlands are available at: https://www.klimaatakkoord.nl/.

[5] See, also, Committee on Climate Change (2018) and Riera et al. (2019), for studies in the case of UK and Belgium, as well as for European Commission (2018) for additional background on a climate neutral economy and the role of agriculture.

[6] See, also Don (2004) for further discussion of Tinbergen's work.

[7] See, also, Wicke et al. (2015) who advocate for model collaboration as an approach to better treat uncertainties and improve the information that is available for policy-makers to design policy interventions.

[8] The present paper has set the basis for the methodological approach used within the H2020 project 'SUpport for Policy RElevant Modelling of Agriculture (SUPREMA)'. In the context of SUPREMA, the modelling of several forward-looking scenarios for assessing the implications of changes in demand for meat products, as well as a policy reform were assessed by means of the modelling system developed in this study and further extended to EU level. Further details are available at: https://cordis.europa.eu/project/id/773499.

[9] As elaborated below, some of the scenarios can be considered as 'extreme cases' since they focus on mitigation packages that are not very likely to be fully implemented in the coming years.

'Climate Table' in view of the National Climate Agreement in the Netherlands.[10] Section 4 concentrates on the process of linking the suite of models that were used for this study. Section 5 focuses on the scenario results, while some concluding remarks are provided in Section 6. Apart from that, a technical description of the models that were employed, as well as some additional details on the models used and the extensive description of the scenarios are presented in Annexes A and B respectively.

2. Activating an extensive knowledge base and bringing optimisation into the policy-making process

Designing targeted, effective and cost-efficient policies, and assessing their impacts on the sustainability and viability of the food system is a complex issue.[11] Policy vision documents usually draft some general principles, a direction to go, but are usually vague with respect to the target values of policy objectives, while often a lot remains open about the way how to achieve the policy intentions. This complexity only underscores the need of the provisioning of proper policy research and support services to responsible policy makers as well as the stakeholders. The methodological approach followed in our research is derived from the work of Dani Rodrik on 'economics rules' (Rodrik, 2015, 2018). His approach starts with a reflection on the role of (economic) models. He argues that models rarely get rejected even though the malleability of the social world implies to no single model can do justice to reality everywhere and at all times. His observation holds over disciplines and maybe especially applicable to large scale models, which require large investments and maintenance efforts. Not only he rejects the falsificationist ideal of the philosophy of science, but he transforms his view in a rather positive message on the role models could play and their use. Models are tools to support the analysis of complex issues and key variable interaction patterns (IMF, 2011; Mrakovcic, 2019).[12] They are composed of theoretical knowledge, a set of basic assumptions and expert information, and applied to a specific empirical domain (e.g. Dutch primary agriculture), including the parameterization that is needed for this. Moreover, since he emphasises the partial nature and limitations of models, *the* model or integrated model does not exist. Each model tells its own story and has its own focus and associated strengths and weaknesses. Whereas the need for modelling support to address today's complex policy challenges is obvious, which model or models to use is less obvious. Drawing attention to a different field, Reis (2018) also discusses the role of modelling to forecast macroeconomic variables. An interesting point of his contribution is the fact that after emphasising the size of the challenge that models face in the mentioned discipline, he also advocates for an 'integral' approach in which the different elements that matter for macroeconomics are brought 'together as a core, as opposed to a disparate collection of benchmarks for different subfields of macroeconomics'. In the broader context of sustainable development, Polasky et al. (2019) also claim for an integral approach that combines economics, social and natural sciences to improve our understanding of its social, environmental and economic dimensions. These authors also advocate for using econometric tools and combining economic data with natural sciences as the starting point for producing more robust projections than those based on expert judgement.

Rodrik (2015, 2018) argues that the key challenge for researchers in providing policy support is to first identify carefully the policy questions at hand, the various aspects associated with it, which for our case also includes an assessment of the different disciplines from which knowledge is needed.[13] Having identified the policy question another step is to account for the policy context. Having a clear view on the contextual issues is key for being able to select a proper set of assumptions for the analysis as well as to determine the proper borders of the analysis (delimitation). Subsequently, the researchers' task is to select out of the available models (library) the best set of tools to help answering the specific policy question. Even within a discipline (e.g. economics) this may already require using multiple models, but this holds even more so in the case of cross-disciplinary assessment (UNEP, 2014; Rodrik, 2015, 2018). In this process of selecting and combining of models several questions have to be considered: How many models should we have? What are the relationships between them? When combining them, should we link them by soft or hard linkages? In what detail do we need to represent economic activities, behavioural issues (e.g. which different actors?), biophysical processes (e.g. livestock processes such as enteric fermentation, resulting in emission of the greenhouse gas methane (CH_4) and soil processes such as nitrogen (N) leaching and emission of the greenhouse gas nitrous oxide (N_2O)) and institutional details (e.g. regulatory constraints and policy incentives)? How does the diversity of models actually help with explaining what is going on, both in behavioural as well as physical terms? How to properly account for the different scale levels (e.g. parcel, farm, regional, national, international) and their interaction? This need for modelling cooperation or 'complementarity' has been also emphasised in the context of designing/assessing policies for the green economy by UNEP (2014), which also highlights the fact that 'no perfect model exists'.

In this study we use key insights from Rodrik's approach and extent it to the specific field at hand, which is characterized by a close interaction of behavioural (economic, policy) and physical processes (agronomical, environmental and ecological). The extensions include the application to a cross-disciplinary setting rather than only economics and the emphasis on the importance of the researcher-modelling tool interaction.[14] The research is not only about selecting and combining the proper set of models, but also about exploiting the expert knowledge researchers have in using these models. As such it is acknowledged that proper model use requires often many steps, choices and assumptions, which makes us to explicitly consider the modellers' expertise as a separate asset in the model use analysis. Models are not only used, but often also adjusted and tailored to the specific issues at hand, which requires the use of expert judgement. This holds even more for forward-looking assessments that require estimates about the availability of future technologies (technical uncertainty) and their potential adoption (behavioural uncertainty). As regards the key insights or principles used in our approach these may be summarised as follows:

- Complex policy problems require a combination of tools or models as *the* model or the established toolbox usually does not exists.
- The selection of models should be driven be an examination of the policy or research problem at hand as well as its contextualization.
- The selected models need to be combined in a smart way, while allowing for 'flexible linkages' including soft linkages as well as 'hard' linkages, and direct as well as indirect linkages.

[10] Available at: https://www.klimaatakkoord.nl/binaries/klimaatakkoord/documenten/publicaties/2019/06/28/klimaatakkoord/klimaatakkoord.pdf.

[11] See Jurgilevich et al. (2016) for some discussion towards circularity within the food system. See, OECD (2020) for a description of the key challenges that food policy needs to address and the urgency for a new approach with forward-looking policy packages that globally address the food systems.

[12] Henriksen (2013) defines the role of economic models as 'devices used by actors to induce policy change'. Moreover, Heimberger et al. (2020) argue that 'models are potential carriers for certain political convictions and, hence, allow actors drawing on such models to exert power in political decision-making under certain conditions'.

[13] Ryan and Garrett (2003) discuss the interaction between social sciences research output, policy impacts and the different methodologies for their assessment in the agricultural field.

[14] See, also Exposito et al. (2020) for further discussion of model interaction in the context of hydro-economic modelling.

– The combined model (or thus defined 'toolbox') use needs to be guided by the expertise of the researchers/modellers, which play a key role in defining the proper set of (consistent) assumptions and to make the model-adjustments that maybe needed.
– Interpreting, assessing the results from the modelling effort including multiple models in a way that provides a reliable and balanced presentation of the impacts, addressing policy maker and stakeholder needs also requires the contribution of the researchers of all involved disciplines.

An additional extension or innovation in our approach relative to what is discussed by Rodrik is that special attention is paid to the 'translation' of policy visions into a framework of requirements that can be used as an intermediate or hybrid tool to steer the communication between models from different disciplines. Thereby, guaranteeing coherence and consistency. This intermediary tool helps to specify the policies into a specific set of operational requirements or criteria to 'feed' into the models. Moreover, the model also provides a representation of the environmental boundaries, i.e. the limits in terms of emissions, livestock units, etc. that defines the operation space based on policy objectives. Having the advantage that it can support policy makers in the design and fine tuning of scenarios or policy implementation modalities. Developing such an intermediary tool turned out to be a valuable asset, especially in the context where the policy solutions are complex and the stakeholder interests were divergent. Actually, this approach turned out to be very helpful to support a constructive policy building process, where stakeholders were brought into accept a 'give and take' bargaining approach, rather than in a polarized deadlock situation of opposing interests and wishes. For this we developed a policy optimisation model, distinguishing the policy side (e.g. environmental regulations, including nutrient-specific emission ceilings) as well as the set of relevant economic activities, and their contributions to various policy objectives (see further details in Section 4).

3. Defining the scenarios by means of a policy optimisation model

3.1. Rationale

The current, i.e. 2019, policy debate on future pathways for the agricultural sector in the Netherlands was requesting forward-looking input to assess the potential impacts of a choice of mitigation strategies. A well-stablished approach to satisfy this type of request is through the simulation of a baseline and a set of alternative scenarios by using a quantitative model. When looking for such a tool, the combination of two partial equilibrium models that represent different aspects of the Dutch agricultural sector seemed to be the most suitable approach. In this case the AGMEMOD (Van Leeuwen et al., 2008; Annex A.1) and INITIATOR (De Vries et al., 2003; Annex A.2) models were used, both operated by Wageningen University and Research.[15]

After selecting the models, the design of the scenarios was not exempt of challenges. In view of the uncertainty around the future and the different (and even conflicting) interests, several rounds of discussions with key stakeholders took place with the purpose of agreeing on the scenarios that would be simulated. In short, the following three elements shaped each scenario: (i) two environmental boundaries, defining the operation space via 'Intended' and 'Stricter' environmental emissions policies (Table 1; Table B.1),[16,17] (ii) the focus of agriculture in 2050, being agriculture more productivity driven or nature inclusive; and (iii) the mitigation package, i.e. a set of measures that could be implemented in order to reduce environmental emissions from agriculture.

Table 1
Environmental boundaries for 2050.

