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

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This study was carried out by Wageningen Economic Research in close collaboration with Livestock Research and Plant Research and subsidised by the Dutch Ministry of Agriculture, Nature and Food Quality through the Knowledge Base Programme 34: Circular and Climate Neutral;[KB-1-2A-4]

Wageningen Economic Research
Wageningen, December 2021

REPORT
2021-095
ISBN 978-94-6447-030-7

John Helming, Co Daatselaar, Wim van Dijk, Erwin Mollenhorst, Hassan Pishgar-Komleh, Sjaak Conijn and Pella Brinkman, 2021. *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.* Wageningen, Wageningen Economic Research, Report 2021-095. 54 pp.; 3 fig.; 9 tab.; 50 ref.

In this report we present a model toolbox consisting of the Bio-Economic Farm Models (BEFMs) DairyWise and Farmdyn together with tools that focus on specific farm management aspects to analyse integrated aspects of circular agriculture at farm level. Based on a conceptual model regarding relevant policy questions, indicators and model requirements, knowledge and modelling gaps are pointed at. It is concluded that combined model use can overcome part of the modelling gaps, but not all. The combined model use is demonstrated analysing the impact of a tax on chemical fertiliser on a dairy farm on sandy soil and an arable farm on clay soil. The report ends with recommendations regarding research directions in the field of modelling circular agriculture aspects at farm level, sharing and harmonising key modules and investments in quality and quantity of different networks of model developers and users. We also give recommendations for researchers and modelers who are looking for possibilities of combined model use.

Key words: Farm level models, ex-ante analysis, policy impact, circular agriculture, combined model use.

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Wageningen Economic Research Report 2021-095 | Project code 2282200633

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Executive Summary

The focus of this report is on a model toolbox for circular-agriculture policy assessment at farm level. Decisions regarding transition and investments towards circular agriculture are taken by the individual farmer. As a result, knowledge on how (a 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 is essential for the development of a circular agriculture that achieves its ambitions and policy objectives and provides solutions for all involved stakeholders. Based on the above-mentioned integrated knowledge requirements of farm management it is concluded that Bio Economic Farm Models (BEFMs) should be at the core of the model toolbox. Because our focus is on BEFMs available within Wageningen Research, DairyWise and Farmdyn were selected as the most suitable BEFMs regarding dairy farming. The simulation model DairyWise gives a detailed and integrated description of biophysical and economic processes on dairy farms, including feeding, animal production, fertilisation, plant production and emissions. Besides dairy farming, the optimisation model Farmdyn also enables modelling of arable farms and mixed dairy and arable farms. Additional tools added to the toolbox focus on grassland management and aspects of arable farming especially tools for soil health. It appears that none of the above-mentioned BEFMs and tools fulfils all the requirements needed to give quantitative answers to the complex questions related to impacts of circular agriculture at farm level. We show, however, that the different models and tools in the toolbox can be used in combination. Combined model use contributes to scientific validity of the individual models and tools, enlarges the scope of the analysis and enables answering more complex questions. This can be achieved despite the possible overlap in modules and differences in methodology, e.g., simulation versus optimisation. The toolbox is applied to assess the economic and environmental impacts of a circular-agriculture policy scenario on a representative dairy and arable farm in a specific region in the Netherlands. The combined model use can be further improved by harmonisation of most relevant overlapping data and assumptions, including behavioural assumptions. The report ends with recommendations regarding research directions in the field of modelling circular agriculture aspects at farm level that fill the current knowledge gaps. We also formulate recommendations regarding combined model use, implementation of economic policies and environmental modules in a model toolbox, sharing and harmonising key modules and investments in quality and quantity of different networks of model developers and users. Finally, we give recommendations for researchers and modelers who are looking for possibilities of combined model use.

1 Introduction

1.1 Motivation

In 2018, The Dutch Minister of Agriculture launched the vision document *Landbouw, natuur en voedsel, waardevol en verbonden* (LNV, 2018) in which the ambition is expressed for a circular and biodiverse agriculture. Circular agriculture was defined as an agricultural 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 transition towards a more circular agriculture in the Netherlands is considered important because according to the ministry the current agricultural production system in the Netherlands is competitive thanks to numerous innovations, but is also characterised by leakages, wastefulness, inefficiencies and other unwanted effects (LNV, 2018). Examples are leakages of nutrients to the ground and surface water, incomplete use of recyclable elements from agricultural and industrial production and emission of greenhouse gasses (GHGs). This is unsustainable as the current agricultural production system contributes to global warming and damages eco-systems as the biodiversity is threatened and water, soil and air are polluted. According to the ministry, existing regulations to reduce environmental impacts of agricultural production are only directed at parts of the agricultural system. This hampers the transition to more circular agriculture. A taskforce recommended to focus regulations on goals and achievements (what) rather than on means (how). This should give more freedom to producers in the agricultural sector to achieve the goals.

