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Model Collaboration between Farm Level Models with Application on Dutch Dairy and Arable Farms Regarding Circular Agricultural Policy

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Abstract: The ambition of the Dutch Ministry of Agriculture is to stimulate the transition to circular agriculture. The objective of this paper is to develop and apply a farm level model toolbox for circular-agriculture policy assessment. Transition to circular agriculture affects farm management practices and outcome in the field of finance and economics, soil quality, use of finite resources, emissions, and biodiversity. Based on this, there is a need for an integrated assessment at farm level. Therefore, Bio Economic Farm Models should be at the core of the model toolbox. Model collaboration enables answering more complex questions and enlarges the scope of the analysis. Challenges of model collaboration are among others overlapping modules, different approaches (optimisation versus simulation), and existence of different networks of model developers and users. It is argued that a governance structure and networking will foster model collaboration. To stimulate transition to more circular agriculture practices and as a demonstration, the model toolbox was applied to assess the economic and environmental impacts of a tax on N from mineral fertiliser on a representative dairy and arable farm in a region in the Netherlands. It was found that a tax on N from mineral fertiliser has relatively large income effects, while the impacts on various environmental indicators are relatively limited.

Keywords: bio-economic farm models; tax policy; environment; model governance; DairyWise; Farmdyn

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1. Introduction

In 2018, The Dutch Minister of Agriculture launched the vision document "Agriculture, nature and food: valuable and connected (in Dutch: Landbouw, natuur en voedsel, waardevol en verbonden)" [1] in which the ambition is expressed for a circular and biodiverse agriculture. Circular agriculture was defined as an agricultural production system that produces a minimum amount of environmental and biodiversity losses, having closed nutrient cycles as much as possible at local, national, and international scales by 2030. Further elements are, amongst others, an improved socio-economic position of farmers, a decreased carbon (C) footprint, and an improved quality of ecosystems. The farmers, their decisions, and their farms are an important part of the agricultural production system. In this paper, we define a farm as a place where land, labour, capital, and intermediate inputs are used for primary agricultural production. Ex-ante evaluations of circular agriculture policy measures based on farm models and tools can help to estimate economic and environmental impacts taking into account possible changes in farm management practices. These estimates and insights are essential for policy design.

A conceptual model to analyse circularity at the farm level has been presented in [2]. This conceptual model was described in terms of relevant policy questions, indicators, and farm model requirements. From this conceptual model it was concluded that for an integrated assessment of circular agriculture impacts at farm level, bio-economic farm models (BEFMs) play an important role. These models allow integrated assessment of economic, agronomic, biophysical, and environmental effects of policy measures related to circular agriculture at farm level. However, given the wide range and complexity of policy questions, the large number of indicators and the interrelationships of themes and scales related to circular agriculture, individual BEFMs cannot fulfil all the necessary requirements [2]. Model collaboration helps to solve this problem and to broaden the scope of the analysis [3,4]. As an example of model collaboration, Lesschen et al. [5] combined different types of models to analyse the impacts of scenarios regarding climate change at regional and national levels.

The objective of this paper is that we investigate model collaboration at farm level. The model collaboration is tested to analyse economic and environmental impacts of a baseline and a tax on nitrogen (N) from mineral fertiliser for a representative dairy and arable farm in the Netherlands. A tax on N from mineral fertiliser is an economic policy measure often mentioned to decrease the use of mineral fertiliser and to stimulate circular agriculture.

Another objective is to discuss the theory and governance of model collaboration of partly overlapping models and tools developed by different modelling networks, with a focus on farm models and tools. We discuss possibilities of different types of model collaboration at farm level and the specific challenges of collaboration of models and tools that are developed by different networks, with different objectives and modelling approaches (e.g., optimisation versus simulation).

For the dairy farm, we combined the BEFMs DairyWise [6] and Farmdyn [7]. DairyWise has been applied to different aspects of circular agriculture. Vellinga and Hoving [8] used DairyWise in combination with the Introductory Carbon Balance Model to show that mitigation of methane emissions by increasing the amount of maize silage in the ration can be offset by land use change. DairyWise was also used to study cost effectiveness of greenhouse gases (GHG) [9] or ammonia (NH_3) [10] emission mitigation options at farm level or to assess the environmental (GHG and NH_3) and economic effects of mono-digestion of manure on dairy farms [11]. Furthermore, [12] compared DairyWise with three other farm-scale models regarding their ability to estimate GHG emissions. More recently, [13] have used DairyWise to calculate the economic impact of NH_3 emission reducing measures in the context of the Dutch N policy. Applications of Farmdyn to different aspects of circular agriculture can, for example, be found in [14–18]. These applications mostly focus on Germany, analysing marginal abatement costs curves of GHG emissions at farm level and impacts of nitrate policies on German livestock farms. Farmdyn was also used to analyse impacts of reduction of GHG from peat soils in Dutch agriculture. Here, the focus was on dairy farm management impacts of rewetting peat soils, including impacts on emission of NH_3 [19,20]. Daatselaar et al. [21] used Farmdyn to analyse integrated effects of a switch to more permanent grassland on dairy farms with silage maize. The analysis was based on dairy farms in the Dutch Farm Accountancy Data Network (FADN). The amount of GHG emission, including C sequestration, slightly decreases, but ammonia emission increases for the reported four groups of average farms. This is because of higher ammonia emission rates from manure application on grassland. Average abatement costs per average farm group differentiated between 77 and more than 1000 Euro per ton CO_2 eq.

For the arable farm we combined the BEFM Farmdyn and the tool Nutriëntenbalans Akkerbouw (Nutrient balance Arable farming, NA). The NA tool has been developed recently for calculating N and phosphorus (P) surpluses on arable farms based on the cropping plan, crop yields, and the fertilisation of the crops [22]. It represents the state of the art regarding modelling emissions on individual arable farms.

Individual models could not achieve the results of the tax policy that will be assessed in this paper on their own. The tax policy is an example of a complex policy that allows combining the strengths of an economic optimization model like Farmdyn with the detailed environmental and production (grass and crop growth, milk, feed requirements, herd management) modelling in DairyWise and NA. As both DairyWise and NA are no optimizations, but simulation models, they are not able to 'search' for the economic optimal solution in the new scenario. The isolated models could never present results for dairy and arable farms. As DairyWise only focusses on dairy farms and NA only on arable farms. NA also lacks the whole farm approach. Given the above arguments, it is not tested whether the same type of results could be achieved without model collaboration.

The structure of the paper is as follows. Section 2 discusses in more detail the theory of model collaboration. In Section 3, model features and aspects of circular agriculture covered by the selected BEFMs and the NA tool are shortly described. Section 3 also discusses some technical details of the models that are important for the baseline and the circular policy intervention case assessment. In Section 4, the results of the policy intervention are analysed for a representative dairy farm on a sandy soil and for a representative ware potato farm on clay soil. In Section 5, the governance of model collaboration and importance of networking are discussed. Section 6 ends with conclusions and recommendations. Recommendations focus on model collaboration and corresponding governance and network needs.

2. Various Forms of Model Collaboration

Model collaboration at farm level allows answering more complex questions and broadening the scope of the analysis. The importance of model collaboration in general is also an important finding of the EU H2020 project SUPREMA [3,23]. According to [3], "the 'collaboration' between different approaches offers possibilities to 'fill' the gaps that a single model has and strengthens the capacity to assess the direct and indirect impacts of a particular shock. Therefore, the use of models in an integrated manner can improve the quality of information for policy-makers and contribute to better-informed decision-making [24]." Model comparison has a role to play in the learning process of modellers, possibly coming from different modelling networks and disciplines and can become the 'seed' for additional model improvements [3,12,16].

Wicke et al. [24] identified three forms of model collaboration:

- Comparison of Models. This focuses on the methods, representation, and parameterisation of assumptions and uncertainties in input data, and/or on results and uncertainties in underlying data and approaches.
- Alignment and harmonisation of models. This focuses mainly on input data, level of aggregation, and scenario definitions.
- Integrations of models. Integration of models includes different kinds of model linkages, ranging from using the results from one model as input to another model to full model integration.

The focus of this paper is on all three aspects of model collaboration. The different forms of model collaboration are interrelated [24]. Model comparison contributes to the harmonisation of data and models, improves the insight into specific contributions that different models can make, but also identifies additional options for model integration and can be used as a validation of the model outcomes [24].

Model collaboration often involves important efforts for further harmonisation among model inputs and outputs [4,25–29]. The problems of model collaboration are especially related to different methodologies, data sources, IT, network of modellers, etc. Type of models can be different (simulation, optimisation) as well as scale and targeted aspects/disciplines of the analysed system, e.g., economic, agronomic, and environmental. Often this requires solving problems in definition of variables, data requirements, aggregation of data and availability and access to data.