Topic	Intended environmental goals	Stricter environmental goals
Greenhouse gas emissions	Meet Paris Agreement, climate neutrality of land use and agriculture at EU level	Meet Paris Agreement, climate neutrality of agriculture and land use within the Netherlands
Ammonia emission	NEC ceiling and PAN[a] incl. nature recovery measures	Habitats Directive (critical deposition value is achieved for 95%)
Nitrogen and phosphorus leaching	Minimum implementation of the Water Framework Directive and Nitrates Directive. Comply with manure application regulations (no over fertilization).	Stricter interpretation of the Water Framework Directive and Nitrates Directive. Comply with manure application regulations (no over fertilization).
Circularity and area-based agriculture	Land based dairy farming, feed materials produced in Europe and manure application in Europe	Land based dairy farming, feed materials produced in the North-western Europe and manure application in North-western Europe

[a] Programmatic Approach to Nitrogen.

In this context, researchers could think in terms of the following problem to determine the size: 'If the environmental space is *X*, the character of agriculture is *Y* (e.g. nature inclusive), and *Z* is the mitigation package implemented, the maximum number of activities (e.g. livestock units and area of crops) that fits all is *W*. Hereby, the concept of optimisation à la Tinbergen (1969) becomes extremely relevant since it can deliver insights on the 'optimal' composition of the agricultural sector, i.e. the objective values that will drive the subsequent analysis. Therefore, the policy optimisation model that is presented here is used to 'draw' the scenarios that will be used as model input for: (i) AGMEMOD, to determine the economic impacts on/through the agricultural sector; and (ii) INITIATOR, to translate the effect of changes in agricultural production into environmental effects. Moreover, to provide additional insights on how economic impacts are distributed through the supply chain of agricultural products an Input-Output (IO) model (Annex A.3) was used to further split the price effects simulated by AGMEMOD.

Before discussing further the measures that are included in each scenario, Table 1 focuses on the environmental use of the space in the different scenarios, while further explanation of the agricultural orientation and the technical measures is provided in Sections 3.2. and 3.3.

3.2. Future orientation of the Dutch Agriculture

The discussion about the orientation of the Dutch agriculture in the coming years can be condensed into a single question. Is the Netherlands committed to further develop a productivity driven agriculture with technical mitigation options? In other words, this is the continuation of the current production-driven method, aimed at optimising the

[15] The standard version of the AGMEMOD model that is used for preparing mid-term market outlooks runs to 2030. However, for this particular study, a model version of AGMEMOD that runs to 2050 was developed. GDP growth and population assumptions for the period 2030–2050 rely on the Shared Socio-Economic Pathways that have been extensively used in climate studies, being the baseline for this study consistent with the SSP2 'middle of the road' scenario.

[16] The goals are defined in terms of ceilings for: (i) nitrogen (N) excretion; (ii) phosphorus (P) excretion; (iii) emission ceiling for methane (CH_4) and nitrous oxide (N_2O); (iv) total CO_2 emissions (including CH_4 and N_2O); (v) ammonia (NH_3) emission ceiling; (vi) nitrogen (N) load to water; and (vii) phosphorus (P) load to water. For each goal two variants, 'Intended' and 'Stricter', have been assumed.

[17] See Annex for further details on the assumptions for the use of the environmental space.

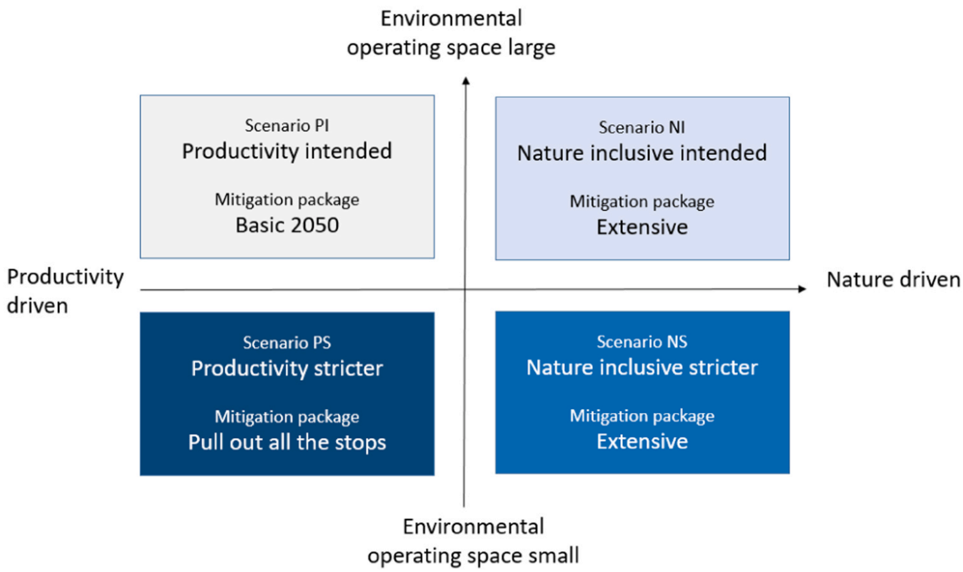

Fig. 1. Overview of the scenarios.

conditions for high productivity per animal and per hectare, i.e. a strong input-driven agriculture. Although it accepts 'corrections' to lower the environmental pressure (e.g. by applying innovative technical solutions) it in essence adheres to the dominant productivist paradigm as described by Thompson (2017). Alternatively, one could ask whether a 'nature inclusive' direction with lower inputs from livestock farming and arable land use is the most suitable path to follow in the upcoming years. If that is the case, the system should move towards a development path that is more based on the use of natural processes, with the required inputs being lower for livestock farming and arable land use. This approach will result in lower productivity per animal and per hectare. In her vision for Dutch agriculture, Minister of Agriculture Nature and Food Quality Schouten makes a choice for a circular agriculture emphasising the need for a proper ecological embeddedness of agriculture, which links to a more nature inclusive direction (LNV, 2018). Keeping in mind these two questions, this study explores the following two variants that are linked to the mitigation packages as explained in Section 3.3: (i) 'productivity driven' agricultural system; and (ii) 'nature inclusive' agricultural system (see also Fig. 1).

3.3. Scenario development: technical measures

In the context of this study, depending on the adopted perspective with regard to the orientation of agriculture, a set of mitigation measures was formulated in terms of reduction of greenhouse gas emission, ammonia emission, and N and P leaching and run-off. In the case of a 'productivity driven' agriculture two types of mitigation packages were included depending on the environmental space, i.e. a basic and a more 'drastic' mitigation package; while an additional package was assumed for a more 'nature inclusive' agricultural system. In particular, the following three types of mitigation packages were formulated:

- 'Basic 2050': a package of mitigation measures suitable for productivity driven agriculture that are currently socially accepted, e.g. regarding animal welfare, or landscape, and not very costly. Assumptions on autonomous trends in productivity increases and their effects on emissions were included in this package. This package was applied in the productivity driven scenario with 'current' environmental goals.
- 'Pull out all the stops': this is a package that incorporates the most effective mitigation measures that are suitable for productivity driven agriculture, with no limitations regarding social acceptability or costs. These measures have a higher productivity level than those included in the 'basic' package. This package was adopted for the productivity driven scenario with 'Stricter' environmental goals.
- 'Extensive': a package of mitigation measures suitable for nature inclusive agriculture, i.e. measures that are not conflicting with the principles of 'nature inclusive' agriculture (see, above). This includes a lower productivity increase compared to other packages, a lower use of external inputs, and access to pasture or an outdoor area for livestock. The same package was applied in the scenario with 'current' and 'strict' environmental targets.

In a second step, for each measure an emission reduction fraction for greenhouse gas emissions, ammonia, and N and P leaching and run-off was estimated based on literature (c.f. Vellinga et al., 2018; Groenestein et al., 2019; Groenendijk et al., 2017), expert consultation (Lesschen et al., 2020), or calculated with the Global Livestock Environmental Assessment Model (GLEAM; MacLeod et al., 2017; Annex A.4). Emission reduction fractions per measure were then aggregated to a total emission reduction fraction per mitigation package. In first instance, an optimal effectiveness of the mitigation technique and a full implementation of the technique was assumed. In practice, a lower effectiveness and implementation rate can be expected.

The combination of the elements described in Sections 3.1–3.3 results in four different scenarios that are presented in Fig. 1.

Further details on the scenarios and the assumptions that were adopted in each case are presented in Annex B (Tables B.1 and B.2.).[18]

3.4. Policy optimisation tool

As suggested in the general approach for modelling presented in Tinbergen (1969), we proceed to describe the conditions that the expected socio-economic optimum for the Dutch agricultural sector should fulfil (Table 2). These conditions are represented within a MS Excel-based model that is solved by means of linear programming and

[18] When modelling the baseline and the scenarios in AGMEMOD, all Member States were included in the model run. However, due to the fact that the focus of the study was the Dutch agriculture, the mitigation packages (and any other scenario-specific elements, e.g. yield developments for certain crops, constraints regarding livestock units, etc.) were applied only in the Dutch case. In other words, identical assumptions for all the other Member States were assumed across the different scenarios.

Table 2
General conditions.