The farmers and their farm are an important part of the above-mentioned agricultural production system. With a farm we mean the place where land, labour, capital and intermediate inputs are used for primary agricultural production. Knowledge on how (a transition to) circular agriculture affects farm management practices in the field of soil quality, use of finite resources, emissions and biodiversity is essential for the development of a circular agriculture that achieves its ambitions and policy objectives and provides solutions for all involved stakeholders. To achieve this there is a need to strengthen and enhance the concept of circularity at the farm level. Decisions regarding transition and investments towards circular agriculture are taken by the individual farmer. Also, most of the environmental and biodiversity losses occur at farm level. To support these decisions regarding transition and investments at farm level, instrumentation is needed for monitoring and for integrated assessments of economic, agronomic, biophysical and environmental effects of policies, goals and achievements related to circular agriculture. The TaskForce Verdienvermogen kringlooplandbouw (2019) recommends using dashboards, allowing insights into the progress and transition towards circular agriculture at different scales. Dashboards could also be used as a tool to remunerate farmers for their efforts in the field of circular agriculture. According to the taskforce these dashboards should be based on measurements rather than calculations and on a set of indicators that is comprehensive and unchallenged. A disadvantage of dashboards is that they will give a picture of achievements in the past but cannot be used for ex-ante policy analysis.

Here is a need for integrated and forward-looking bio-economic farm models (BEFMs), modelling different technologies to produce the same type and quality of product, but with different costs, benefits and emissions attached to it. These models can help to identify opportunities for farmers to comply with the environmental and biodiversity requirements related to circular agriculture. At the same time BEFMs help the government to define circular agriculture requirements that are technical and economical feasible for the sector. Dashboards are part of these BEFMs.

1.2 Objective of the report, methodology and demarcation

Within the Knowledge Base (KB) theme 'Circular and Climate Neutral Society' of Wageningen Research, a four-year project called 'Transform current linear primary production chains into production cycles (Subtheme 2A-4): Models Across Scales' has been established to support the transition to a circular agriculture. The objective of this project is to develop an integrated set of models and tools (i.e., a toolbox), accounting for various aspects, scales (of closing cycles) and indicators. This toolbox should be used for monitoring and integrated assessment of policy scenarios for increased circularity with the aim to support policy makers, farmers and other stakeholders such as researchers. An example of a toolbox applied to policy questions regarding climate change can be found in Lesschen et al. (2020). Different from Lesschen et al. (2020) this report is directed at the development and application of farm level tools and models for ex-ante analysis of impacts of policies related to circular agriculture for individual farms.

The aims of this report are the following:

- To develop a conceptual framework including the identification of the type of research and policy questions related to circular agriculture at farm level, the identification of relevant indicators and model and tool requirements and functionalities.
- To make an inventory of existing farm models and tools, to compare them and to assess their usefulness for evaluating circularity at farm level. How do the selected models and tools address the above-mentioned research and policy questions, indicators and tool requirements and functionalities? What are their strengths and previous uses? To explore whether and how available farm level models and tools are complementary to each other and could be connected to analyse the above-mentioned research and policy questions related to circular agriculture at farm level. To what extent can models be combined to overcome modelling gaps and to answer more complex questions and to broaden the scope of the analysis?
- Discuss to what extent the models and tools and combined use of models and tools need to be improved (given the toolbox requirements, research agenda, policy expectations etc.) and give recommendations for further development of models and tools in the field of circular agriculture.

Given the central role of integrated and forward-looking BEFMs to analyse impacts of policies related to circular agriculture we selected the BEFMs DairyWise (Schils et al., 2007) and Farmdyn[1] up front. Both DairyWise and Farmdyn focus on ex-ante assessment of impact of policies on farm management and trade-offs between economic and environmental issues. These are the only two BEFMs available within Wageningen Research. DairyWise and Farmdyn are developed by different groups within Wageningen Research, respectively Wageningen Livestock Research and Wageningen Economic Research. Comparison of these two BEFMs and combined use stimulate further cooperation between these Wageningen Research groups.

While ex-post models like Kringloopwijzer can be very useful as dashboards for reporting farm performances, e.g., on nutrient cycling and losses, they are less useful for policy analysis, especially when simulation or optimisation options are missing. Ex-post models, therefore, were considered to be outside the scope of this report. The ex-post model and potential dashboard Kringloopwijzer, however, is included as a module in DairyWise to present model results coherently.