Given the difficulties related to the different types of model collaboration, it is important to be explicit regarding the additional value of the model collaboration. As such, it is useful to distinguish between model collaborations to more realistically analyse:

- different economic levels and spatial scales (e.g., farm level, sector level, regional and global market levels, including trade). For example, a micro-model with all input and output prices fixed could take price changes from market models [26];
- different disciplines (economic, agronomic, environmental, ecological). For example, an economic model may be linked to a biophysical model in order to assess the environmental impacts associated with certain economic behaviour of farmers [3].

Any attempt of model collaboration will start with researchers defining what the real aim is that they would like to establish. The answer to this question should deliver a clear definition of the flow of information that will be exchanged and the feedback loops among the different models under consideration.

In this study, research teams were quite experienced and could start from pre-selected models and tools. Based on our experiences, the following recommendations for researchers and modelers can be provided regarding model collaboration:

- Search intensively for available models and involve the respective contact persons.
- Learn about the discovered models and what answers they can provide on their own, explore if useful combinations of the discovered models can improve the answers; if this is the case, set up a model collaboration between those models.
- When a new model is needed, it is recommended to build it modularly and incorporate already existing modules from other models (re-use of models/modules).

3. Features of BEFMs DairyWise and Farmdyn and the Nutrientenbalans Akkerbouw (NA) Tool

The BEFMs Farmdyn and DairyWise focus on ex-ante assessment of the effects of policies on trade-offs between economic and environmental impacts at farm level and on farm management. These two BEFMs, available in Wageningen Research (WR), are often used for farm level policy assessments. DairyWise gives a detailed and integrated description of biophysical and economic processes on dairy farms by means of simulation, including feeding, animal production, fertilisation, plant production, and environmental emissions. Based on a combination of farm-specific and normative input values, e.g., related to feeding at nutritional requirements, it calculates economic and technical indicators. By default, DairyWise assumes fertilising at legal application standards (N in manure, total N from manure and fertilisers, total phosphate in manure and fertilisers). Strengths and weaknesses of a farm can be detected, and consequences of changes can be assessed based on the calculated technical and economic indicators, e.g., differentiation from defaults as fertilising at legal application standards. Unlike Farmdyn, N and P excretion per animal is endogenous in DairyWise as a function of the nutrient content of the feed ration. DairyWise can be used for integrated scenario development and evaluation by scientists, policy makers, extension workers, teachers, and farmers.

Farmdyn is a profit maximising, mixed-integer programming, bio-economic model at the individual farm level, simulating a farmer’s decisions regarding agricultural production and investments in a comparative static or dynamic setting on specialised and mixed arable and dairy farms, beef cattle and pig farms (Farmdyn delivers a template for different types of farms. Currently, the templates for beef and pig farms are not developed for the Netherlands). The crop list includes all arable and horticultural crops that are relevant for the EU and Dutch arable sector, including silage maize and different grassland management options (e.g., grazing intensity, cutting frequency, and fertilisation levels). Just like DairyWise it includes details regarding production, income, investments, and emissions on farms. Regarding economy, the model can be used in different ways. In the dynamic setting, Farmdyn gives a time path of yearly results explicitly accounting for multiple period production, investments, financial constraints, and farm liquidation.

However, in this study, we will apply the comparative static version, with revenues and costs for one period only.

The NA is a simulation tool developed for the calculation of N and P surpluses on an arable farm based on the cropping plan, crop yields and the fertilisation of the crops [22]. The motivation for the development of the NA was the demand of arable farmers for a tool to proof that a farm is eligible for applying farm specific application standards for N and P. In addition to the N and P surpluses, the NA calculates the fate of the N surplus (in forms of NH_3, NO_3, N_2O, N_2), the organic matter supply, and the GHG-emissions. Initially, the NA tool was developed as a registration instrument, but it also offers the possibility to do simulations regarding farm management adjustment (e.g., changing the fertilisation (type, amount, and application method) and cropping plan, inserting catch crops).

Model content features of the selected BEFMs and the NA tool are summarised in Table 1 and described in more detail in Appendix A. Table 1 shows that both DairyWise and Farmdyn include various farm management measures (technologies) for key activities on the farm (e.g., feeding and fertilising). For the DairyWise and Farmdyn model collaboration, it is important that nutrient excretion per animal is endogenous in DairyWise, while Farmdyn can determine the optimal N from mineral fertilisation given the tax. Circular agriculture aspects and indicators covered by the BEFMs and the NA tool comprise the use of external inputs (e.g., mineral fertilisers, concentrates, and crop protection agents), nutrient and GHG emissions, economy, organic matter supply, and share of permanent grassland. This is rather incomplete compared to the conceptual model as described in [2].

Table 1. Comparison of selected features of the BEFMs and NA tool.

Model	DairyWise	Farmdyn	NA
Model type	Simulation	Optimisation	Simulation
Max. no. of crop and animal activities	Limited to dairy and forage crops	Dairy, beef and pigs, case specific number of grassland activities, maximum 33 arable and horticultural crops.	45 arable and horticultural crops
Feed constraints	Energy, protein, min/max shares of feed ingredients	Energy, protein, min/max shares of feed ingredients	N.A.
Fertilising constraints	Fertilising at legal application standards (default) but adjustment is possible. Different manure application methods	Fertilising lower or equal to legal application standards. Different manure application methods	Type and dose of manure and fertiliser, application method (broadcast/row application)
Grassland management	Grassland calendar, i.e., planning of grazing and cutting, at field level	Different grassland options for grazing and silage with different N intensity levels and number of cuts per ha grassland	N.A.
Nutrients excretion per farm	Depending on excretion per animal based on feed ration and number and composition of the animal herd	Depending on number and composition of the animal herd, fixed excretion figures independent from feed ration	N.A.
Crop rotation	No, just share of land use and age of grassland before conversion to arable land and vice versa	Fixed acreage of arable land and grassland.	Yes
Temporal resolution	Year	Year, month	Year
Behavioural aspects	Feeding at nutritional requirements and fertilising at legal application standards	Maximisation of revenue minus variable costs and depreciation. More complexity in dynamic and stochastic mode possible. Several decision rules for risk utility possible	Implicitly accounted for in the fertilisation registration on the farm
Environmental Policy representation and indicators			
Nitrate and Water framework directive	Yes	Yes	Yes
Economic policies (CO_2 pricing, taxes)	No	Yes	No
Environmental indicators	NH_3, CH_4, N_2O, CO_2, GWP *, nutrient balance NPK	NH_3, CH_4, N_2O, CO_2, GWP *, nutrient balance NPK	N and P balances

* GWP: Global Warming Potential.

4. Model Collaboration between DairyWise, Farmdyn and the NA Tool: Methodology and Baseline and Scenario Results

In this paper, the model collaboration between Farmdyn and DairyWise covers all three aspects: alignment and harmonisation of models (e.g., alignment of input data, e.g., N-response curve and scenario definitions), comparison of models (comparison of baseline and scenario results), and integration of models (connecting environmental impact module from DairyWise to Farmdyn).

Model collaboration between Farmdyn and NA covers two aspects: alignment and harmonisation of models (input data, level of aggregation, and scenarios) and on integration of models. Harmonisation of input data especially relates to base fertilisation of the crops. The integration of Farmdyn and NA is based on one way data exchange as NA is completely complementary to Farmdyn. Results of Farmdyn with respect to cropping plan and fertiliser use are input to NA to model corresponding nutrient surpluses and emissions.

The circular agriculture scenario concerns a tax on mineral N fertilisers. The aim of such tax is to reduce the use of mineral N fertilisers and to stimulate circular agriculture. The costs of the tax at farm level can be compared to the costs to produce renewable fertilisers from processed manure [30]. If legally allowed, renewable fertilisers from processed manure could replace the mineral fertilisers (see Section 4.3).

The main difference between simulation (DairyWise) and optimisation (Farmdyn) models is that the first provides an explicit recommendation for action in a certain economic scenario, for example, the optimal input of mineral N fertilisers in a situation with a tax on N from mineral fertilisers. Profit maximisation is most often used to find this optimal solution; however, alternative objective functions—e.g., risk preferences, specifying a minimum income or maximum emission levels—are possible as well. Simulation models allow users to assess how a system responds to a specific change of farm management and to better understand how it operates (Simulation models like DairyWise are used in experiments with farmers to detect the behaviours of farmers. Subsequently, it can be applied in a model for optimisation purposes. This is another form of model collaboration, but it is rather expensive). DairyWise is not able to directly analyse responses to changes in input prices, but can include behavioural aspects via input from, e.g., farmers, experts, other researchers, literature, or other models. Harmonisation of DairyWise and Farmdyn especially concerns harmonising the slope (yield changes per kg N reduction) and the possible range of the N input from mineral fertilisers per ha grassland. DairyWise allows endogenous change in N and P excretion per animal from changes in feed regimes and fertilisation, while this is exogenous in Farmdyn. For reason of consistency of environmental impacts and because of the detailed modelling of processes and emission sources, the environmental impact module from DairyWise is connected to the economic results from Farmdyn. This can be seen as model integration.

Results of model collaboration between DairyWise and Farmdyn are discussed in Section 4.1. Section 4.2 discusses model collaboration between Farmdyn and NA. Section 4.3 gives a discussion of the results.