Topic	Conditions
P excretion	• The amount of P that could be produced as a by-product of livestock farming activities must not exceed 172.9 million kg P_2O_5.
N excretion	• The volume of N that could be produced as a by-product of livestock farming related to the diet composition must not exceed 504.4 million kg N.
Greenhouse gas (CH_4 and N_2O) emissions	• The volume of GHG emissions related to agricultural activities should be kept below a certain ceiling; depending on the cases this ceiling is set as 11 or 1.9 Mton CO_2 eq.
Animal production rights and sectoral linkages	• The number of fattening pigs and sows in the Netherlands should be in compliance with the available number of pig rights (8.7 million rights). A fattening pig requires one right; one sow is equivalent to 2.7 rights. • The number of broilers and laying hens in the Netherlands should be in compliance with the available number of poultry rights (67.2 million rights). A laying hen requires about one right; while one broiler is equivalent to 0.63 rights. • Substitution between animal types should be based on P excretion per animal. • Changes in the number of fattening pigs should be linked to changes in the number of sows. • Changes in the number of broilers should be linked to changes in the number of laying hens. • Changes in the number of dairy cows should be linked to changes in the number of other grazing animals.
Land use	• Total land used must not exceed available area (area available is scenario dependent for certain activities). • There is some CO_2 sequestration related to arable farming, maize land, biomass production and grassland. There are also CO_2 emissions related to these activities. • Peatland and forestry areas cannot fall below a certain level (this is scenario dependent). • Conversion between areas is allowed based on fixed ratios. • Depending on the scenarios, dairy cows should be fed according to different ration (minimum grass and maize intake requirements). Therefore, the dairy herd should be linked to grassland and maize land to ensure that the required feed components are locally produced. • Might be the case that minimum requirements with regard to arable land, forestry and nature area need to be considered.
NH_3 emission	• The amount of NH_3 that could be emitted from livestock farming, grassland and arable farming should be kept below the ceiling stablished by regulation.
Proportionality	• To avoid 'aggressive' substitution between livestock numbers, i.e. one activity is crowded-out from the model as a result of an explosive increase in another one, some proportionality between the size of the dairy herd and livestock numbers of other livestock activities should be assumed.

constitutes the policy optimisation tool.[19]

Combining the abovementioned conditions with a set of institutions that comprises: (i) arable farming, excluding maize production; (ii) maize land; (iii) grassland; (iv) biomass; (v) forestry and nature; (vi) peat grazing land; (vii) dairy cattle; (viii) fattening-pigs; (ix) sows; (x) broilers; (xi) laying hens; and (xii) other (grazing) animals; the 'skeleton' of the intended policy optimisation model is derived and can be mathematically solved by means of linear programming.[20] Further details on the constraints are provided in Table 3.

An additional feature of the proposed model is the inclusion of several goal functions to weight the activities, and therefore, take into account the economic value that is generated by each activity unit (area of land or livestock unit). More specifically, four options are included as described as follows. Firstly, all activities are treated linearly, i.e. one area of land is treated equally to a livestock head since activities are assigned initial weights equals to 1. Two additional goal functions based on gross margins are also included, being one of them based on AGMEMOD data and the other one on national statistical sources. Finally, the model also allows for a non-linear goal function that brings economic value into the model.[22]

In short, the methodological approach that was used for this study relies on a modelling system that involves some exchange of information across several models. Both AGMEMOD and INITIATOR have a recognised reputation in their own field (European Commission, 2019; De Vries and Kros, 2011), being the cooperation between them particularly suitable in view of the complementarity of the variables that they include.[23] As presented below, the optimisation model is on the one hand a simple representation of the environmental regulatory constraints that are in the Netherlands, while on the other hand it is a representation of the activities and their associated emissions. The emission and production information included in the optimisation model is perfectly aligned with the production and emission data/-coefficients/output of both AGMEMOD and INITIATOR. The outcome of these linkages are the results presented in Section 5, which go beyond the 'standard' AGMEMOD production results.

4. Linking the policy optimisation model with existing large scale models

The process of linking models is full of challenges, and therefore, any attempt of 'connecting' two or more modelling tools should start with model developers asking themselves about the 'real' meaning of 'model linkage' within their exercise.[24]This question could lead to an extensive debate that modellers should conclude with a clear definition of the flow of information and the feedback loops among the different models that they want to consider. The existence of the mentioned exchange of information ensures that running a sequence of models becomes a 'true' system of analysis. An important contribution in this regard is given by Wicke et al. (2015) who emphasise the notion of 'model collaboration', being its outcome a better treatment of uncertainties and an improvement of the information that is delivered to policy-makers during the decision process. Within 'model collaboration', the authors distinguish among: (i) alignment and harmonization of models; (ii) comparison of models; and (iii) integration of models. These different categories are not mutually exclusive and quite often model collaboration involves more than one of these items, e.g. an initial model comparison could be needed to identify the input data or the assumptions that needs to be

[19] Additional details on the policy optimisation tool are available from the authors upon request.

[20] See, Shapiro (1979) for a full description of the principles of mathematical linear programming.

[22] See, Howitt (1995) for reference.

[23] An usual input from the INITIATOR model is agricultural production, which needs to be calculated exogenously. When it comes to the simulation of agricultural production at EU Member State level, the AGMEMOD model is a key player in the field. In the case of the modelling of environmental indicators, which are not represented within AGMEMOD, INITIATOR offers a rich set of model outputs to assess this dimension.

[24] This section partly builds on the outcomes of the internal discussion among different modelling teams that took place in the context of SUPREMA. The project deliverables are available at the SUPREMA website.

Table 3
Description of key constraints.[21][1]

Broad topic	Description of the constraint	Applicable to activity	Active in scenario[a]
P	The amount of P_2O_5 that could be produced as a by-product of dairy farming activities must not exceed 84.9 million kg P_2O_5.	Dairy farming	BA, PI, NI, PS, NS
P	The amount of P_5 that could be produced as a by-product of pig farming activities must not exceed 39.7 million kg P_2O_5.	Fattening-pig farming, sow farming	BA, PI, NI, PS, NS
P	The volume of P_2O_5 that could be produced as a by-product of poultry farming activities must not exceed 27.4 million Kg P_2O_5.	Broiler farming, laying-hen farming	BA, PI, NI, PS, NS
P	The volume of P_2O_5 that could be produced as a by-product of other (grazing) animals farming activities must not exceed 20.9 million kg P_2O_5.	Other (grazing) animal farming	BA, PI, NI, PS, NS
GHG	The volume of GHG emissions (Mton CO_2-eq) related to agricultural activities should be kept below the target (11 Mton CO_2), including CH_4 and NO_2.	Arable farming, maize production, biomass production, grassland, forestry and nature, dairy farming, fattening-pig farming, sow farming, broiler farming, laying-hen farming, other (grazing) animal farming	PI, NI, PS, NS
PR&L	The number of fattening pigs and sows in the Netherlands should be in compliance with the available number of pig rights (8.7 million rights).	Fattening-pig farming, sow farming	BA, PI, NI, PS, NS
PR&L	A ‘fixed’ ratio between the number of sows and the number of fattening pigs is assumed. For the baseline, (-)0.165 has been assumed as the mentioned ratio.	Fattening-pig farming, sows farming	BA, PI, NI, PS, NS
PR&L	The number of broilers and laying hens in the Netherlands should be in compliance with the available number of poultry rights (67.2 million rights).	Broiler farming, laying-hen farming	BA, PI, NI, PS, NS
PR&L	A ‘fixed’ ratio between the number of broilers and the number of laying hens is assumed. For the baseline, (-)0.726 has been assumed as the mentioned ratio.	Broilers farming, laying-hen farming	BA, PI, NI, PS, NS
PR&L	A ‘fixed’ ratio between the number of other grazing animals and the dairy herd is assumed. This ratio is around (-)1.888 in the baseline case.	Dairy farming, other grazing animal farming	BA, PI, NI, PS, NS
LU	In the baseline case, total area excluding peatland taken out of production will not exceed 1.548 million ha.	Arable arming, maize production, biomass production, grassland, forestry and nature	BA, PI, NI, PS, NS
LU	In the baseline case, peatland area cannot fall below 150 thousand ha.	Peatland	BA, PI, NI, PS, NS
LU	In the baseline case, a certain amount of feed for dairy cows should be locally produced in the Netherlands. It is assumed that the 0.513 ha of grassland are needed to feed a dairy cow.	Dairy farming, other grazing animal farming	PI, NI, PS, NS
LU	In the baseline case, a certain amount of feed for dairy cows should be locally produced in the Netherlands. It is assumed that the 0.111 ha of maize are needed to feed a dairy cow.	Dairy farming, other grazing animal farming	PI, NI, PS, NS
N	The total amount of N in livestock manure must not exceed 504.4 million kg.	Dairy farming, fattening-pig farming, sow farming, broiler farming, laying-hen farming, other (grazing) animal farming	BA, PI, NI, PS, NS
NH_3	The volume of ammonia that could result from livestock farming, grassland and arable farming should be kept below the ceiling stablished by regulation (if any).	Arable farming, grassland, dairy farming, fattening-pig farming, sow farming, broiler farming, laying-hen farming, other (grazing) animal farming	PI, NI, PS, NS
PO	A ‘fixed’ ratio between the size of the dairy herd and the size of the pig herd is assumed. This ratio is around (-)0.2684 for the baseline.	Dairy farming, fattening-pig farming	PI, NI, PS, NS
PO	A ‘fixed’ ratio between the size of the dairy herd and the size of the poultry herd is assumed. This ratio is equal to (-)0.0414 in the baseline case.	Dairy farming, laying-hen farming	PI, NI, PS, NS

[a] BA = Baseline; PI = ‘Productivity intended’ scenario; NI = ‘ Nature inclusive intended’ scenario; PS = ‘Productivity stricter’ scenario; NS = ‘Nature inclusive stricter’ scenario. The technical coefficients of the model are scenario dependent since they are given by the mitigation package that is considered in each case.

aligned when linking two models.[25] With regard to the flow of information among tools, it is very important to establish a mechanism that permits to translate the assumptions or the outputs of a model into elements which can be used to ‘feed’ another modelling tool. In other words, the process of linking models involves some standardisation of assumptions and data between models. This is so since quite often models have different years of reference, different sources of data that result in differences in levels for the same variable, etc. Alternatively, two models could be also linked by implementing a certain mechanism present in one model into another one. Without having to deal with the standardisation process, this exercise naturally brings ‘closer’ the results of both models since the ‘logic’ of the system behind is the same one. Once the ‘relationships’ among models are defined, an important item becomes the assessment/measurement of the ‘thinness’ of those linkages. Although there is no standard typology of model linkages, modellers could distinguish between ‘hard’ and ‘soft’ linkages.[26] The most

[25] See, Creutzig et al. (2012) for further discussion on the importance of design of integrated model toolbox, and also, van Meijl et al. (2018) for an illustration of model inter-comparisons in the context of climate change and mitigation on agriculture.

[26] In the context of Wicke et al. (2015) soft linkages are defined in those cases in which ‘models are connected exogenously by transferring the outcomes of scenario model runs from one component or model to another’; while hard linkages are those in which ‘models exchange information and solve iteratively, so the solutions are internally consistent between models’. See, also, Perez-Dominguez et al. (2008) for alternative definitions and further discussion on soft and hard linkages.

Table 4
Categorising model linkages.