Some more specialised tools available within Wageningen Research that focus on specific management aspects and with specific functionalities important for circular agriculture are used and discussed in this report as well. Nutrientenbalans Akkerbouw (NA) (Schröder and Rutgers, 2018), Aaltjesschema[2] and Nemadecide[3] focus on arable farms and soil health. The tool CNGRAS (Conijn, 2005) focuses on grassland management and could potentially contribute to existing grassland management modules in DairyWise or Farmdyn. These tools are developed by Wageningen Plant Research.

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[1] http://www.ilr.uni-bonn.de/em/rsrch/Farmdyn/FarmdynDoku/

[2] www.aaltjesschema.nl

[3] www.nemadecide.com

1.3 Targeted audience

The developed (and extended) toolbox and its applications are highly relevant for farmers and policy makers to support the transition to a circular, climate positive and sustainable primary agriculture. Researchers and modellers will gain from new insights into pros and cons of (combined) use of existing farm level models and tools. Also, for society, insights into impacts of circular agriculture policy measures on agricultural production and investments, the number of farmers and trade-offs between economics and environment are important.

1.4 Set-up of the report

Chapter 2 describes the conceptual model focusing on the type of policy questions/scenarios, relevant indicators with regard to circularity and model features and requirements. Chapter 3 discusses the selected BEFMs DairyWise and Farmdyn and the above mentioned additional tools and concludes about their ability to address the relevant research and policy questions, circularity indicators and model features and requirements as described in Chapter 2. This highlights the modelling gaps as compared to the conceptual model. Combined use of different models contributes to scientific validity of the individual models. Combined use also helps to overcome the above-mentioned modelling gaps and to answer more complex questions and to broaden the scope of the analysis. Combined model use is discussed in Chapter 4. Chapter 5 concludes and gives recommendations for further model development in the field of circular agriculture.

2 Conceptual framework

2.1 Type of (policy) questions

For the conceptual framework of the toolbox it is important to know which type of (policy) questions regarding circular agriculture should be answered. A first indication is given in the vision document *Landbouw, natuur en voedsel, waardevol en verbonden* (LNV, 2018) and the Mansholt Lecture 2018 *Circularity in agricultural production* (De Boer and van Ittersum, 2018). Based on these documents and information from running projects for the agricultural production of food, feed and bio-based products the following questions are expected to be relevant in the perspective of the goals of circular agriculture:

- Reduction of external inputs:
  - Which type of recycling products from the food chain returns to primary farms to substitute feed or fertiliser? And how do these products affect animal and crop production and what is the environmental and the economic impact?
  - What are the possibilities to use crop residues for feed and bio-based products? And what are the consequences for the farming practice (e.g. soil fertility, mechanisation)?
  - What are the possibilities of increased local feed production (from own land and nearby arable farms). What are possibilities on livestock and arable farms? Which consequences does this have for the different aspects of circularity?
- Direct collaboration between livestock and arable farms:
  - What are the effects of land exchange for economy (e.g. loss of payment rights/greening premiums if requirements for the Common Agricultural Policy (CAP) are less easily met (e.g. maintaining the area of permanent grassland)), soil health and pesticide use (among others lower cropping frequency for crops e.g. potatoes) and C sequestration in the soil (shares of temporary and permanent grassland)?
- Farmers' income:
  - How can farmers' income be maintained or increased in a circular agriculture?
  - What are the possibilities of economic incentives e.g. resource input taxes and farmer payments in order to stimulate circularity?
- Soil quality:
  - How can circular agriculture improve soil quality?
- Losses of nutrients and pesticides:
  - How can the nutrient efficiency be improved by farm management measures (e.g. feed rations, precision agriculture, growing catch crops, adapting crop rotations, improved varieties) in order to decrease emissions to air, losses to water and decrease mineral fertiliser use?
  - How can the use of pesticides be decreased in order to decrease emissions and their ecological impact?
- Resource use:
  - How to reduce the use of finite resources e.g. phosphorus (P), fossil energy and water?
- Climate mitigation:
  - To what extent can farmers contribute to climate mitigation by decreasing GHG emissions and increasing C sequestration in the plant-soil system?
  - What is the impact of climate change on crop production and environmental effects?
- Biodiversity:
  - How can farmers contribute to increased aboveground and underground biodiversity? What is the effect of crop rotations, intercropping, strip-cropping and mixed cropping? And what is the effect of measures that improve soil quality?
- Animal health and welfare:
  - What is the effect of changes in the feed ration on animal health and welfare? More specifically, what is the effect of species rich grassland or lower manure application levels? Or of increased levels of by-products in the ration?