4.1. Model Collaboration between DairyWise and FarmDyn: Baseline and Scenario Results

Table 2 gives basic statistics of a representative dairy farm on sandy soil in the Netherlands as calculated from the Dutch FADN database. A more detailed description of basic inputs can be found in Table A1 in Appendix B.

Table 2. Basic characteristics of a representative dairy farm on sandy soils in the Netherlands (Source: own calculations from Dutch FADN, average of bookkeeping years 2017 and 2018).

Parameter	Unit	Value
Animals	Number	94 cows, 31 calves and 29 heifers
Milk production	kg/cow per year	8600
Animal housing		Cubicles and slatted floor
Manure type		100% slurry
Total pasture area	ha	37
Total silage maize area	ha	9
Grassland use system		Combined grazing and mowing

Milk production per cow was considered as an exogenous parameter in both Farmdyn and DairyWise with an average milk production of 8600 milk per cow per year. Manure (100% slurry) was applied on the grass and maize land to a maximum allowed level of 230 kg N per ha. In DairyWise, additional mineral N fertiliser was applied according to legally allowed levels.

4.1.1. N Response Curve for GRASSLAND

Figure 1 shows the response on mineral fertiliser N for a situation with a manure N rate of 270 kg manure N per ha grassland (applied slurry and excreted during grazing; situation in the baseline and scenario) for DairyWise. For the baseline, the effective N from manure and mineral fertiliser (about 215 kg N per ha) was 32% lower than the calculated N demand (315 kg N per ha, based on national fertiliser recommendations) [31]. The grassland N response relationship in DairyWise is used as input in Farmdyn to parameterise the relationship N input and grassland yield for the different grassland management options in Farmdyn. Consequently, this mimics the slope of DairyWise (Figure 1). Grassland yield in DairyWise refers to the field net yield, including feeding and storage losses and excluding field losses and the grassland yield in Farmdyn refers to feed intake, excluding feeding, storage, and field losses. Based on these response relationships and the price ratio between produced grass and mineral N fertiliser, Farmdyn calculates the optimal mineral fertiliser N rate, respecting the legally allowed levels of N from animal manure and total N from animal manure and mineral fertiliser.

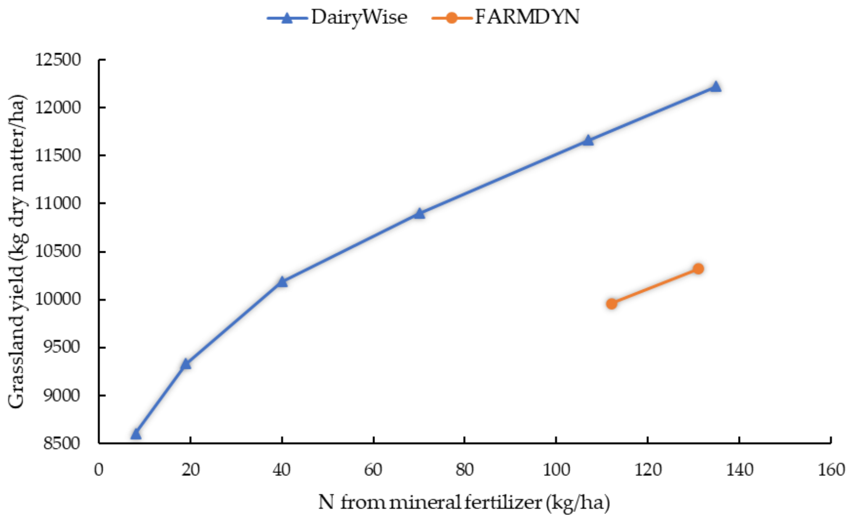

Figure 1. The response of mineral N fertiliser rate on grass yield for Dairy Wise and the economic optimal N input per ha grassland in the baseline (131 kg N per ha) and scenario (113 kg N per ha) in Farmdyn. Grassland yield from DairyWise includes feeding and storage losses and excludes field losses (net yield removed from the land); grassland yield from Farmdyn excludes feeding, storage, and field losses (feed intake).

4.1.2. Baseline Comparison

Comparing the baseline results of DairyWise and Farmdyn (Appendix B) showed almost similar figures for most of the studied parameters. Farmdyn assumes a legal allowed maximum of 250 kg N from animal manure per ha per farm as is the case on dairy farms with derogation in the sand regions in the North of the Netherlands. DairyWise assumes a maximum of 230 kg N per ha per farm—270 kg N per ha on grass (including N from pasturing) and 60 kg N per ha on maize—as is the case on dairy farms with derogation in the remaining (mid and south) sand regions in the Netherlands. The lower fertilisation rate of silage maize in DairyWise is explained by the crop rotation of silage maize with grass and the extra mineralisation from the incorporated grass sward. Other differences are, e.g., grass yield, consumption of grass silage by the herd, crude protein content in purchased concentrates, and excretions of N and P by the herd. These differences are in some cases related and can be explained by the different data sources and approaches and calculation methods and rules applied in DairyWise and Farmdyn. For our purposes, it is important that mineral N input per ha grassland in DairyWise (135 kg N per ha grassland) is about equal to the economic optimal N input per ha grassland in Farmdyn (131 kg N per ha grassland). Since different grassland management options are available in Farmdyn and there are some restrictions for grass production, exact calibration was impossible. In this respect, it is also important to note that in DairyWise in the baseline scenario, part of the grass output is sold outside the farm. Contrary to this, Farmdyn assumes no market for grass output for this representative dairy farm.

4.1.3. Scenario results; Economic impacts from Farmdyn

The results showed that applying the '100% tax on N from mineral fertiliser' scenario lowers the use of mineral fertiliser by 18 kg N per ha (from 131 to 113), which is equal to 14%. As a result, the price elasticity of N from mineral fertiliser for this farm is −0.14: 14 percent decrease in use of N from mineral fertiliser divided by 100% increase in price of N from mineral fertiliser. Farm income decreases with about 4500 Euro or about 8% of the farm income in the baseline (55,000 euro). The decrease in income is caused by 3400 Euro of increased costs of mineral fertiliser (due to the imposed tax) and about 2400 Euro of increased costs of concentrates (to compensate for the lower feed production). A part of the high costs can be saved by, e.g., less application of machinery for cultivation of grass (less cuts, lower frequency of mineral N application). This cost saving is around 1300 euro. With the assumption that in-farm management will be the same and equal amounts of mineral fertiliser will be used at a 100% higher price, the reduction in the income would be around 4600 euro.

4.1.4. Scenario Results: Technical and Environmental Impacts from DairyWise

Based on separate calculations regarding reduction of the N fertilisation in DairyWise, it became clear that by adapting the N regime to 60% of the optimal N fertilisation level, the optimal situation (after implementation of the tax) can be achieved in Farmdyn. Table 3 represents the technical results and environmental impacts calculated by DairyWise. Reducing the mineral N application lowered the grass yield (before losses during feeding and storage, but after field losses) from 12,223 kg to 11,663 kg dm per ha. This reduction in the grass yield can be explained by the reduction of mineral N application. Results showed the reduction of ammonia emissions from barns and manure storage facilities (from 1454 kg to 1373 kg NH_3 per farm per year). Similar reductions were observed for other NH_3 emission sources (like grazing and manure application). The reduction in N regime also caused lower N and P in animal excretions and lower nitrogen surpluses at soil and farm levels. The reduction in N surpluses was higher at farm level. Differences in GHG emissions are presented in Table 3. A small reduction in GHG emissions for the alternative scenario was seen. Given the fact that applying lower N application on grassland results in lower grass yields, additional maize and concentrates need to be purchased to fulfil. The purchased feeds increased the GHG emissions. On the other hand, less imported mineral fertilizer results in reduction of the total GHG emissions. Additionally, GHG emissions related to enteric fermentation were slightly diminished by the lower N-regime as feeding maize silage results in lower enteric fermentation compared to feeding grass silage. Therefore, a lower methane level was reported for this scenario. Finally, GHG emissions related to feed production were lower for the alternative scenario with less mineral N application. When all is summarized, total GHG emission were slightly lower with lower N-regimes.

Table 3. Model results from DairyWise for a simulated dairy farm on sandy soil at two different N fertiliser levels.