Linkage	Hard	Soft
Direct	Standard hard model linkage, i.e. the components of the different models are related in a structured manner (A)	It is a soft linkage, but other model information is used more or less as it comes from the model (B)
Indirect	Model linkage does not exist/not relevant. (X)	It is a soft linkage. It is indirect because an expert uses a model to make a model-informed guess about information to input into (another model) (C)

first tier in which economic and emission models deliver their output to the policy optimisation tool. This output is used to calculate the technical coefficients of the model and for its calibration. The second tier reflects how the solution of the policy optimisation tool, i.e. optimum livestock units and area is translated into input for AGMEMOD, which is 'hardly' linked to INITIATOR. More specifically, the production volumes that are calculated by AGMEMOD are translated into emissions by the INITIATOR model. Additional 'soft' linkages are established with the IO tool, which receives information from AGMEMOD on changes in prices and input from the policy optimisation model with regard to changes in production volume with respect to the baseline values. It should be noted that the latter model linkage is only active in the case of the scenarios.

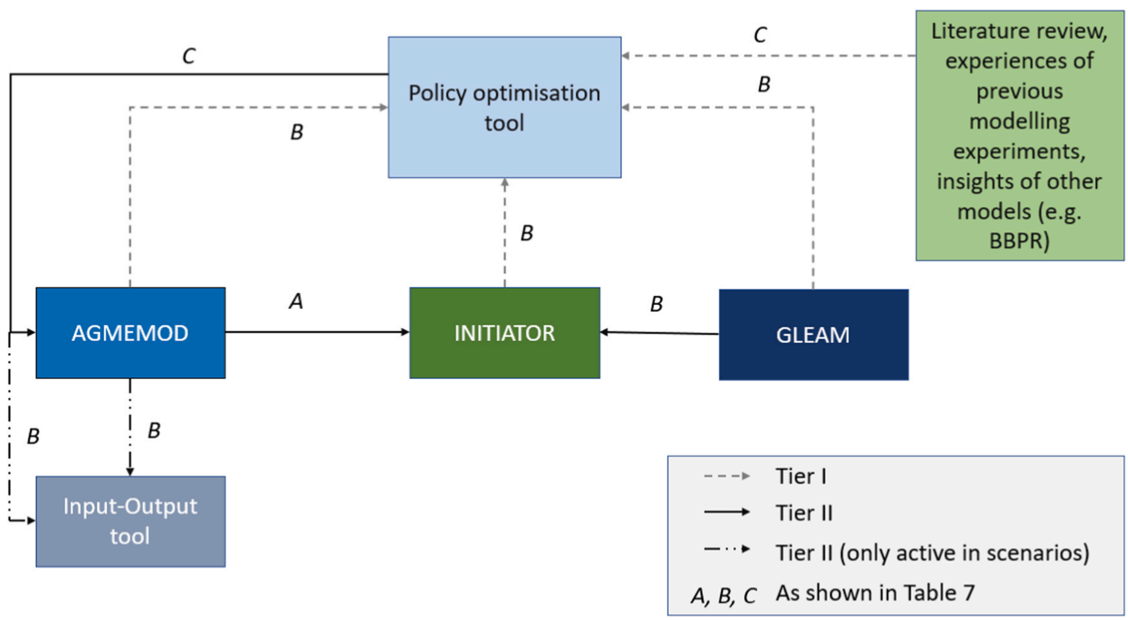

Fig. 2. Integrated model toolbox.

explicit form of models linkage is 'hard' linkages, which in the current exercise have been unidirectional, but could also be multi-directional (iterative simulation), depending on the complexity of the causality that need to be considered (see also the reference to iterative model linkage in Section 6 below). More specifically, 'soft' linkages can be assumed in those cases in which the relation between the models is unidirectional or/and the information exchange is not done in a structured and systemic manner. 'Soft' linkages have also been assumed in those cases in which expert judgement of the output of a model is done in order to derive input for another model. Another dimension that modellers should assess when categorising the linkages is whether the relationship between the model components that are linked is 'direct' or 'indirect', being 'direct' in those cases in which the outcome of a model is used in another one more or less as it is obtained from the first model. Based on this discussion, we propose the typology shown in Table 4.[27]

Focusing on the modelling exercise of this contribution, Fig. 2 provides an overview of the different tools that have been brought together. As shown below, the outcome of the linkages is a two-tier system, with a

A key remark of this exercise is that there is higher value in linking two models that individually provide a detailed modelling of aspects which are related compared to the development of a larger model with a lower level of detail. In other words, it is more valuable to link AGMEMOD (which provides a very good modelling of agriculture production) to INITIATOR (which can calculate the emissions associated in an accurate way) than adding a 'stylised' representation of emissions within the AGMEMOD model.

5. Results and discussion

5.1. Scenario results

In the context of this study a broad range of quantitative outcomes resulting from the different modelling tools (AGMEMOD, INITIATOR, LP, BBPR, input-output model, etc.) was generated. In order to preserve space, this section only reports a limited selection of variables.

Focusing on the AGMEMOD simulation, Fig. 3 reports on the estimated production volumes for the set of scenarios described in Fig. 1. It should be noted that each scenario considers different reductions in livestock units as calculated by the policy optimisation model. Investments and cost elements have not been directly included in the AGMEMOD modelling. Production in 2050 is estimated to be below current levels in most of the cases. The only exception is the 'Productivity stricter' scenario, in which crop production remain around the current levels. This is driven by the positive prospects for revenues of

[21] To preserve space not all the constraints that are included in the model are reported in this table. The model includes additional constraints to reflect issues that were raised during the policy debate although might not be active in the scenarios since they are not binding.

[27] See, also, Perez-Dominguez et al. (2008) for further discussion on model linkages, as well as an alternative typology to categorise them. See, also the contribution by Van Tongeren et al. (2001) regarding the fact that 'no model can serve all purposes'.

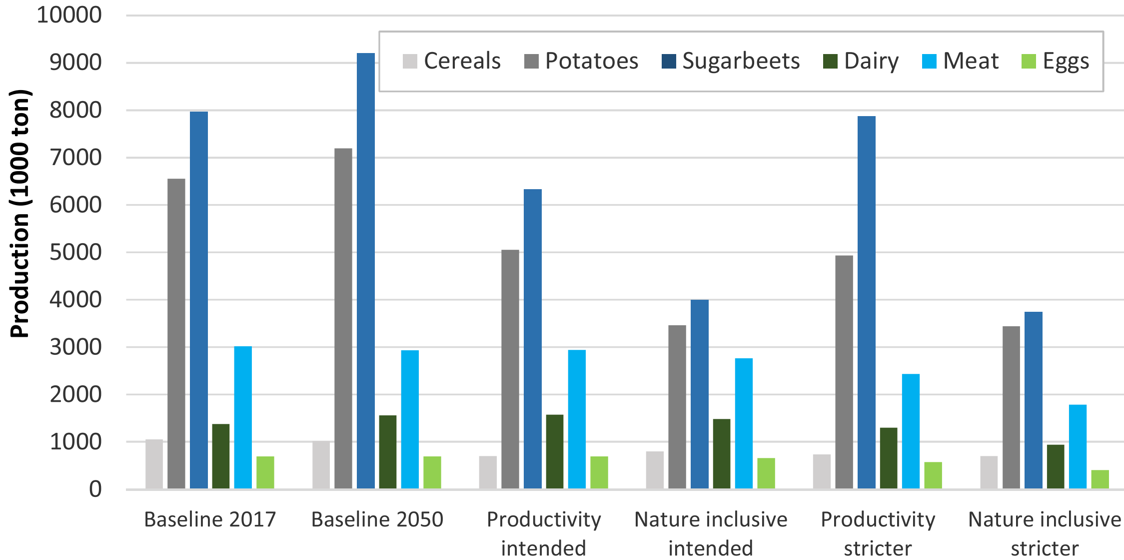

Fig. 3. Production volumes for selected commodities.

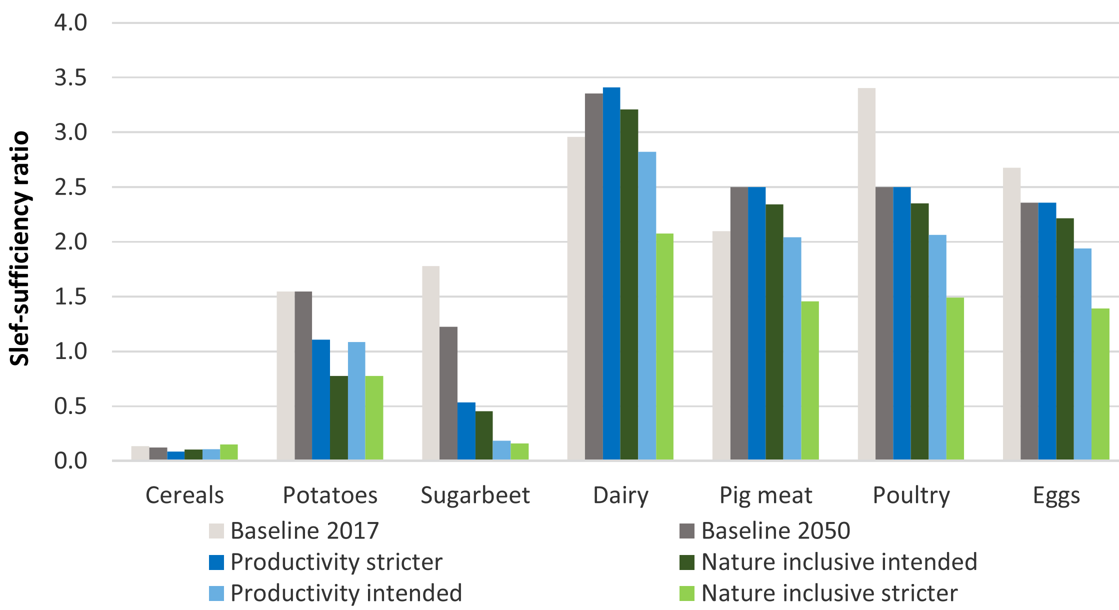

Fig. 4. Self-sufficiency ratios for selected commodities.

key crops such as potatoes and sugar beets. Regarding the livestock sectors, milk production increases by 13% in the baseline scenario compared to 2017. In all scenarios it is assumed that the milk yield per dairy cow is increasing overtime, making possible an increase in production in a context of declining livestock units. In the 'Productivity intended' scenario, animal production volumes are similar to the ones reported for the baseline in 2050. The figure reports an 'aggregate' meat category since the initial assumption is that the different livestock sectors must contribute proportionally to the emission reduction. According to the 'Nature inclusive stricter' scenario livestock production is estimated to decrease by 40–50%.