2.2 Indicators

Indicators are needed to evaluate (farm) scenarios in terms of the goals of circular agriculture as mentioned in Section 2.1. In Table 2.1 an overview is given of possible indicators based on expert knowledge regarding evaluation of farm systems. Also, specific publications regarding indicators for circular agriculture (Berkhout et al., 2019; Erisman and Verhoeven, 2019) and biodiversity (Biodiversiteitsmonitor Akkerbouw, 2020; Biodiversiteitsmonitor Melkveehouderij, 2018) were taken into account. It must be emphasised that at the moment the development of indicators regarding circular agriculture is still in progress and that the results of running projects on this issue should be taken into account during the further development of the toolbox.

We have distinguished direct and indirect indicators. Direct indicators indicate to what extent the goals for a specific theme (e.g. emissions, biodiversity and climate) are realised or refer to direct aspects of circularity (e.g. the use of side streams). The indirect indicators are derived from the direct indicators. For example, the direct indicator for biodiversity is the number of organisms per unit area or soil volume, while organic matter content in the soil or the share of permanent grassland is an indirect indicator for biodiversity.

Reduction of external inputs

External inputs on farms, especially those containing nutrients, mainly apply to fertilisers and feeds. So, the use of these products and the use of side streams substituting fertilisers and feeds are appropriate indicators. Side streams refer to biomass streams that are produced in the whole food system and that are not suitable for human consumption e.g. crop residues, food-industry by-products, food waste, wastewater and biomass from nature land.

Another indicator mentioned in the report of the Commissie Grondgebondenheid is the amount of protein (or total feed) grown on own land (or in the nearby environment).

One of the principles of circular agriculture is that crop products that can be used for human food should not be used as feed. Regarding this aspect, Berkhout et al. (2019) mentioned different indicators as the share of feed ingredients that can be used for human consumption (e.g. cereals) or the share of feed crops grown on land also suitable for food production.

Economics

Farmers' income is a major farm indicator being a basic driver for farm management. In order to assess farmers' income, insight into costs (variable and fixed costs) and benefits (products x price) is necessary. We did not include indicators regarding behaviour aspects as they were not mentioned in the studied literature. It is recommended to look at this further e.g. considering indicators for risk behaviour.

Soil quality

For soil quality, a set of chemical, physical and biological parameters are defined, including their threshold levels (Hanegraaf et al., 2019). For evaluating scenarios with farm models these indicators may be less suitable as they cannot always be calculated easily. Some of these indicators are also used as input parameters in farm models (e.g. soil P content). However, these basic parameters can be affected by the scenarios. For some of them, e.g. soil organic matter content, models are available to quantify them. In addition, indirect indicators could be used. Examples of these indirect soil indicators, commonly used in farm models, are the organic matter supply and balance, the nutrient balance, and more indirectly, the share of rest crops in a crop rotation, the share of early harvested crops or machinery type. Rest crops refer to crops with a relatively extensive crop management especially regarding mechanisation (e.g. cereals). They also have a function to keep the cropping frequencies of intensive cash crops under the threshold level.

For biological soil health, the amount of bacterial and fungal biomass can be used as indicator. For soil-borne pathogens the number per unit soil volume is a common indicator. Indirectly the risks of plant parasitic nematodes as related to crop rotation and sequence may be a suitable indicator. Tools are available to assess these risks (www.aaltjesschema.nl, Nemadecide).

Nutrient losses

Nutrient losses refer to nitrogen (N) and P losses to ground and surface water and gaseous emissions e.g. ammonia (NH_3), nitrous oxide (N_2O) and nitrogen oxides (NO_x). These losses can be calculated from farm, crop and fertilisation data (mostly available in farm models) in combination with default emission factors. Regarding nutrient losses to water, the nitrate (NO_3) concentrations in the groundwater are more easily estimated than losses to surface water. Nutrient concentrations in the surface waters on the farm may also be affected by nutrient sources from outside the farm. Therefore, it is a more complicated indicator for use at farm level. The N and P losses to ground and surface water can also be indirectly estimated by the N and P soil surpluses and soil mineral N in the autumn.

For evaluation of a farm, besides nutrient surpluses, the nutrient use efficiency (NUE = output/input) can be a useful additional indicator. However, NUE should always be combined with the nutrient surplus as the same NUE can result in different nutrient surpluses. Especially for local issues as NO_3 leaching N surplus is a more appropriate indicator than NUE.