Item			N Regime in Percent of Agricultural Optimum	
			Baseline (68%)	**Scenario (60%)**
Effective [1] N supply grassland	Total	kg N/ha/year	213	185
	Animal manure	kg N/ha/year	78	78
	Mineral fertiliser	kg N/ha/year	135	107
Grass yield [2]		kg dm/ha/year	12,223	11,663
Ammonia emissions	From barns + animal manure storages	kg NH_3/farm/year	1454	1373
	From grazing	kg NH_3/farm/year	110	103
	From animal manure and fertiliser application	kg NH_3/farm/year	882	851
	Total NH_3 emission	kg NH_3/farm/year	2445	2328
	Total NH_3 emission	kg NH_3/ha/year	57	54
Excretions	N before deduction of any NH_3 emissions (whole herd including young stock)	kg N/farm/year	14,258	13,787
	P (whole herd including young stock)	kg P_2O_5/farm/year	5469	5357
N surplus	N farm surplus	kg N/ha/year	158	148
	P farm surplus	kg P_2O_5/ha/year	−8	−4
GHG emissions	From rumen fermentation	g CO_2 eq/kg FPCM	511	509
	From animal manure storage	g CO_2 eq/kg FPCM	137	137
	From feed production	g CO_2 eq/kg FPCM	91	87
	From energy resources	g CO_2 eq/kg FPCM	50	50
	From imports	g CO_2 eq/kg FPCM	334	326
	Total allocated to milk production	g CO_2 eq/kg FPCM	1123	1109
	Total before allocation	g CO_2 eq/kg FPCM	1399	1382

[1] Plant available N from manure and mineral fertiliser. [2] Yield after harvest losses, before conservation and feeding losses.

4.2. Model Collaboration between Farmdyn and NA: Baseline and Scenario Results

To apply Farmdyn and NA, a representative ware potato farm was selected. Appendix C shows input data used and assumptions. The farm was on clay soils in the Netherlands, which was calculated from the Dutch FADN database (bookkeeping year 2017). Farmdyn calculates under restrictions the optimal crop acreage (ha), yield per crop (tonnes per ha), animal manure and mineral fertiliser input per crop (kg N and P_2O_5 per ha; Table 4). These outputs of Farmdyn can directly be used as input in NA to calculate GHG emissions, N and P surpluses, the fate of the N surplus, and organic matter supply. Many of these parameters are also approximated by Farmdyn, but the NA gives a more detailed picture. In this case, harmonisation especially means checking whether effective N and P supply per crop per ha and the use of animal manure per ha (farm level) in Farmdyn align with the legally maximum allowed N and P application standards in NA. As for the dairy farm, a baseline and a scenario with a tax on N from mineral fertiliser were compared. For the dairy farm, a tax level of 50% was taken instead of the 100% on the dairy farm. Applications with Farmdyn in de Koeijer et al. [30] showed that on dairy farms, a higher tax is needed to realise a comparable impact than on arable farms. This is due to the fact that the economic effect of a reduced mineral N rate is stronger on an arable farm than on a dairy farm. Table 4 shows that average farm income of ware potato farms on clay soils was about 40,000 Euro over the period 2013–2017.

Table 4. Specification of a representative ware potato farm on clay soil in the Netherlands in base and in scenario with 50% tax on mineral fertiliser.

Parameter	Base	50% Tax on N from Mineral Fertiliser
Total acreage	61	61
• Winter wheat	23	23
• Ware potato	19	19
• Sugar beet	9	9
• Onions	10	10
Crop yields		
• Winter wheat	9.5	9.2
• Ware potato	52.1	52.1
• Sugar beet	104.1	103
• Onions	52.9	52.9
Fertilisation		
• Animal manure		
○ N, kg/ha	65	65
○ P_2O_5, kg/ha	39	39
• Mineral fertiliser		
○ N, kg/ha	167	144
○ P_2O_5, kg/ha	17	17
Farm income (Euro)	40,000 [1]	36,000

[1] Average over period 2013–2017. Calculated from Dutch FADN; Source: calculations with Farmdyn.

4.2.1. Farmdyn

Table 4 shows that the imposed tax on mineral N fertiliser did not affect the optimal crop composition on the arable farm. The mineral N fertiliser decreased with 23 kg N per ha due to a lower N supply on winter wheat and sugar beets resulting in a somewhat lower crop yield (Table 4). For these crops, the financial saving on mineral fertiliser exceeds the loss in crop revenue. As the yield response on N fertilisation is quite weak, only minor effects on crop yield were calculated. The manure supply was the same for the two scenarios, based on the legislation regarding maximum amount of N and P from animal manure per ha per crop.

The tax scenario reduces mineral fertiliser N input with about 14%. For the arable farm, a price elasticity of mineral fertiliser N of -0.28 was calculated: 14 percent reduction of mineral N fertiliser divided by a 50% higher price of the mineral fertiliser.

Income loss due the 50% tax on mineral fertiliser is about 4000 euro, or about 10% of the average farm income in the base (Table 4). This income loss results from a lower financial yield of about 1500 Euro and higher costs of mineral fertiliser of about 2500 Euro (due to the tax) resulting in an income loss of 4000 Euro. When no changes in crop management were done, the tax would have caused an income loss of about 4330 Euro. so only about 330 Euro more than with farm management changes included. This relatively small difference show that price measures have a limited effect on the use of mineral N fertilisers. Further innovations in nutrient and crop management that increase N efficiency—e.g., precision technology, varieties with higher N efficiency, more green manure crops, legumes—may also help to decrease mineral fertiliser demand, but it is questioned whether these measures are always economically feasible.

4.2.2. Nutriëntenbalans Akkerbouw (NA)

In Table 5, the outcomes of the calculations with the NA tool are presented. The tax scenario reduced the N surplus with 15 kg N per ha. The NH_3 emission increased somewhat due to the fact a larger part of the animal manure was applied on winter wheat.

This increases the risks of NH_3 emission as the manure is applied more superficially on winter wheat.

Table 5. N and P_2O_5 surplus, NH_3-N emission, effective organic matter supply, and GHG emissions of the two scenarios (base and fertiliser tax) for the arable potato farm on clay as calculated by the NA tool.

Parameter	**Base**	**50% Tax on N from Mineral Fertiliser**
Nutrient surpluses		
• N surplus, kg/ha	83	68
• P_2O_5 surplus, kg/ha	−11	−8
NH_3-N emission, kg/ha	13	14
Organic matter: Effective organic matter [1] supply (kg/ha)	1810	1810
GHG emissions:		
• Total (kg CO_2 eq/ha) [2]	2941	2730
○ CO_2 direct	601	601
○ CO_2 indirect	906	783
○ N_2O direct	1307	1230
○ N_2O indirect	127	116

[1] Applied organic matter (organic manure, crop residues) that is still present after one year. [2] CO_2 direct: fuel consumption; CO_2-indirect: fertiliser use; N_2O direct: use of N in manure and fertiliser and N in crop residues; N_2O indirect: resulting from NH_3 and NO_3 emission.

Most of the effective organic matter (EOM) supply is coming from crop residues (1515 kg EOM per ha) and only a minor part comes from the manure (265 kg EOM per ha). The tax measure did not change the EOM supply.

The total amount of GHG emissions of the arable farm in the base scenario is about 2900 kg CO_2 eq per ha. About 45% of the emission comes from CO_2 emission and about 55% from N_2O emission. The tax measure decreases the GHG emissions with about 200 kg CO_2 eq per ha caused by a lower mineral N fertiliser use, affecting the indirect CO_2 emission and the direct N_2O emission.

4.3. Discussion and Conclusion of Baseline and Scenario Results

Comparing the baseline results of DairyWise and Farmdyn (Appendix B) showed limited differences between key model output parameters. However, substantial differences were observed for some parameters such as the grassland yield and grass silage use by the herd. Full understanding of above-mentioned differences in model outcome is difficult because processes of grassland management, fertilising, and feeding are modelled in a different manner. As noted by Hutchings et al. [12], full understanding of differences between model outcome requires detailed model knowledge of all models involved. For our model collaboration purposes and scenario, the most important part was the calibration of the implicit N response curve from Farmdyn to the N response curve in DairyWise.

Regarding the tax on N from mineral fertilisers, it was found that income effects are relatively large, while the impacts on various environmental indicators are relatively limited. This is especially true for dairy farms. The decrease in N surplus on the average dairy farm equals about 10% against about 18% on the average ware potato farm. At the same time, the scenario assumes a tax on N from mineral fertiliser that is twice as high on dairy farms as compared to the ware potato farm. The GHG emission reduces with about 1% and 7% on the average dairy farm and ware potato farm, respectively.

Moreover, from literature it is known that that the percentage change in use of N from mineral fertiliser per percentage change in price of N from mineral fertiliser, the so-called price elasticity of N from mineral fertiliser is very low in agriculture, especially in the short run [32]. According to Sud [32], this is explained by "lack of knowledge regarding alternative practices amongst farmers, strong risk aversion tendencies, behavioural factors and lack of alternatives". Basically, substitution between nutrients from animal manure and mineral fertiliser is not possible on dairy farms that have to transport their surplus manure to other farms due to the manure legislation. Farms that are able to import manure on their farm such as, e.g., arable farms and extensive dairy farms, are paid for supplying manure application room. Therefore, also on these farms the available manure application room is limited or limited by agronomic restrictions, e.g., regarding the amount of animal manure that can be applied on onions and sugar beet.

Especially for the dairy farm, the impact of the tax on use of N from mineral fertilisers is very sensitive to slope and range of the implicit N response curve in Farmdyn. Grassland management measures to achieve the same protein and/or dry matter yield with lower N input might be applied to dampen the income effect of the tax. As an example, protein yield could be increased by early harvesting of silage grass or more clover in the grassland. These changes in farm management practices might increase production costs (early harvesting of grass silage) and/or decrease grassland yields (more clover in grassland).