In terms of the trading position of the Netherlands (Fig. 4), substantial changes can be expected in view of a stable consumption and a declining production. Overall, it is expected that the Netherlands will reduce its exporting capacity, or even switch from an exporting to an importing 'role'. As shown in Fig. 4, the Netherlands remains as an importing country for cereals, with a self-sufficiency level of the order of 10–15%. Regarding sugar beet, the self-sufficiency rate in all scenarios falls below 100%, becoming the Netherlands a net importer for this product. A similar situation could be expected for potatoes in the case of the two 'Nature inclusive' scenarios. Moreover, the Netherlands is expected to remain an exporter of dairy products and eggs in all scenarios. For example, in the Productivity Intended scenario, the Netherlands has an estimated self-sufficiency ratio of approximately 3.4 for dairy and 2.4 for eggs (Fig. 4). The picture is more mixed in terms of different meat products. While the self-sufficiency ratio is estimated to increase in the case of pork, it is expected to decrease in the case of poultry when looking at the baseline case. This reflects a consumer's preference shift with less read meat and more white meat being part of the diet in 2050. With eggs, just as with dairy, the Netherlands maintains a self-sufficiency ratio that is in any case around 1.4 or higher. The Netherlands therefore remains an egg exporter in all scenarios.

Although not reported in this article due to a limitation of space, a full range of market indicators were generated during the simulation. Therefore, key outcomes in terms of 'farm-gate' prices and consumption are briefly discussed as follows. More specifically, the simulation

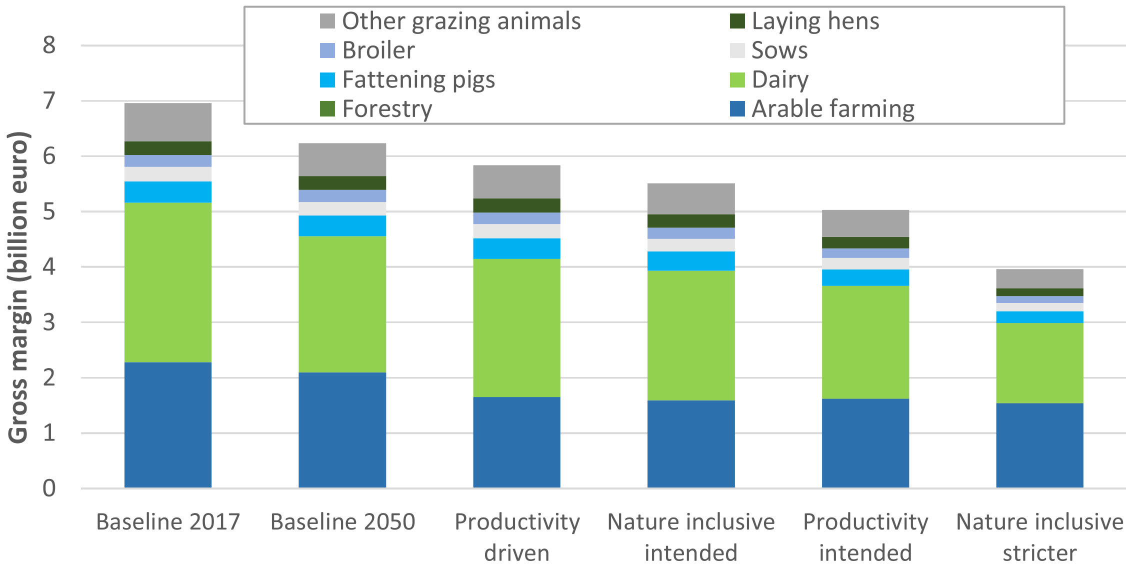

Fig. 5. Gross margins by agricultural activity.

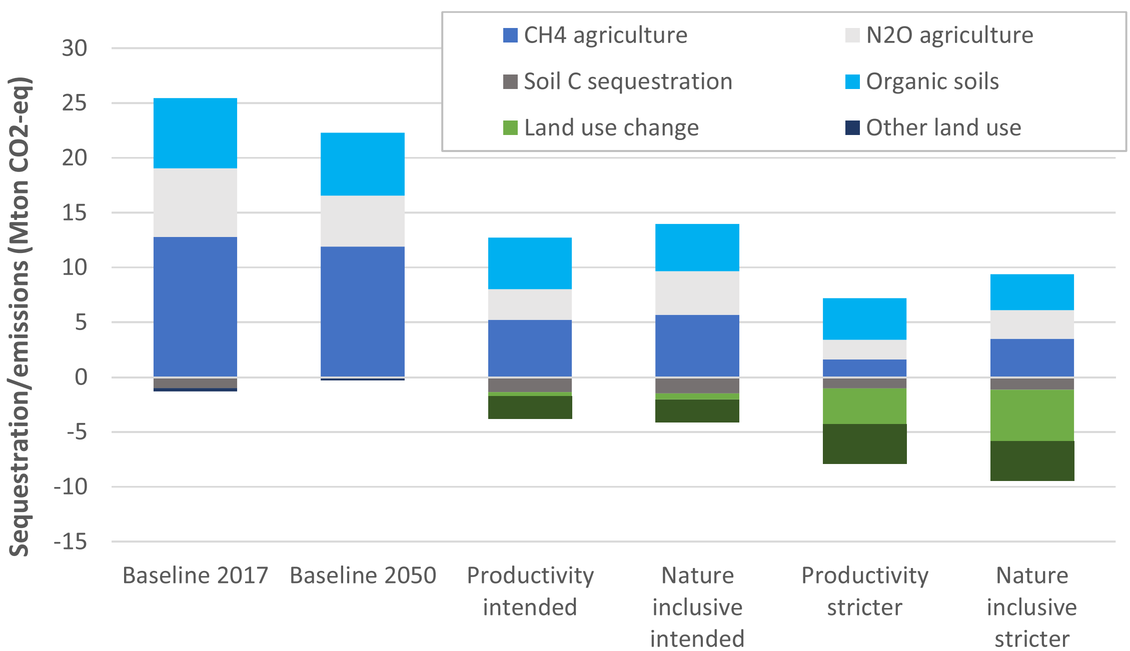

Fig. 6. Estimated emissions from Dutch agriculture. Note: Emissions are presented as positive numbers while sequestration is presented as negative ones.

suggests fairly limited adjustments in the prices of agricultural products in most cases, with price increases being less than 10% for all scenarios except the one in which a strict national target is adopted. These price developments will have a very limited impact on human consumption, since the transmission between farm-gate prices to retail prices is also 'weak' and the relative share of agriculture products over total consumer spending is small.

Another important indicator to look at is the evolution of the 'gross margin' of the different agricultural activities, as calculated by the policy optimisation model (Fig. 5). A general remark with regard to this item is that the impact on gross margins is probably underestimated since the net costs associated to the different measures have not been fully captured due the high uncertainty around their quantification.[28] When looking at the agricultural sector as a whole, the baseline 2050 case suggests that the gross margin would be slightly above 6 billion euros. In the case of the 'Productivity driven' scenario, the total gross margin of the sector as a whole is estimated to decrease by around 1.2 billion euros (−10%), reflecting the 'income' loss that farmers due to the constraints on production and the implementation of emission-saving innovations. Moreover, the simulation suggests that in the case of the

[28] In this context, 'Gross margin' is essentially revenues minus the most important and 'predictable' costs (e.g. feed cost in case of livestock production), but excluding detailed cost items (e.g. veterinary services, energy costs) related to the characterisation of the future production systems (2050).

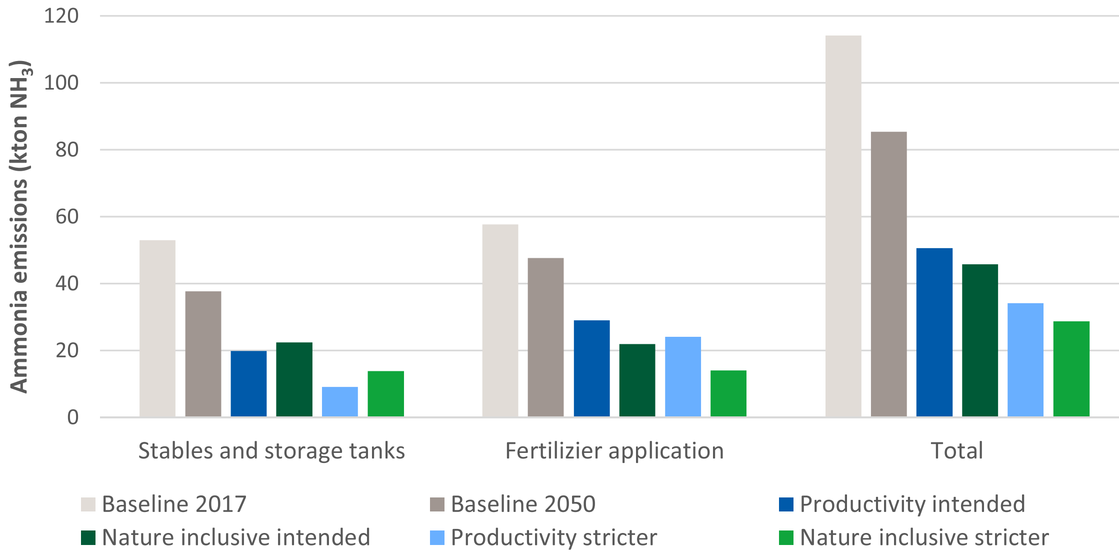

Fig. 7. National NH_3 emissions from stables and manure storages, manure application fertilizer use and grazing, and the total emissions (ktonnes NH_3). Note: Total fluxes from stables and manure storage tanks includes grazing emissions while fertilizer application includes fertilizer and crop ripening emissions.

'Nature driven' scenario that includes an stricter national target the gross margin of the sector could be more than 2.26 billion euros (20%) lower than in the 2050 baseline case. When looking at the sectoral composition in the case of the later scenario, about 1.5 billion of the gross margin that is lost comes from the dairy sector, which has the largest share in the calculated total gross margin and is also the most affected one.