Pesticide emissions

The most goal-oriented indicator is the concentration of residues of pesticides in the ground and surface water or in the soil. Indirect parameters are environmental risks of pesticides for aquatic and soil organisms according the MBP system (milieubelastingpunten; Leendertse et al., 2019) or the use of pesticides. The risk indicators are more useful than just the pesticide use. For the calculation of the risk-indicators, information about the characteristics of the active ingredients and the application technique is necessary.

Resource use

For sustainable farms the use of finite resources should be decreased and as far as possible be substituted by renewable resources. Relevant indicators are the use of fossil energy, the use of mined nutrients like P and the use of water.

Climate

Currently, indicators regarding climate change are mostly focusing on the GHG emissions that can be calculated from farm data (e.g. fertilisation, feeds) in combination with default emission factors. In addition, the C capture in soil is an important indicator although not that easily assessed. Model calculations are necessary taking into account the long-term behaviour of C in the soil as related to crop rotation and the use of organic manure.

Although not mentioned in the overview in Table 2.1, the effects of climate change (high temperatures, drought, flooding) on the crop production may also be interesting indicators. In Van Dijk et al. (2020) for grass, maize and arable crops the vulnerability for extreme weather conditions was estimated. The used methodology may be a basis for the development of risk indicators.

Biodiversity

Most direct indicators are indices for beneficial organisms e.g. farmland birds, insects, pollinators, soil and water organisms. Commonly mentioned indirect indicators are the area/share of permanent grassland or species-rich grassland, the area of functional agricultural biodiversity (FAB) elements, landscape elements and the number of packages with nature conservation elements. Payments for these activities expressed per ha utilised agricultural area are also a possible indicator. Also the risk indicators of the use of pesticides for soil and aquatic organisms and N and P concentrations in the surface water may be useful.

Animal welfare

Erisman and Verhoeven (2019) mentioned the use of antibiotics and grazing intensity. The latter also has an effect on N losses (NH_3, NO_3) and feed quality.

Table 2.1 *Potential indicators regarding circular agriculture*

	Direct indicator	Indirect indicator
Reduction *of external* inputs		
Fertilisers	Use of mineral fertilisers	
	Use of side streams for fertilisation purposes	
Feeds	Use of concentrates	
	Use of side streams for feed purposes	
	%-feed protein from own land	
	Share of feed ingredients suitable for human consumption	
	Area of feed crops on soils also suitable for growing food crops	
Economics	Farm income per unpaid labour unit	
	Total fixed costs and total variable costs	
	Share fixed costs in total costs	
Soil quality	Chemical	
	e.g. C, N, P, K, pH	Organic matter supply and balance
		Percentage regional organic inputs including from own farm
		Soil nutrient balance
	Physical	
	e.g. texture, penetration resistance	Machine use
		Share of rest crops in the rotation
		Share of early harvested crops in the rotation (e.g. before 1 September)
	Biological	
	e.g. bacterial and fungal biomass	Share of permanent grassland vs ley-arable crop rotations
	Soil-borne pathogens	Risks of soil-borne pathogens
Nutrient losses	Gaseous N emissions	Farm N balance
	NH_3	
	N_2O, NO_x	
	N and P losses to ground and surface water	
	N and P concentration in ground and surface water	Soil mineral N in autumn Soil nutrient balance
Pesticide emissions	Concentration of residues of pesticides in ground and surface water and in the soil	Environmental risks pesticides for aquatic and soil organisms (MBPs, etc.)
		Pesticide use
Resource use	Use of mineral fertilisers (e.g. P)	
	Use of fossil energy	
	Water use and water footprint	
Climate	GHG emissions	
	C capture in soil	Organic matter supply and balance
		Share of permanent grassland vs ley-arable crop rotations
Biodiversity	Indices farmland birds, insects and pollinators, soil and water organisms	Share permanent grassland and species-rich grassland, land use (e.g. arable vs. grassland)
		Land use (e.g. arable vs. grassland)
		Area and share high nature value farmland

	Direct indicator	Indirect indicator
		Area non-production land
		Area FAB elements
		Number of nature conservation packages
Animal welfare	Veterinary costs	Hours grazing
		m^2 in barn per animal

2.3 Toolbox requirements

The (policy) questions in Section 2.1 and the indicator list in Section 2.2 give input to features and requirements of models and tools to analyse questions regarding circular agriculture at farm level. Given the large number of indicators related to circular agriculture, the toolbox should include bio-economic farm models (BEFMs) that include behavioural, economic, biophysical, technical and agronomical processes and aspects and interrelationships between all these aspects. The farm level is the main level at which measures for circularity are applied and for farmers’ decisions. More general requirements of BEFMs are discussed in Britz et al. (2021). These general requirements are integrated in the list of requirements and features below.