Use of innovative precision farming technologies enables increased efficiency of the fertilizers. These technologies and related investments are quite costly. Adoption of such economy of scale investments would be stimulated by structural change with farms exiting the sector and corresponding growth of continuing farms. This is, however, a slow process among others explained by the concept of sunk costs in agricultural production [33].

The costs of the tax on farm level can be compared to the costs to produce renewable fertilisers from processed manure. When legally allowed, renewable fertilisers from processed manure could replace the mineral fertilisers. A study from de Koeijer et al. [30] shows that the costs to produce renewable fertilisers is equivalent to 100% tax on mineral fertilisers. In addition, the substitution will be limited because of the limited availability of renewable fertiliser from processed manure [30].

5. Model Collaboration: Governance and Networking

DairyWise, Farmdyn, and the NA tool are developed and used by different groups within WR, respectively Wageningen Livestock Research (WLR), Wageningen Economic Research (WEcR), and Wageningen Plant Research (WPR). The cooperation between these institutes and models has been made possible within the Knowledge Base (KB) theme 'Circular and Climate Neutral Society' of WR. A four-year project called 'Transform current linear primary production chains into production cycles (Subtheme 2A-4): Models Across Scales' was established in 2019 within this KB to support the transition to a circular agriculture. The objective of this project was the development of an integrated set of models and tools (i.e., a toolbox), accounting for scales (of closing cycles), various aspects and indicators focussing on primary agricultural production. This toolbox should be used for monitoring and integratedly assessing policy scenarios for increased circularity with the aim to support farmers, policy makers, and other stakeholders including other researchers. The project offered the possibility to bring together networks of farm level model and tool developers and users from different institutes and with different backgrounds, objectives, programming languages, and IT solutions. Given the overlap between BEFMs and the current governance and economic incentive structures, this would normally not happen under the condition of competitive budgets [34].

The KB project mentioned above is actually an example of good model governance and networking [3,34]. It opens the possibility to broaden the use of the models in the network by re-using existing tools and to exploit the potentials of harmonisation of data and modules and shared maintenance and development of new modules within a larger user community. To extend this type of model collaboration to other regions, used models need to be adapted or other models need to be applied to fit local circumstances. According to Britz et al. [34], a network of farm models and tools should enable users and developers to accumulate domain knowledge in building, parameterising, and applying the collaboration between the models. Britz et al. [34] point at the importance of defining (i) the thematic domain of the network, (ii) common standards as software engineering rules and, (iii) actions of the network, e.g., give directions to which farm model enhancements are best suited to the farm models in the network. Equally important is that the network stimulates innovation and educates new staff that engage in joint activities and discussions, help each other, and share information [34].

6. Conclusions and Recommendations

The main objective of this paper was to investigate model collaboration between different BEFMs and a tool focussing on emissions from arable farming to broaden the scope of an ex-ante analysis of scenarios related to circular agriculture at farm level. A baseline calculation and scenario with a tax on N from mineral fertiliser was analysed to demonstrate a possible policy measure to enhance circular agriculture and to demonstrate the usefulness of model collaboration at farm level.

Challenges of model collaboration are among others overlapping modules, different approaches (optimisation versus simulation) and existence of different networks of model developers and users. A good example is the overlap between DairyWise and Farmdyn. We discovered complementarities, e.g., regarding more detailed grassland management modules in DairyWise or the suitability to analyse economic policies as taxes and subsidies in Farmdyn. Model collaboration allows exploiting these complementarities, e.g., including response curves from DairyWise in Farmdyn. In this case, we harmonised the N-response curves.

Model collaboration is also a manner to validate the model outcomes. When comparing the results of DairyWise to Farmdyn, it became clear that model results differed due to differences in input parameters, e.g., emission and feed content parameters.

Farm models and collaboration between farm models are important tools for ex-ante policy assessment at farm level. To increase the network of model developers and users it is recommended to invest in model documentation and tools to transfer knowledge to new model users. To further foster model collaboration between different models and a growing number of users, a governance structure and networking is needed. A meta-platform beyond the level of individual models to answer more complex questions and to permit broader and cross-cutting assessments, could serve these purposes.

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Appendix A. General Description of Selected BEFMs and the NA Tool

Appendix A.1. Farmdyn

Farmdyn is a bio-economic, mixed-integer programming model at individual farm level that simulates a farmer's decisions regarding agricultural production and investments in a comparative static or dynamic setting [7,35]. The model was developed at the University of Bonn and is primarily used for the analysis of farm-level responses to various environmental and policy scenarios, using data on farm structure, machinery, buildings, animal feed rations, etc., available in a German context. Farmdyn is used at Wageningen Economic Research since late 2018 and is adjusted stepwise to Dutch conditions by exploiting information available from data sources like the Dutch Farm Accountancy Data Network (FADN) or quantitative information on farming operations (management handbook Quantitative information (-Kwantitatieve Informatie Veehouderij (KWIN-Veehouderij)) [36,37]), such that it becomes applicable to analyse representative or individual arable and dairy farms in the Netherlands.

Appendix A.2. General Description (Taken from [34])

Farmdyn allows simulating optimal farm management and investment decisions under restrictions such as prices, technology, or policy instruments for arable and dairy farming systems. Farm branches and other biophysical processes such as feeding and fertilisation, and fertiliser and animal manure policy restrictions can be added in a modular fashion to the core model. The model is capable of running every individual (dairy and arable) farm in the Dutch FADN, using farm specific financial-economic and technical data (e.g., input and output prices, crop yields, and milk production per cow). Number of operations per crop, field operation per period, labour hours per operation, machinery need for the different operations and prices, life span and maintenance costs of machineries are taken from KWIN.

In case of dairy farms, the model differentiates among others by grazing share of the cows and differentiated grassland management options. Feeding requirements for the dairy herd capture a cost minimal feed mix from own produced fodder and different types of concentrates at given requirements per head (energy, protein, dry matter) for each cattle herd. The default Farmdyn setting allows defining up to 10 different types of grassland management options by the following attributes: 1. Total dry matter output and nutrient content of grass, 2. Level of effective nitrogen input from animal manure and mineral fertiliser, 3. Distribution of fresh grass and grass silage over months, 4. Number of cuts (only applicable for grass silage). The different types of grassland management each produce three types of fresh or silage grass (early, middle, and late). Production of early silage grass requires more cuts per year. In this paper the allowed types of grassland and the corresponding dry matter output and the total level of nitrogen input are harmonised with DairyWise. Roughage can be exported from the farm or imported. A module describes in detail the measures of the Dutch Nitrate and Water Framework directive. Farmdyn allows experiments with different animal manure types and related storage and application chains. Animal manure can be used on the own farm or exported from the farm. Animal manure import is allowed as well.

The cropping module optimises the cropping pattern subject to land availability, reflecting yields, prices, machinery and fertilising needs, and other variable costs for a list of arable crops. Crop rotational constraints are included as maximal shares. The crops can be differentiated by tillage (ploughing, minimal tillage, no tillage) and intensity level (normal and reduced fertilisation in 20% steps). Operation and machinery data are taken from above mentioned management handbooks.

Appendix A.3. DairyWise

DairyWise [6] is an empirical simulation model that simulates the technical, environmental, and financial processes of a dairy farm. Technical and economic indicators are modelled by a combination of farm-specific and normative input values. Strengths and weaknesses of a farm can be derived from these technical and economic indicators, and effects of changes can be assessed. DairyWise has been used by scientists, policy makers, extension workers, teachers, and farmers for developing and evaluating integrated scenarios.

Appendix A.4. General Outline

DairyWise integrates all the main subsystems of a dairy farm into a farm model [6]. The requirements of the herd, calculated by the DairyHerd model, and the supply of homegrown feeds, calculated by crop models for grassland and corn silage, are balanced by the FeedSupply model, which is the central component of the model. The results of the FeedSupply model are fed into several technical, environmental, and economic submodels. These sub-models simulate several issues, like cycling of N and P, leaching of NO_3^-, emissions of NH_3 and GHG, energy use, and financial results. The main output is a farm plan that describes all material and nutrient flows, as well as ecological and economic consequences.

DairyWise is a farm level model that includes the dairy cattle and young stock herd, home-grown grass, maize, as silage or corn cob mix (CCM), triticale, lucerne, and fodder beets. Imports of feed, animal manure, and mineral fertiliser and exports of grass, crops, milk, meat (live animals), and animal manure can be included in the model. Animal feed requirements, milk, meat and manure production, and crop growth are modelled.

Depending on the data availability, DairyWise can be run with different levels of detail in its inputs. Minimally, one should provide animal numbers and data on feed land and crop management, and some additional variables. For each category, there is an option to elaborate the inputs and change default values.

As explained previously, DairyWise consists of various models. GrassGrowth [38,39] and maize models [40] are used as crop models. The animal models consist of a DairyCow [41], YoungStock, and DairyHerd model [42]. The FeedSupply model balances the energy and protein requirements of the herd with the supply from homegrown and imported feeds.