Before moving onto the description of the environmental results some comments regarding the outcomes of the IO modelling are due. In terms of the changes in added value and employment, the analysis includes both the impact in the primary sector and the impact on the sectors related to the agricultural sector. In the most extreme scenario, 'Nature driven' including an ambitious national target, both the added value and the employment could fall by 35–40%. Compared with the current situation, the mentioned decline represents a loss of around 7 billion euros in terms of value added for the Dutch economy as a whole. This is equivalent to a loss of around 1 billion euros for the primary agricultural sector. Nevertheless, these estimates should be carefully considered since the present value added indicator does not provide any insight regarding the 'additional' social costs that are likely to emanate in the case of the various scenarios, In other words, it can be expected that the social costs (recovery of investments to improve the quality of the air, water, soil, etc.) will be lower in the 'nature inclusive' scenarios compared to the 'productivity driven' scenarios. Thus, for a more comprehensive 'picture' it would be necessary to combine the contribution of the agricultural sector to the economy in the form of added value and the social costs (as an economic measure of 'pass-through' effects).

In terms of greenhouse gas emissions, Fig. 6 reports the simulated results for the different scenarios as calculated by the INITIATOR model. For the sake of completeness, this figure also includes land use-related emissions, including the entire greenhouse gas balance for agriculture and land use.

Fig. 6 shows a decrease in the emissions of CH_4 and N_2O together of about 16 Mton CO_2 eq for the Baseline 2050. This outcome is due to the autonomous technological progress that increases productivity, i.e. this allows for a reduction in the number of cows compared to the present situation even if methane emissions per cow increase. Focusing only on N_2O emission, the estimated decrease is the result of lower fertilization since there is no longer any over-fertilization of animal manure (which

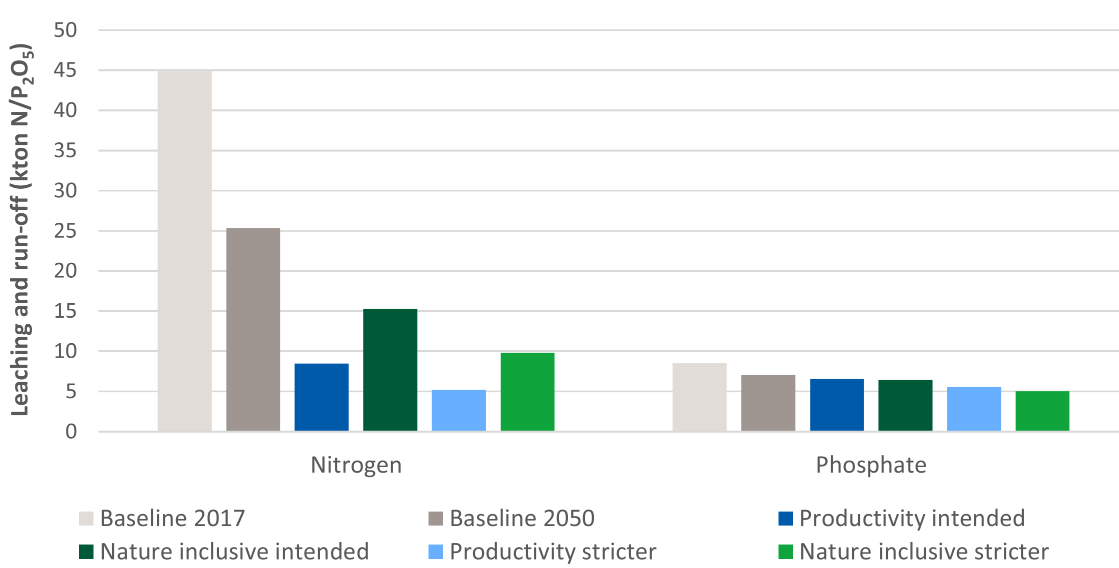

Fig. 8. Estimated N and P leaching to groundwater and run-off to surface water (kton N/P_2O_5).

do occur in the Baseline 2017). In the case of the 'Productivity intended' scenario, CH_4 and N_2O emissions together are expected to remain below the emission ceiling of 9 Mton CO_2 eq. However, this assumes full implementation and effectiveness of the measures described above. In terms of the 'Nature inclusive intended' scenario, the lower reduction potential requires a limited shrinking of livestock in order to remain below the emission ceiling. In terms of the 'Productivity stricter' scenario, CH_4 and N_2O emissions together are at the lowest level (3.5 Mton CO_2 eq). This can be partly explained due to the decrease in livestock (−19%), but also due to the use of low-emission CH_4 housing together with no grazing. The CH_4 and N_2O emissions are higher in both 'nature inclusive' scenarios than in the corresponding 'productivity' scenarios. This is due to longer grazing time (resulting in higher CH_4 emissions) as well as a less effectiveness measure package (resulting in higher N_2O emission). As a result, in the 'Nature inclusive stricter' scenario, it is required additional CO_2 sequestration, through a larger increase in area of forest in order to meet the objective of net climate-neutral agriculture and land use by 2050.

In terms of ammonia emissions (Fig. 7), INITIATOR also estimates that total NH_3 emission in the baseline scenario in 2050 are 85 kton of NH_3, which in line with the stablished ceiling within the current policy framework for policy implementation. The Productivity stricter scenario is with 51 kton NH_3 emissions just above the stricter policy target of 50 kton, the other three scenarios are below it. These are rather severe reductions which require a complete renewal of the stables into very low emission stables which are able to quickly remove all manure to storage and separation into liquid and solid manure. The stable type are still in an experimental stage and it is not sure whether the intended emission reduction is actually feasible. Furthermore, large investments are required and of course supporting policy.

Focusing on nitrogen and phosphate load to groundwater and surface water (Fig. 8), the estimates at national level indicate a drastic decrease for the 2050 scenarios. The national policy goals for the total nitrogen losses to groundwater and surface water have already been achieved on the basis of current policy as included in the 2050 reference scenario. This is partly due to the decrease in agricultural area, but more importantly, this reflects the fact that there is no longer any overuse of animal manure. In the other scenarios, the leaching and run-off is even lower due to the measures taken. In the 'nature inclusive' scenarios, the leaching and run-off of nitrogen and phosphate is higher than in the 'productivity driven' scenarios, following from lower crop yield and more pasture grazing; resulting in a lower nutrient use efficiency. At local and regional scale, especially on sandy soils that are prone to leaching, the risk of exceeding the application standards especially for nitrogen still remains. However, the high background load and the accumulation of phosphate in the past might prevent the achievement of the intended policy goals.

Finally, we refer to Linderhof et al. (2020) who also simulate several scenarios for the Netherlands, with specific representation of the agricultural sector within a system dynamics model for energy policy. More specifically, Linderhof et al. (2020) explore how investment subsidies combined with carbon levies could be used to support the adoption of technological mitigation options in order to achieve a low-carbon economy by 2050. Important items that are highlighted are the role of land use, as well as the need for reducing other type of emissions such as methane and nitrogen oxide.[29] All scenarios that are modelled present high shares of renewables in 2050, implying a substantial use of biomass (either imported or locally sourced), solar power and/or wind power which might exacerbate the existing land competition for alternative uses in the Dutch territory.

[29] The single largest emission source for methane in the Netherlands is livestock farming, accounting for two-thirds of all methane emissions in the Netherlands (CBS, 2019).

5.2. Policy implications

The scenarios analysed above specify different policy targets, i.e. small or large environmental operating space; while making different assumptions about the directions in which Dutch agriculture may develop, i.e. productivity driven or nature-driven. As such the study raises several policy issues. The first one is about the choice of the proper policy objectives, which should take into account the multiple commitments that The Netherlands has made with respect greenhouse gas emission reductions and nutrient emissions, e.g. N, ammonia, P, etc. As the current policy debate in The Netherlands shows, this is not yet clear and a politically contested issue. Then the next policy challenge is to think of designing a set of policy measures that could help to achieve the fixed policy targets. From our study it appears that there are two important policy dimensions which should be distinguished. Firstly, there is the design and selection of policy measures that contribute to making new emission reducing innovations available and which subsequently help farmers to adopt such measures or make investments in new technologies, e.g. the building of low-emission stables. The second dimension relates to policy measures facilitating the structural adjustments in the animal sectors, e.g. reduction of livestock numbers. Aside from direct regulation, e.g. via a restrictive licencing of agricultural activities, there are several other ways to facilitate this. One way could be to divide the environmental operating space in individual user rights, which then are distributed over the producers, and which could be made subject to a degree of 'depreciation' to ensure a gradual reduction of the emission targets in such a way that the final objective will be achieved (Poppe and Jongeneel, 2020).

The Netherlands has already gained experience with such an approach. In 2018, it implemented a phosphate quota system in the dairy sector, which brought phosphate emissions from agriculture successfully below the national emission ceiling. Moreover, the tradability of such rights among farmers can contribute to cost-efficient emission reductions. In addition, the mentioned rights could be purchased by the government as part of a buy-out policy (as this is currently applied in the Dutch pig sector) or by other external private sector parties (currently not allowed in the Netherlands). National policies in this respect could be supplemented by EU policy measures aimed at improving sustainability and climate neutrality, e.g. the EU Green Deal roadmap, the Farm to Fork strategy and the new CAP, etc., which could then generate more leverage and also provide an instrument to soften negative consequences on farm income.

Some final remarks in terms of the implications of this contribution that go beyond the Dutch policy arena are needed. On the one hand, this paper has presented a methodology for policy assessment that could be used for any other EU Member State given the existing modelling tools. In particular, with the appropriate efforts to generate a proper baseline, the AGMEMOD model could be linked to the EU counterpart of INITIATOR, i.e. the MITERRA-Europe model.[30] This would make possible the simulation of the impacts related to the implementation of a specific mitigation package, generating similar indicators to the ones that have been presented in Section 5.1. On the other hand, the lessons learnt from this policy assessment could be also of inspiration for policy-makers in other regions since it has been confirmed that an appropriate policy mix could permit the achievement of a sustainable path. The development and the subsequent adoption of emission reducing technologies and management measures, reducing livestock numbers and extending agroforestry activities are key elements that could favour the transition towards a sustainable pathway. However, it is up to policy makers in other countries to identify the 'appropriate' combination that will fit to their particular set of targets. This is so since the 'solution' is highly dependent on the initial situation, the challenge that they face and goals that they would like to achieve. Coming back to the terminology proposed by

[30] This system has been already tested in the context of the H2020 SUPREMA project.