- The farm models should cover a wide range of production activities to depict different farm branches that have different options regarding circularity.
- The tools and farm models should include various technology representations; alternative input intensities for each farming activity with related detailed input, output, and emission coefficients.
- The tools and models should allow adoption and investments in new techniques, new crops and new recycling products for feed and fertilisation purposes, preferably over a longer time horizon (dynamic setting). In a circular agricultural system, current used products will partly be substituted by recycled products and this may have consequences for farm management.
- The tools and models should allow for more behavioural aspects than only pure profit maximisation (e.g. allow switching to alternative specifications of the objective function to include risk preferences, other farmer’s preferences, or cost of long-term capital goods).
- The tools and models should cover all relevant policies. Both demand and control (e.g. emission standards) and economic incentives (e.g. taxes and subsidies, marketable permits).
- Application to a dataset of a large number of individual farms to show the big variations in farm characteristics, management and behaviour should be possible. In fact, this is not the strength of an individual farm model or tool as with all of them you can run them for as many cases as necessary. However, using models that already contain or can be linked to a broad dataset of individual farms may make this more efficient.
- Upscaling to sector, regional or national levels must be possible as farm management and structural changes at the farm level (e.g. farm size) have an effect on the sector (e.g. total production, market prices, number of farms, etc.) or national level and vice versa. This also requires linkages to individual farm data.

2.4 Conclusions regarding the conceptual model

Conceptually the circular agricultural farm model is very complex. This has to do with the wide range of policy questions, indicators and farm management options that can be associated with circular agriculture. Moreover, goals of circular agriculture are still in discussion and the concept of it is still in progress. On the other hand, with available farm models and tools a part of the questions regarding circular agriculture can already be answered but often they are not (able to be) used together in order to provide a more integrated evaluation. The challenge will be to connect relevant tools and, where necessary, extend models with new modules for aspects of circular agriculture not yet covered in current models. Figure 2.1 depicts the concept of a model toolbox where different models and tools can be connected into a generic modular model.

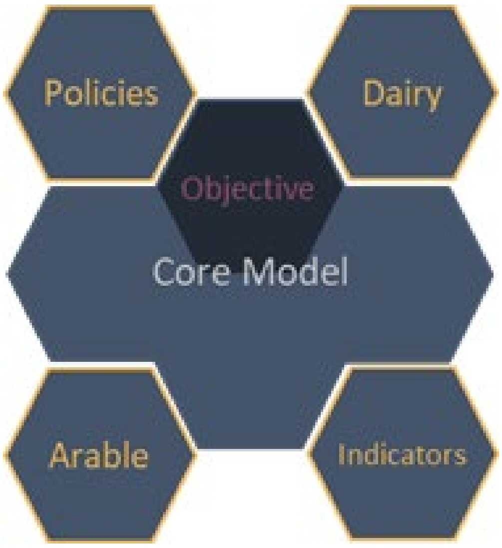

Figure 2.1 *Core Model with alternative choices for farm branches*

3 Review of selected models and tools

Existing models and tools are reviewed to discover to what extent they comply with the conceptual model for circular agriculture as described in Chapter 2.

3.1 Selection of tools and models

In Chapter 1 the central role of integrated and forward-looking BEFMs to analyse impacts of policies related to circular agriculture was already discussed. The BEFMs DairyWise and Farmdyn focus on ex-ante assessment of policies on farm management and on trade-offs between economics and environment at farm level. These are also the only two farm level models available in Wageningen Research.[4] Both DairyWise and Farmdyn contain features that comply with requirements for BEFMs as described in Section 2.3. DairyWise is a simulation model that gives a detailed and integrated description of biophysical and economic processes on dairy farms, including feeding, animal production, fertilisation, plant production and environmental emissions. Farmdyn is an optimisation BEFM that maximises individual farm income on specialised and mixed arable and dairy farms, beef cattle and pig farms.[5] It describes in detail the interrelationship between production, income, investments and emissions on farms. Both DairyWise and Farmdyn include various technology representations for key activities on the farm and allow modelling of adoption and investments in new technologies. In principle both models can be linked to datasets with large numbers of individual farm data to take into account heterogeneity between farms and for upscaling to sector level. For these purposes Farmdyn is standard connected to the individual farms in the Dutch FADN (Bedrijveninformatienet). Complying with the requirement to model adoption and investment over a longer time horizon, Farmdyn can be used in a dynamic setting. Behavioural aspects other than pure profit maximisation are not endogenously modelled in DairyWise and Farmdyn.[6] This is also because of behavioural data regarding farmers' preferences, attitudes and beliefs are not standard available.