Next to the mentioned models, DairyWise performs several additional calculations on, e.g., nutrient cycling, energy use, GHG emissions, and economic parameters.

DairyWise output encompasses, among other things, data on economic performance, feed supply, nutrient cycling, mineral and energy balances, GHG emissions, labour demand, and consequences of animal manure policies. Some outputs are based on the "Annual Nutrient Cycle Assessment" [43] (in Dutch: "KringLoopWijzer Melkveehouderij" (KLW)) calculations.

Appendix A.5. Nutriëntenbalans Akkerbouw

With the Nutriëntenbalans Akkerbouw (NA), N and P surpluses on an arable farm can be calculated. Required input data for the tool comprise the crop composition, crop production levels, and the nutrient supply with manure and mineral fertilisers [22]. The reason for developing the tool was the demand to be able to prove the need for farm specific legal allowed N and P fertilisation levels (application standards). The current legal levels refer to an average animal manure use and average crop production levels. Farmers with high crop production claim that a higher nutrient supply is necessary in order to keep the crop production at a high level. The NA can potentially be used for validating this claim. In addition to the nutrient surpluses, the NA also calculates the fate of the N surplus (via NH_3, NO_3, N_2, N_2O), the GHG emissions (CO_2 and N_2O), and the organic matter supply.

The NA comprises a registration module and a forecast module. The registration module calculates the nutrient surpluses based on the fertilisation and crop production data for a specific year. With the forecast module the effects of changing the farm management can be explored, e.g., changing the crop composition, insertion of green manure crops, or adjusting the fertilisation.

Limitations for the use of NA are:

- The tool is made for arable farms. Besides arable crops, also a limited number of vegetables and flower bulb crops often grown on arable farms, are included, but grass is excluded.
- The calculation of surpluses is limited to N and P.
- The calculations only comprise nutrient emission indicators, organic matter supply, and GHG-emissions. Economic indicators are excluded.

Per crop/field the data for nutrient supply and crop production levels are needed. Data regarding nutrient supply refer to dosage, timing, and method of application, both for organic and mineral fertilisers. For organic fertilisers the N (total N and NH_4-N), P, and organic matter contents are needed. If not available, default values can be chosen.

Next to fertilisation and crop production data, a couple of soil parameters are needed: organic matter content and P soil content.

Appendix B. Characteristic (Input Data) of Representative Dairy Farm on Sandy Soil and Baseline Comparison of DairyWise and Farmdyn

This appendix describes the characteristics of the representative dairy farm on sandy soils and a baseline comparison between the model outcomes of Farmdyn and DairyWise. Table A1 shows the characteristics as taken from the Dutch FADN database and averaged to the representative dairy farm on sandy soil. The predominant crop on the farm is grass used for grazing or ensilaging. In addition to grass production, 9 ha of land is under maize cultivation.

Table A1. Characteristics of representative dairy farm on sandy soil.

Parameter	Unit	Farm
Number of dairy cows	Number	94
Replacement rate of dairy cows	%	30
Soil type of grassland		Sandy soil
Ground water level for grassland		V
N yielding capacity of grassland	kg/ha	138
Grassland renewal percentage	%	10
Total pasture area	Ha	37
Pasture area for dairy cows	Ha	26
Pasture area for calves	Ha	4.4
Pasture area for heifers	Ha	6.6
Total silage maize area	Ha	9
Soil type of maize land		Sandy soil
Ground water level for maize land		VI
Number of years in rotation for maize	Year	5
N yielding capacity for silage maize	kg/ha	138
Catch crop for silage maize		Yes
Type of catch crop		Grass
Total own area	Ha	30
Total lease area	Ha	16
Fat percentage of milk	%	4.42
Protein percentage of milk	%	3.56
Lactose percentage of milk	%	4.51
P content of milk	mg P/100 g	97
Milk production	kg/cow per year	8600
Grassland use system		B
Additional roughage in summer	kg dry matter/cow/day	6
Barn type—dairy barn		Barn with cubicles and slatted floor

Table A1. *Cont.*

Parameter	Unit	Farm
Animal manure storage under barn	Month	3
Barn type—young cattle barn		Barn with cubicles and slatted floor
Animal manure storage under young stock barn	Month	3
Type of animal manure storage outside the barn		Silo
Content of animal manure storage outside the barn	m^3	1000
Slurry application method on grassland		Shallow injection
Slurry application method on silage maize		Injection
P rights	kg P_2O_5	4000

A selection of baseline results of Farmdyn and DairyWise are shown in Table A2. Model outputs are classified in different categories including herd characteristics, feed use by herd, and mineral and organic fertilisation. Parameters are identified as endogenous (Y, result of modelling) or exogenous (X, input by the user) parameters. Full understanding of differences of results between DairyWise and Farmdyn is difficult because of different feed-back loops within the models. This is also noted by Hutchings et al. [12]. Important differences can be explained by for example different modelling approaches (optimisation versus simulation), different modelling of grassland management, and feed requirement of the dairy herd. One substantial difference between the outputs of these two models was the amount of concentrate in the diet of the farm, where the yearly concentrate consumption per farm was calculated to be 256,108 kg and 280,356 kg by Farmdyn and DairyWise, respectively. This difference can be explained by the differences in energy and/or protein content of other feed components such as fresh grass and grass silage. In other words, the shares of feed components in the total diet are interdependent as the herd feed demand is calculated based on the energy contents of feed components. Given the lower energy content of fresh grass and grass silage, a larger value was calculated for the concentrate requirement in the DairyWise model. In the mineral and organic fertilisation category, similar results were obtained from both models. In case of grassland, higher applied N from animal manure was reported in Farmdyn while in DairyWise, the N from mineral fertiliser was higher.

Table A2. Characteristics of representative dairy farm on sandy soil.

Item	Unit	Type of Parameter in the Model (Endogenous (Y)/Exogenous (X))		Farm	
		Farmdyn	DairyWise	Farmdyn [1]	DairyWise
(A) Herd characteristics					
Dairy cows	#	X	X	94	94
Milk production	kg/cow/year	X	X	8600	8600
Urea content	mg/100 mL milk	X	Y	22	28
(B) Feed use by herd					
Fresh grass	kg dm/farm/year	Y	Y	134,420	165,819
Grass silage	kg dm/farm/year	Y	Y	247,335	234,790
Maize silage	kg dm/farm/year	Y	Y	130,617	130,784
By-product	kg dm/farm/year	Y	—	29,610	
Concentrates	kg/farm/year	Y	Y	256,108	280,356
Energy content concentrates	VEM/kg dm	Y	Y	1044	1073
Protein content concentrates	g CP/kg dm	Y	Y	189	151.7

Table A2. *Cont.*

Item	Unit	Type of Parameter in the Model (Endogenous (Y)/Exogenous (X))		Farm	
		Farmdyn	DairyWise	Farmdyn [1]	DairyWise
(C) Mineral and organic fertilisation					
Grassland					
Applied N from animal manure	kg N/ha/year	Y	Y	264[1]	187
N from mineral fertiliser	kg N/ha/year	Y	Y	131	135
Silage maize					
Applied N from animal manure	kg N/ha/year	Y	Y	193	59.6
N from mineral fertiliser	kg N/ha/year	Y	Y	53	83
(D) Animal excretions					
Nitrogen before subtraction of any ammonia losses (whole herd including young stock)	kg N/farm/year	X	Y	16,000	14,258
Nitrogen based on RVO-tables (4 and 6)	kg N/farm/year	X	Y	13,383	15,077
Phosphorus (whole herd including young stock)	kg P_2O_5/farm/year	X	Y	4963	5469
Phosphate based on RVO-tables (4 and 6)	kg P_2O_5/farm/year	X	Y	—	4884

[1] Farmdyn includes excretion of N during pasturing. This is not included in applied N from animal manure in DairyWise.

Appendix C. Farmdyn Representative Arable Farm Input Data and Assumptions

Based on technical-economic data of individual farms in the Dutch FADN (year 2017), a representative ware potato farm on clay soil was constructed. This was done by using cluster analysis. The total crop area of the farm is 61 ha. The crop composition plan and the financial yield (crop yield × price) minus direct costs (e.g., seed, crop protection) per crop as derived from the Dutch FADN (bookkeeping year 2017) are given in Table A3. The fertilisation costs are not included but added later on.

Table A3. Crop composition and financial yield minus seed, crop protection and other direct costs (Euro per ha) for an average ware potato farm on clay soil in the Netherlands, bookkeeping year 2017. Source: Dutch FADN, bookkeeping year 2017.