Tinbergen, the mentioned ‘solution’ will depend on the institutions involved, the conditions to be satisfied, as well as the constraints that can be derived from them.

6. Concluding remarks

Focusing on the methodological aspects, the present exercise can be considered as ‘proof of principle’ of a modelling approach that advocates for informing the policy-making process by the integrated use of a number of models that cover different dimensions of the problem at hand. This approach is highly preferred to the traditional one in which the decision process is not inclusive and only based on the needs of a part of the stakeholders that are involved. In the latter, the simulation of the potential impacts of the policies under discussion could be informed by the outcomes of a partial-equilibrium model or even by an expert consultation. This is so since the phenomenon under consideration is analysed in a narrower sense, with many interactions not being fully captured or even acknowledged. Broadly speaking, integrated model use and letting models ‘working together’ is becoming increasingly relevant when analysing the agricultural system, as different models may cover distinct aspects of such a system, e.g. economic, agronomic, environmental, etc. This will permit researchers to answers the increasingly complex and multi-dimensional questions that policy-makers needs to tackle nowadays.

Moreover, this contribution is an attempt to revitalise the use of optimisation models (Tinbergen, 1969) in the context of the current policy debate in which increasingly policy-makers face multi-dimensional problems. Its focus is on emphasising the value added of this modelling approach when using it as a tool to create a common understanding among the different parties that are involved in a multi-dimensional problem. In the context of the discussion about the future environmental regulation, the present policy optimisation tool has become particularly helpful in order to facilitate the interaction between the different stakeholders and assist the design of strategic policies by translating the different policy options in trade-offs. Another important success of this experience is that this tool has permitted to introduce a more collaborative approach within the policy-making process. This is particularly relevant when dealing with issues like climate neutrality and circularity whose achievement involves complex trade-offs, e.g. closing loops and reducing waste when performing an activity could involve the use of more energy-intensive technologies eventually leading to an increase in emissions per unit of production.

In other words, the present approach highlights the importance of developing a modelling framework that connects in an integrated manner several modelling tools that are well-known for dealing with specific problems. Depending on the particularities of each model the ‘link’ between them will be more or less structured (‘hard’ versus ‘soft’ linkages); as well as more or less direct (direct versus indirect linkages). This integrated approach also allows modellers, policy makers and other stakeholders to obtain ‘richer’ insights and acknowledge the role of uncertainty in a better way. Therefore, an important element is to consider the differences between the outcomes of various models and understand their causes.

With regard to the scenario results, this contribution illustrates how the integrated use of several models has delivered important forward-looking insights regarding economic effects, environmental impacts, and land use among others.

Finally, a note on the way forward is needed. Although this modelling exercise has been a successful experience to improve previous simulations of environmental policies and their potential effects in the case of the Dutch agricultural system, there are still aspects that were not fully incorporated. For example, a better modelling of elements such as consumer behaviour/preference shifts that relates to the protein transition could become quite relevant in view of its potential role to shape the future of the sector.[31] Drawing attention to the upcoming CAP framework, there is a need for further analysis of the possible mechanisms that could be in place to arrange supporting policy measures, e.g. pricing of CO_2 sequestration using eco-schemes, evaluation of farm performance for receiving direct payments, etc. Other important points of attention in this regard are modelling and explaining farmer participation in voluntary adoption of agri-environmental and climate-schemes, as well as compliance issues both with respect to voluntary and regulatory arrangements (Herzfeld and Jongeneel, 2012). Elaborating on this will also have consequences for model linkage since the explicit introduction of such behavioural aspects are likely to require iterative model use in order to ensure behavioural consistency between economic and bio-physical models. Furthermore, keeping in mind the broad goal of circularity, there is a pressing demand for extending/improving the modelling of those aspects that are associated with enhancing the sustainability of agriculture. In particular, a better/more detailed representation of soil, losses, waste, reuse and recycling activities in modelling tools and special provisions in model linkages would be key to respond to upcoming policy questions in the near future.

CRediT authorship contribution statement

Ana Rosa Gonzalez-Martinez: Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Software programming, Visualization. **Roel Jongeneel:** Conceptualization, Methodology, Funding acquisition, Validation, Investigation, Writing - original draft, Writing - review & editing. **Hans Kros:** Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Software programming. **Jan Peter Lesschen:** Conceptualization, Methodology, Funding acquisition, Investigation, Writing - review & editing, Project administration. **Marion de Vries:** Formal analysis, Writing - original draft. **Joan Reijs:** Conceptualization, Methodology, Funding acquisition, Project administration. **David Verhoog:** Formal analysis.

Declaration of Competing Interest

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

Annex A. Technical descriptions of the models

A.1 The AGMEMOD model

AGMEMOD stands for ’AGricultural MEmber states MODelling’ (https://agmemod.eu/). Since 2001, it has been developed by the AGMEMOD Partnership, a consortium of national university institutes and research agencies from EU countries and potential accession countries (Chantreuil et al., 2011). It is a dynamic, partial, multi-country, multi-market equilibrium system which solves in a GAMS environment (Van Leeuwen et al., 2008). It can provide significant detail on the main agricultural sectors in each EU Member State, with most equations being estimated econometrically at the individual Member State level. Where estimation was not feasible or meaningful, parameters have been calibrated. The country models contain the behavioural responses of

[31] A first attempt to explore the potential impact of the protein transition on EU agriculture has been done in the context of the SUPREMA project by using the system AGMEMOD-MITERRA.

economic agents to changes in prices, policy instruments and other exogenous variables on the agricultural market. Within AGMEMOD, all commodity prices clear all markets under consideration.

The current AGMEMOD version consists of the EU28 Member States, the Former Yugoslav Republic of Macedonia, Turkey, Russia and Ukraine (AGMEMOD Consortium, 2010, 2011). Moreover, some attempts of introducing a regional disaggregation have been done in the case of Germany and Ukraine. A bottom-up approach has been used to integrate country models into AGMEMOD. For each commodity in each country, agricultural production as well as supply, demand, trade, stocks and domestic prices are derived from econometrically estimated equations. One element of the supply and demand balance for each commodity is used as a closure variable to make the balance consistent. For a closer representation of market dynamics, the specification of the equations that are used for a given commodity can differ across countries. AGMEMOD's projections offer an interesting combination of econometric results and expert knowledge. In other words, the modelling systems' projections are validated by standard econometric methods and through consultation with experts who are familiar with the agricultural market in the regions under study. The AGMEMOD model provides output for the following agricultural commodities: (i) cereals (soft wheat, durum wheat, barley, maize, rye, other grains); (ii) oilseeds (rapeseed, sunflower seed, soybeans, cotton seeds, vegetables oils and meals); (iii) livestock and meat (beef and veal, pork, poultry, sheep and goats); (iv) milk and dairy products (butter, skimmed milk powder and cheese); (v) fruits and vegetables sector (tomatoes, oranges, apples, olive oil); (vi) industrial crops (sugar beets tobacco and cotton) and potatoes; and (vii) bioethanol (from grains) and biodiesel (from oilseeds).

A.2 The INITIATOR model

INITIATOR (Integrated NITrogen Impact Assessment Tool On a Regional scale), was developed to gain insight in the fate of all major N flows at different spatial levels in the Netherlands. In addition, it assesses the effects and interactions of policies and measures in agriculture on nitrogen and GHG emissions, changes in soil organic carbon stocks and nutrient losses to water for the Netherlands. It includes N inputs by manure and chemical fertilizer, N deposition and N fixation, N uptake, emissions of ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxides (N_2O) and di-nitrogen (N_2) to the atmosphere and N leaching/runoff to ground water, and surface water (De Vries et al., 2003). The model is based on agricultural census data, with livestock numbers for each livestock category, type of housing system, and the special delineation of each farm in the Netherlands, using a procedure as described by Van Os et al. (2016). The annual N excretion in manure is calculated by a multiplication of the livestock numbers for each farm with the annual N excretion rate per animal for 65 livestock categories. The emissions of NH_3, NO_x and N_2O from housing and manure storage systems are calculated by a multiplication of the N excretion and element specific emission fractions (NH_3, NO_x, N_2O) for different livestock categories, depending on the type of emission (a maximum of 65 categories in case of NH_3 emission).

The N excretion, corrected for volatilization, is input for a manure and chemical fertilizer distribution module that predicts the inputs of N to the soil by manure and chemical fertilizer. This distribution module includes rules based on the current policy on manure and chemical fertilizer use according to the manure and ammonia law (Kros et al., 2019). The INITIATOR soil module then calculates the soil emissions of NH_3, NO_x and N_2O, and the N leaching and runoff with a consistent set of simple linear equations (De Vries et al., 2003). In this study, changes in mean ground water levels, calculated by NHI, are used to modify the rates of nitrification and denitrification and thereby the N_2O emissions and N leaching. The NH_3 emissions from soils are calculated by a multiplication of the different N inputs (application of manure and chemical fertilizer and excretion by grazing cattle) with specific N emission fractions for these inputs. Measures can affect livestock numbers, excretion or emission fractions or parameters in INITIATOR that influence losses of elements to ground water, surface water and atmosphere.

The NH_3 emissions from housing and manure storage systems and from fields, calculated by INITIATOR, are used as input for OPS (Operational Priority Substances), a detailed atmospheric transport model (Sauter et al., 2015), to assess the NH3 deposition due to agricultural NH_3 emissions. OPS simulates the atmospheric process sequence of emission, dispersion, transport, chemical conversion and finally deposition for a wide variety of pollutants including SO_x, NO_y, NH_x and fine particles.

Moreover, it can be combined with other economic models, such as AGMEMOD, for projections purposes. INITIATOR offers a transparent and detailed calculation of GHG emissions and other environmental indicators for the use of biomass, including around 40 different types of crops. Although, the current version of the model does not include any feedback due to changes in crop yields related to technological progress, this can be include by a linkage with a farm model, like FSSIM (Kros et al., 2015).