Some more specialised tools available within Wageningen Research that focus on specific management aspects and with specific functionalities important for circular agriculture are analysed in this report as well, namely CNGRAS, Nutriëntenbalans Akkerbouw (NA), Aaltjesschema and Nemadecide*.* These tools are either complementary to (NA, Aaltjesschema, Nemadecide) or could potentially replace existing modules (CNGRAS) in DairyWise and Farmdyn.

In the following sections the contribution of the tools and models to the toolbox is discussed with a focus on DairyWise, Farmdyn and NA.

3.2 Farmdyn

Farmdyn is a bio-economic, mixed-integer programming model at individual farm level that simulates farmer's decisions regarding agricultural production and investments in a comparative static or dynamic setting. 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 has

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[4] Farm level models (BedrijfsWijzers) for pigs, poultry, calves and sheep are available at Wageningen Livestock Research, but focus mainly on technical and economic performance and are much less elaborate on, e.g., environmental issues. Furthermore, these models have not been updated technically since 2014. These models are, therefore, not considered as BEFMs in this report.

[5] Farmdyn delivers a template for different types of farms. The templates for beef and pig farms are currently not developed for the Netherlands.

[6] Farmdyn does feature different approaches to model risk behaviour of farmers, including the target MOTAD approach. However, until now this has not been developed for the Dutch agricultural sector.

been used at Wageningen Economic Research since late 2018 and the dairy and arable modules are adjusted stepwise to Dutch conditions. The description of Farmdyn is presented in Appendix 1.

Farmdyn has been applied to different aspects of circular agriculture. Heinrichs et al. (2021) employed the bio-economic model FarmDyn, representing French and German dairy farms to analyse the impacts of coupled support on legume production. Lengers et al. (2014) analyse marginal abatement costs of GHG on dairy farms in Germany. Mosnier et al. (2019) compare results of Farmdyn regarding GHG emissions in French dairy production with the results of other models. Schäfer et al. (2017) apply Farmdyn to analyse investments in biogas plants on dairy farms in Germany. A final example of a Farmdyn application can be found in Kuhn et al. (2020). In this paper the impacts of the 2017 German fertilisation regulation on various farm types are assessed by coupling a crop growth model to Farmdyn. For the Netherlands, Farmdyn was used to analyse impacts of reduction of GHGs from peat soil in Dutch agriculture. Here the focus was on dairy farm management impacts of rewetting peat soils, including impacts on emission of ammonia (Poppe et al., 2021; de Koeijer et al., 2020).

3.2.1 Circular agriculture indicators covered by Farmdyn

In this section it is shown to what extent Farmdyn covers the potential indicators regarding circular agriculture presented in Section 2.

Reduction of external inputs
Farmdyn contains a feed requirement module for different kinds of cattle, fattening pigs and sows. The feeding ration in Farmdyn consists of different types of concentrates, different types of arable crops, and soybean meal. Arable crops as silage maize, winter wheat, winter barley, summer peas and summer beans can be sold or fed to the animals. Soybean meal as a protein supplement and a source of metabolisable energy can be imported on the farm to feed the animals. The exact composition of the concentrates is not known, only the nutrient content. Therefore, it is difficult to include the mixed concentrates into an indicator as the share of feed ingredients that can be used for human consumption. Linkages to biophysical and georeferenced databases are needed to calculate the share of feed crops grown on land also suitable for food production. Farmdyn allows calculation of the amount of protein (or total feed) grown on own land and the protein content of the ration as an indicator for the risks of ammonia emissions. Crop by-products and industry by-products are not included as separate feeds.

Yield functions for the grass and arable crops are included that relate output to nitrogen input. The farmer can choose the optimal feed and fertilisation mix depending on prices of inputs and outputs.

Economy
The dynamic version of Farmdyn calculates yearly income over a long time period. Yearly revenue includes sales of marketable outputs, subsidies and interest gained. Yearly costs include variable costs of purchased inputs and fixed costs from maintenance, insurance, depreciation and interest paid from use and investments in machinery, stables and buildings. The dynamic version of Farmdyn allows endogenous modelling of farm exit and farm growth.