Crops	Share in Total Cropping Area (%)	Financial Yield Minus Seed, Crop Protection and Other Direct Costs (Euro Per ha)
Winter wheat	27	1166
Ware potatoes	26	2786
Sugar beet	15	3881
Onions	12	3854
Grass seed	5	1206
Winter barley	4	848
Summer peas	3	1361
Arable root crops	2	−537
Remaining crops (seed potatoes, maize silage, set aside, arable vegetables)	3	

Typically, this method of defining a representative farm leads to a cropping plan with a large number of individual crops. In order to get a more realistic cropping plan, only crops having a share of more than 7.5 percent in the total crop area were chosen for the optimisation in Farmdyn. The applied procedure for optimisation mainly results in an increase in the cropping share of winter wheat. Upper limits for cropping frequency are included for the high margin crops individually. These upper limits are based on the range of observed shares in the cropping plan of the farms in the FADN. On top upper limits are included for crop groups, e.g., the root crops. To enrich the income calculation, costs for mineral fertiliser, animal manure, hired labour, and machinery costs (based on machinery needs, prices, depreciation rates, and maintenance costs) are added in Farmdyn. Machinery prices, depreciation rates, and maintenance costs are taken from management handbooks. Output prices of arable products can strongly vary among years. Although 2017 is considered quite an average year for arable farms, prices of ware potatoes were very low. Therefore, for baseline reasons, we use three-year average prices. Resulting prices for the selected four crops in our cropping plan are presented in Table A4. Farmdyn also allows including autonomous developments. In this study, it is important that we assume a decrease of the price of sugar beet to the minimum price of 3.25 Euro per 100 kg. An autonomous slight increase in cropping share of high margin crops is included as well.

Table A4. Three year (2015–2017) average price of selected arable products (Euro per 100 kg).

Crops	Average Price (Euro Per 100 kg)
Winter wheat	16
Ware Potatoes	14.3
Sugar beet	4.2
Onions	11.6

For our purposes, especially the modelling of the nutrient needs and the crop yield response to nutrient supply are important. Nutrient demands or input can be fulfilled with nutrients from mineral fertiliser and from (animal) manure. The N supply per crop is based on the legal allowance of N per crop per region per ha (see Table A5). These standards apply to effective N, i.e., the amount that is available for crop uptake. In our study, we assumed that the farm only uses pig manure containing 6.4 kg N and 3.8 kg P_2O_5 per m^3. For the effective N in the pig manure, the legal value of 60% of total N is taken. In the Netherlands, arable farmers are often paid to accept animal manure, but the total manure supply is limited by legislation (max 170 kg manure N per ha). To further control the application of animal manure per crop, an upper limit of 120, 250, and 67 kg total N per ha (from which 60% is assigned effective, see above) is included for winter wheat, ware potatoes, and green manure crops, respectively. It is assumed that animal manure is not applied to sugar beets and onions.

Table A5. N-advice/N application standards (effective N) for the selected arable crops on clay soils.

Crops	Legally Allowed N-Supply (kg Effective N/ha)
Winter wheat	245
Ware potatoes	250
Sugar beet	150
Onions	170
Catch crop	60

For a number of crops, there is a difference between the P uptake and P demand. This is accounted for. That is, for winter wheat, it is assumed that the P demand is low compared to the P uptake. The P demand per ha per crop is assumed constant, independent of the yield of the crop. Crop yield is assumed to be a function of the effective N demand or input. The linear programming model Farmdyn distinguishes between five levels of N demand: normal and 80%, 60%, 40%, and 20% of normal. The corresponding yield coefficients for potatoes and sugar beet are taken from [44]. The yield coefficient for winter wheat is taken from [45]. Results are presented in Table A6. The yield curve is very flat, meaning that a reduction of N has limited impact on yield. Due to a lack of data, effective N demand and yield of onions are assumed to be constant. Catch crops are included in the model, but they have no crop yield and there is no relationship to yield from other crops. It is assumed that crops harvested in summer are always followed by a catch crop.

Table A6. Coefficient of the response curve between yield and N. Source: [30,44] and own extrapolation.

Crops	Normal/Advice	Fert80	Fert60	Fert40	Fert20
Winter wheat	1	0.99	0.96	0.906	0.85
Ware potatoes	1	0.974	0.936	0.906	0.85
Sugar beet	1	0.989	0.963	0.906	0.85

References

1. LNV. Visie Landbouw, Natuur en Voedsel: Waardevol en Verbonden. Available online: https://www.rijksoverheid.nl/documenten/beleidsnota-s/2018/09/08/visie-landbouw-natuur-en-voedsel-waardevol-en-verbonden (accessed on 25 November 2022).
2. Helming, J.; Daatselaar, C.; van Dijk, W.; Mollenhorst, E.; Pishgar-Komleh, H.; Conijn, S.; Brinkman, P. Selected Farm Level Models and Tools for Ex-Ante Analysis of Impacts of Policies Related to Circular Agriculture: Deliverable D2: Progress Report Project KB-1-2A-4: Models across Scale; 2021. Available online: https://edepot.wur.nl/557357 (accessed on 1 July 2022).
3. Gonzalez-Martinez, A.; Jongeneel, R.; Salamon, P. Lighting on the Road to Explore Future Directions for Agricultural Modelling in the EU–some Considerations on What Needs to be Done. *Int. J. Food Syst. Dyn.* **2021**, *12*, 287–300.
4. Pyka, A.; Cardellini, G.; van Meijl, H.; Verkerk, P.J. Modelling the Bioeconomy: Emerging Approaches to Address Policy Needs. *J. Clean. Prod.* **2022**, *330*, 129801. [CrossRef]
5. Lesschen, J.P.; Reijs, J.; Vellinga, T.; Verhagen, J.; Kros, H.; de Vries, M.; Jongeneel, R.; Slier, T.; Martinez, A.G.; Vermeij, I. *Scenariostudie Perspectief voor Ontwikkelrichtingen Nederlandse Landbouw in 2050*; Wageningen Environmental Research: Wageningen, The Netherlands, 2020; ISSN 1566-7197.
6. Schils, R.L.M.; De Haan, M.H.A.; Hemmer, J.G.A.; Van den Pol-van Dasselaar, A.; De Boer, J.A.; Evers, A.G.; Holshof, G.; Van Middelkoop, J.C.; Zom, R.L.G. DairyWise, a Whole-Farm Dairy Model. *J. Dairy Sci.* **2007**, *90*, 5334–5346. [CrossRef]
7. Anonymous. A Highly Detailed Template Model for Dynamic Optimization of Farms (FARMDYN). Available online: http://www.ilr.uni-bonn.de/em/rsrch/Farmdyn/FarmdynDoku/ (accessed on 1 July 2022).
8. Vellinga, T.V.; Hoving, I.E. Maize Silage for Dairy Cows: Mitigation of Methane Emissions can be Offset by Land Use Change. *Nutr. Cycl. Agroecosyst.* **2011**, *89*, 413–426. [CrossRef]
9. Vellinga, T.V.; De Haan, M.H.A.; Schils, R.L.M.; Evers, A.; Van den Pol–van Dasselaar, A. Implementation of GHG Mitigation on Intensive Dairy Farms: Farmers' Preferences and Variation in Cost Effectiveness. *Livest. Sci.* **2011**, *137*, 185–195. [CrossRef]
10. Evers, A.; de Haan, M.; Vermeij, I.; van Schooten, H. *Economische Gevolgen Ammoniakemissie Reducerende Maatregelen: Scenariostudie van Praktijkbedrijven in Overijssel*; Wageningen UR Livestock Research: Wageningen, The Netherlands, 2015.
11. Evers, A.; de Buisonjé, F.; Melse, R.; Verdoes, N.; de Haan, M. *Scenariostudie Mono-Vergisten op Melkveebedrijf met Veengrond*; Wageningen Livestock Research: Wageningen, The Netherlands, 2019; ISSN 1570-8616.
12. Hutchings, N.; Gülzari, Ş.Ö.; De Haan, M.; Sandars, D. How do Farm Models Compare When Estimating Greenhouse Gas Emissions from Dairy Cattle Production? *Animal* **2018**, *12*, 2171–2180. [CrossRef]
13. Reijs, J.; Beldman, A.; de Haan, M.; Evers, A.; Doornewaard, G.; Vermeij, I. *Perspectief voor Het Verlagen van NH3-Emissie uit de Nederlandse Melkveehouderij: Verkenning van Reductiepotentieel en Economische Impact op Sectorniveau op Basis van Integrale Doorrekening Maatregelen op 8 Representatieve Melkveebedrijven*; Wageningen Economic Research: Wageningen, The Netherlands, 2021.
14. Heinrichs, J.; Jouan, J.; Pahmeyer, C.; Britz, W. Integrated Assessment of Legume Production Challenged by European Policy Interaction: A Case-Study Approach from French and German Dairy Farms. *Q Open* **2021**, *1*, qoaa011. [CrossRef]
15. Lengers, B.; Britz, W.; Holm-Muller, K. What Drives Marginal Abatement Costs of Greenhouse Gases on Dairy Farms? A Meta-Modelling Approach. *J. Agric. Econ.* **2014**, *65*, 579–599. [CrossRef]
16. Mosnier, C.; Britz, W.; Julliere, T.; De Cara, S.; Jayet, P.-A.; Havlík, P.; Frank, S.; Mosnier, A. Greenhouse Gas Abatement Strategies and Costs in French Dairy Production. *J. Clean. Prod.* **2019**, *236*, 117589. [CrossRef]
17. Schäfer, D.; Britz, W.; Kuhn, T. Flexible Load of Existing Biogas Plants: A Viable Option to Reduce Environmental Externalities and to Provide Demand Driven Electricity? *Ger. J. Agric. Econ.* **2017**, *66*, 109–123.
18. Kuhn, T.; Enders, A.; Gaiser, T.; Schäfer, D.; Srivastava, A.K.; Britz, W. Coupling Crop and Bio-Economic Farm Modelling to Evaluate the Revised Fertilization Regulations in Germany. *Agric. Syst.* **2020**, *177*, 102687. [CrossRef]
19. Poppe, K.; van Duinen, L.; de Koeijer, T. Reduction of Greenhouse Gases from Peat Soils in Dutch Agriculture. *EuroChoices* **2021**, *20*, 38–45. [CrossRef]
20. de Koeijer, T.; Helming, J.; Greijdanus, A.; Müller, M.; Blokland, P.W. *Modelinstrumentarium voor Groene Cirkels: Demonstratiemodel voor Verkenning Trade-offs Duurzaamheidsindicatoren in Melkveehouderij en Akkerbouw*; Wageningen Economic Research: Wageningen, The Netherlands, 2020; Available online: https://edepot.wur.nl/530490 (accessed on 1 July 2022).