A.3 Input-output analysis

When looking at the structure of an economic system as well as the interdependencies among its components, Input-Output (IO) analysis provides a useful approach to analyse the 'diffusion' of shocks through the system.[32] As it is well-known, IO models permit economists to include (implicitly) supply chains for all sectors in the economy. In other words, an IO table gives in one matrix an overview of the origin of the input and the destination of the output for all sectors of an economy. Linking economic and environmental impacts, a seminal contribution in the field is Leontief (1970) which shows the mathematical representation of an open input-output system with pollution-related activities that are modelled explicitly.[33] With a specific focus on agriculture, Karkacier and Gokalp-Goktolga (2005) use the IO method to analyse the interdependencies between the agricultural and energy sectors in Turkey. Previously, Adelman and Robinson (1986) extended the US IO tables to develop a multisectoral SAM that captures the linkages of the agricultural sector with the rest of the economy.

For this particular case, the calculation of the added value and employment of the agro-complexes relies on the IO tables published by the CBS that have been further processed by Wageningen Economic Research to produce IO tables for the agricultural sector. This set of tables contains more detailed information for primary agriculture and horticulture, as well as for the food industry, than the original CBS tables.[34]

The IO tool that has been developed includes a representation of direct and indirect effects for the following eight sectors: (i) dairy; (ii) pig meat; (iii) poultry meat; (iv) eggs; (v) other livestock; (vi) arable; and (vii) forestry. Within this tool, the supply chain is split in four different stages: (i) primary production; (ii) input supply; (iii) food/feed

[32] See, Christ (1955) for further discussion of the input-output method.

[33] Chen and Zhang (2010) make use of IO analysis to calculate the greenhouse gas emissions that are associated with final consumption and international trade in the case of China. This study concludes that China is a net exporter of embodied GHG emissions.

[34] These IO tables cover 26 agricultural sectors, including forestry and fishery.

Table A.1
Overview of the 'agro-complex' levels.

Sector	Complex: core	Complex: related
Dairy	Primary production of milk, dairy processing industry	Firms supplying inputs to the complex, such as fertilizers, energy, feed; other processing firms, sectors providing services (e.g. contract work), distribution activities (e.g. logistics)
Pig meat	Primary production of fattening pigs, pigs slaughter industry	Firms supplying inputs to the complex, such as feed, energy, veterinary services; other processing firms, sectors providing services (e.g. contract work), distribution activities (e.g. logistics)
Poultry meat	Primary production of poultry meat, poultry meat slaughter industry	Similar as above, but related to poultry meat
Eggs	Primary production of eggs, eggs processing industry	Similar as above, but related to eggs
Other livestock	Primary production of other livestock (meat cows, sheep, horses)	Firms supplying inputs to the complex, such as fertilizers, energy, feed; other processing firms, sectors providing services (e.g. contract work), distribution activities (e.g. logistics)
Arable	Primary production of arable crops	Firms supplying inputs to the complex, such as fertilizers, energy, seed; many firms of the food processing sector, involved in the transformation of arable products such as the milling industry, potato processing industry, margarine, fats and oils industry, starch potato industry, (beet) sugar industry, cacao, coffee and thee industry, tobacco industry, feed industry; other processing firms, sectors providing services (e.g. contract work), distribution activities (e.g. logistics)

processing; and (iv) distribution. Each of the scenarios that are modelled differ with respect to production levels which are defined in terms of volumes and prices. An important characteristic of this IO tool is that impacts are measured at 'agro-complex' levels, being key variables of the model value added, employment, gross revenues and production (domestic and foreign).

Due to the heterogeneous nature of the activities that are included within the agro-complex, further split into sub-complexes has been introduced. These sub-complexes are connected to a specific agricultural production direction. In addition to the primary agricultural sector, the related food industry is also an important part of the agro-complex. Moreover, the supply and service industries, which supply directly and indirectly to primary agriculture and horticulture and to the food industry, form another part of the agricultural production column. This includes feed producers, greenhouse builders and veterinarians, as well as the packaging industry. In addition, the agro-complex also includes those trade and transport activities that are associated with the production and processing of agricultural products. This includes the transport of agricultural end-products for satisfying domestic consumption and exports.

See Table A.1.

A.4 GLEAM

The Global Livestock Environmental Assessment Model (GLEAM) developed by the Food and Agriculture Organization of the United Nations is a modelling framework that simulates the interaction of activities and processes involved in livestock production and the environment. The model focuses primarily on the quantification of greenhouse gases emissions arising from the production of main livestock commodities. The model can operate at (sub) national, regional and global scale. More specifically, GLEAM can use regional or (sub)-national information on production practices and animal parameters. GLEAM differentiates key stages along livestock supply chains such as feed production, processing and transport; herd dynamics, animal feeding and manure management; and animal products processing and transport. Another important feature of the model is that it captures the specific impacts of each stage, offering a comprehensive and disaggregated picture of livestock production and its use of natural resources. GLEAM provides a coverage of different livestock species and their edible products, including meat and milk from cattle, meat from pigs and meat and eggs from chicken. In terms of GHGs, the model covers emissions of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) in order to provide more accurate information on how animal feeding, herd and manure management options can help in mitigation. GLEAM consists of five distinct modules: (a) the Herd Module; (b) the Manure Module; (c) the Feed Module; (d) the System Module; and (e) the Allocation Module. A complete simulation of GLEAM produces multiple outputs which can be either final indicators and maps or intermediate calculations for subsequent operations. [35]

A.5 BBPR

The DairyWise model (BBPR in Dutch, *Bedrijfs Begrotings Programma Rundvee*) is an empirical model that simulates technical, environmental, and financial processes on a dairy farm. The central component is the FeedSupply model that balances the herd requirements, as generated by the DairyHerd model, and the supply of homegrown feeds, as generated by the crop models for grassland and corn silage. The output of the FeedSupply model was used as input for several technical, environmental, and economic sub-models. The sub-models simulate a range of farm aspects such as nitrogen and phosphorus cycling, nitrate leaching, ammonia emissions, greenhouse gas emissions, energy use, and a financial farm budget. The final output was a farm plan describing all material and nutrient flows and the consequences on the environment and economy.[36]

Although Fig. 2 includes a reference to the BBPR model, it should be clarified that in this exercise, no 'actual' runs of this model were used. However, insights from its parameters and outcomes of previous studies using BBPR were taken into consideration as inputs for the LP model.

Annex B. Scenario description

See Tables B.1 and B.2.

[35] Additional details on the GLEAM model are available at: http://www.fao.org/gleam/en/

[36] Further model details and applications are available at: https://www.wur.nl/nl/show/Bedrijfs-Begrotings-Programma-Rundvee-BBPR.htm; https://www.wur.nl/nl/Publicatie-details.htm?publicationId=publication-way-333634343436.

Table B.1
Assumptions for the environmental boundaries.

Item	Current	Baseline 2050	Intended environmental goals	Stricter environmental goals
Emissions (CH_4 and N_2O)	19 Mton	18 Mton	9 Mton	2 Mton
Emissions (LULUCF)	6 Mton	5 Mton	2 Mton	-2 Mton
Ammonia	110 kton	109 kton	100 kton	50 kton
Nutrients leaching	N: 45 kton P: 3.6 kton	N: 45 kton P: 3.3 kton	N: −12% P: −12%	N: −17% P: −17%

Table B.2
Formulated mitigation packages for main livestock categories.

Category		Mitigation package		
		'Basic 2050'	'Pull out all the stops'	''Extensive'
Stables	Dairy cattle	– Primary separation and frequent removal of faeces and urine, with CH_4 and NH_3 removal in manure storage. – Capture and remove part of the CH_4 in exhaled breath.	– Primary separation of faeces and urine. – Closed, airtight stables with CH_4 and NH_3 removal.	– Primary separation and frequent removal of faeces and urine, with CH_4 and NH_3 removal in manure storage. – Capture and remove part of the CH_4 in exhaled breath.
	Pigs	– Primary separation and frequent removal of faeces and urine, with CH_4 and NH_3 removal in manure storage.	– Primary separation of faeces and urine. – Closed, airtight stables with CH_4 and NH_3 removal.	Primary separation and frequent removal of faeces and urine, with CH_4 and NH_3 removal in manure storage.
	Poultry	– Manure drying and frequent removal (common techniques)	– Manure drying and frequent removal (highly effective techniques)	Manure drying and frequent removal (common techniques)
Access to pasture or outdoor area	Dairy cattle	Grazing 80% of national herd, 720 hours per year	No grazing	Grazing 100% of national herd, 3600 hours per year
	Pigs	No access to outdoor area	No access to outdoor area	All animals have access to an unpaved outdoor area
	Poultry	Broilers: no access to outdoor area. Laying hens: access to an outdoor area on part of the farms	No access to outdoor area	All animals have access to an unpaved outdoor area
Animals and productivity	Dairy cattle	Milk production 11315 kg head^{-1} yr^{-1} Genetic selection on lower enteric methane emissions	Milk production 12635 kg head^{-1} yr^{-1}	Milk production 9335 kg head^{-1} yr^{-1} Genetic selection on lower enteric methane emissions
	Pigs	36 piglets sow^{-1} yr^{-1} Feed conversion fattening pigs 7% lower	38 piglets sow^{-1} yr^{-1} Feed conversion fattening pigs 20% lower	30 piglets sow^{-1} yr^{-1} Feed conversion fattening pigs same as current
	Poultry	Laying period 100 weeks Weight gain broilers: 49 g head^{-1} day^{-1} (35% of broilers) or 59 g head^{-1} day^{-1} (65% of broilers)	Laying period 120 weeks Weight gain broilers: 59 g head^{-1} day^{-1}	Laying period 90 weeks Weight gain broilers: 43 g head^{-1} day^{-1}
Feed rations	Dairy cattle	Grass 60%, maize 15%, by-products/concentrates 25% Feed additives for reduction of enteric methane	Grass 50%, maize 20%, by-products/concentrates 30%	Grass 70%, maize 10%, by-products/concentrates 20% Natural feed additives for reduction of enteric methane
	Pigs	Moderate reduction of protein in feed ration	Strong reduction of protein in feed ration	Reduction of protein in feed ration
		Benzoic acid added in feed ration	Benzoic acid added in feed ration	Benzoic acid added in feed ration
	Poultry	Moderate reduction of protein in feed ration	Strong reduction of protein in feed ration	

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