21. Daatselaar, C.; Helming, J.F.M.; Michels, R.; Reinhard, S.; Berkhout, P. Integrale Effecten Klimaatmaatregelen. Available online: https://edepot.wur.nl/555268 (accessed on 25 November 2022).
22. Schröder, J.J.; Rutgers, B. *Kringloopwijzer Akkerbouw: Rekenmodel versie 'April 2018'*; Stichting Wageningen Research, Wageningen Plant Research, Business Unit: Wageningen, The Netherlands, 2018.
23. Jongeneel, R.; Gonzalez-Martinez, A.; Lesschen, J.P.; van Meijl, H.; Heckelei, T.; Salamon, P. Deliverable 1.10 The SUPREMA Roadmap Exploring Future Directions for Agricultural Modelling in the EU. Report Published in the Context of the Project Support for Policy Relevant Modelling of Agriculture (SUPREMA); The European Union's Horizon 2020. Available online: https://www.suprema-project.eu/images/Deliverable_D110.pdf (accessed on 1 July 2022).
24. Wicke, B.; Van Der Hilst, F.; Daioglou, V.; Banse, M.; Beringer, T.; Gerssen-Gondelach, S.; Heijnen, S.; Karssenberg, D.; Laborde, D.; Lippe, M. Model Collaboration for the Improved Assessment of Biomass Supply, Demand, and Impacts. *Gcb Bioenergy* **2015**, *7*, 422–437. [CrossRef]
25. Helming, J.; Tabeau, A.; Kuhlman, J.; van Tongeren, F. Linkage of GTAP and DRAM for Scenario Assessment: Methodology, Application and Some Selected Results. 2006. Available online: https://www.gtap.agecon.purdue.edu/resources/download/2502.pdf (accessed on 1 July 2022).
26. Kuhlman, T.; van Tongeren, F.W.; Helming, J.F.M.; Tabeau, A.A.; Gaaff, A.; Groeneveld, R.A.; Koole, B.; Verhoog, A.D.; Dekkers, J. Future Land-Use Change in the Netherlands: An Analysis Based on a Chain of Models. *Ger. J. Agric. Econ.* **2006**, *55*, 238–247.
27. Perez Dominguez, I.; Gay, S.H.; M'Barek, R. An Integrated Model Platform for the Economic Assessment of Agricultural Policies in the European Union. *Ger. J. Agric. Econ.* **2008**, *57*, 379–385.
28. Creutzig, F.; Popp, A.; Plevin, R.; Luderer, G.; Minx, J.; Edenhofer, O. Reconciling Top-Down and Bottom-Up Modelling on Future Bioenergy Deployment. *Nat. Clim. Change* **2012**, *2*, 320–327. [CrossRef]
29. Van Meijl, H.; Havlik, P.; Lotze-Campen, H.; Stehfest, E.; Witzke, P.; Domínguez, I.P.; Bodirsky, B.L.; van Dijk, M.; Doelman, J.; Fellmann, T. Comparing Impacts of Climate Change and Mitigation on Global Agriculture by 2050. *Environ. Res. Lett.* **2018**, *13*, 064021. [CrossRef]
30. de Koeijer, T.; Luesink, H.; Helming, J. *Vervanging Kunstmest Door Dierlijke Mest: Verkenning van Opties voor de Inzet van Financiële Instrumenten*; Wageningen Economic Research: Wageningen, The Netherlands, 2019.
31. Schoonvelde, H.; van Middelkoop, J.C.; Philipsen, A.P.; van Dongen, C.; Bussink, D.W.; Bos, A.J.; Velthof, G.L.; de Haan, J.J.; Schröder, J.J.; Reijneveld, J.A.; et al. Bemestingsadvies Commissie Bemesting Grasland en Voedergewassen. 2022. Available online: https://www.bemestingsadvies.nl/ (accessed on 1 July 2022).
32. Sud, M. Managing the Biodiversity Impacts of Fertiliser and Pesticide Use: Overview and Insights from Trends and Policies across Selected OECD Countries. In *OECD Environment Working Papers 155*; OECD Publishing: France, Paris, 2020; Available online: http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/WKP(2020)2&docLanguage=En (accessed on 1 July 2022).
33. Balmann, A.; Dautzenberg, K.; Happe, K.; Kellermann, K. On the Dynamics of Structural Change in Agriculture: Internalc Frictions, Policy Threats and Vertical Integration. *Outlook Agric.* **2006**, *35*, 115–121. [CrossRef]
34. Britz, W.; Ciaian, P.; Gocht, A.; Kanellopoulos, A.; Kremmydas, D.; Müller, M.; Petsakos, A.; Reidsma, P. A Design for a Generic and Modular Bio-Economic Farm Model. *Agric. Syst.* **2021**, *191*, 103133. [CrossRef]
35. Britz, W.; Lengers, B.; Kuhn, T.; Schäfer, D. *A Highly Detailed Template Model for Dynamic Optimization of Farms*; Institute for Food and Resource Economics, University of Bonn: Bonn, Germany, 2014.
36. KWIN. Quantitative Information Animal Husbandry. Available online: www.wur.nl/nl/product/Handboek-Kwantitatieve-Informatie-Veehouderij-KWIN.htm (accessed on 1 July 2022).
37. KWIN. Quantitative Information Arable and Field Crops. Available online: www.wur.nl/nl/show/kwin-agv.htm (accessed on 1 July 2022).
38. Vellinga, T.V.; André, G.; Schils, R.L.M.; Oenema, O. Operational Nitrogen Fertilizer Management in Dairy Farming Systems: Identification of Criteria and Derivation of Fertilizer Application Rates. *Grass Forage Sci.* **2004**, *59*, 364–377. [CrossRef]
39. Vellinga, T. *Management and Nitrogen Utilisation of Grassland on Intensive Dairy Farms*; Wageningen University and Research: Wageningen, The Netherlands, 2006.
40. Schröder, J.J.; Neeteson, J.J.; Withagen, J.C.M.; Noij, I.G.A.M. Effects of N Application on Agronomic and Environmental Parameters in Silage Maize Production on Sandy Soils. *Field Crops Res.* **1998**, *58*, 55–67. [CrossRef]
41. Zom, R.L.G.; Van Riel, J.W.; André, G.; Van Duinkerken, G. Voorspelling Voeropname Met Het Koemodel. *Prakt. Rundvee* **2002**, *11*, 1–58.
42. Mandersloot, F.; Van Der Meulen, M.A. Het Melkveemodel; 0169-2291; Proefstation voor de Rundveehouderij, Schapenhouderij en Paardenhouderij. 1991. Available online: https://core.ac.uk/download/pdf/29352317.pdf (accessed on 1 July 2022).
43. De Vries, M.; Van Dijk, W.; de Boer, J.A.; De Haan, M.H.A.; Oenema, J.; Verloop, J.; Lagerwerf, L.A. Calculation rules of the Annual Nutrient Cycling Assessment (ANCA) 2019: Background Information about Farm-Specific Excretion Parameters (Update of ANCA Report 2018). 2020. Available online: https://edepot.wur.nl/533905 (accessed on 1 July 2022).

44. Van Dijk, W.; ten Berge, H.F.M.; van Dam, A.M.; van Geel, W.C.A.; van der Schoot, J.R. *Effecten van Een Verlaagde Stikstofbemesting op Marktbare Opbrengst en Stikstofopname van Akker-en Tuinbouwgewassen*; Praktijkonderzoek Plant & Omgeving BV: Lelystad, The Netherlands, 2007.
45. de Koeijer, T.J.; Renkema, J.A.; Van Mensvoort, J.J.M. Environmental-Economic Analysis of Mixed Crop-Livestock Farming. *Agric. Syst.* **1995**, *48*, 515–530. [CrossRef]