Soil quality
Farmdyn includes an organic matter supply balance. Farm management options to increase organic matter supply on the farm are changes in cropping plan, changes in the quantity and composition of the imported organic fertilisers (pig, cattle and poultry manure, digestate, and green compost). The organic matter supply is only calculated for arable crops.

Nutrient losses
The environmental accounting module in Farmdyn utilises commonly applied methodology for the quantification of NH_3, N_2O, NO_x and elemental nitrogen (N_2), as laid down in IPCC (2006), Haenel (2020) and European Environment Agency (2013, 2016). An extension of the scope of accounting to LCA methodology enables the consideration of emissions prior to on-farm activities such as the provision of major inputs (Frischknecht et al., 2007). Emissions are characterised at midpoint level using characterisation factors from Huijbregts et al. (2016). The farm and soil surface balances are

calculated for N and P (expressed as phosphate, i.e., P_2O_5) indicating N and P prone to loss through run-off or leaching. Leaching of N and P to ground and surface waters is highly depending on environmental and geographical conditions. Therefore, results from the soil surface balances are indicators for potential loss of N and P after field application. Side streams from food processing industry, catering, households and waste (water) treatment are not included. Although Farmdyn provides lots of information regarding the N and P balance, NUE is not covered by the tool but could be calculated from the obtained results.

Pesticide emissions
Farmdyn allows definition of different technologies with different use of pesticides.

Resource use
Farmdyn calculates use of mineral fertilisers and energy. The direct energy consumption is limited to diesel use on the farm.

Climate
Farmdyn allows calculation of the different GHG emissions. Farm management options to mitigate GHG emissions that are currently endogenous in Farmdyn are feeding adjustments, animal manure application techniques/timing of animal manure application, chemical fertiliser application, energy use, herd size, tillage system, crop rotation and soil organic matter balance (as carbon dioxide (CO_2) sink). Other options as stable adjustments/investments and composition of the herd can be changed in scenarios. GHG emissions from purchased concentrates include land use, land use change and forestry (LULUCF).

Biodiversity
Relevant farm management options available (or relatively easy to implement) in Farmdyn regarding biodiversity and nature inclusive transition are mowing and grazing periods on grasslands, use of solid animal manure/straw animal manure, tillage systems (conventional, less-intensive or direct drilling), extensification of the cropping plan, catch crops, pesticide use and blooming field margins.

Animal welfare
The endogenous choice of the grassland management in Farmdyn is also an indicator for the time the cows are grazing.

3.3 DairyWise

DairyWise (Schils et al., 2007) is a whole-farm dairy model that empirically simulates technical, environmental, and financial processes. It calculates technical and economic indicators based on a combination of farm-specific and normative input values. Based on these technical and economic indicators, strengths and weaknesses of a farm can be detected and consequences of changes can be assessed. DairyWise is a tool that can be used for integrated scenario development and evaluation for by scientists, policy makers, extension workers, teachers and farmers. More detailed information about DairyWise can be found in the Appendix 1.

DairyWise has been applied to different aspects of circular agriculture. Vellinga and Hoving (2011) 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. It is also used to study cost effectiveness of GHG (Vellinga et al., 2011) or NH_3 (Evers et al., 2015) 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 (Evers et al., 2019). Furthermore, Hutchings et al. (2018) compared DairyWise with three other farm-scale models on their ability to estimate GHG emissions. More recently, Reijs et al. (2021) have used DairyWise to calculate the economic impact of NH_3-emission reducing measures in the context of the Dutch N policy.

3.3.1 Circular agricultural indicators covered by DairyWise

DairyWise covers the potential indicators regarding circular agriculture defined in Section 2, as follows.

Reduction of external inputs
DairyWise provides detailed information such as protein and energy contents of both own-produced and purchased feeds (including grass, maize, other roughage, by-products and concentrates). However, detailed information on the ingredients of various types of concentrates are not provided by DairyWise. Therefore, also the inclusion of side streams from food processing industry, catering, households, etc. in concentrates are not accounted for in DairyWise. The only side streams included are some by-products from the food processing industry that are fed directly to the dairy herd, like beet pulp or brewer's grain. DairyWise provides the share of own-produced protein in the total ration as indicator in its output. DairyWise separates the self-supplied and purchased feed components. Therefore, all of the outputs including the emissions and nutrient supplies are separated whether it is provided by own farm or from external sources. The portion of the sources on the total input helps farmers to reduce the share of external inputs.

Economy
The financial results of the dairy activities are presented in DairyWise. The gross margin, farm income, and costs (including variable and fixed costs) of milk production are defined to describe the overall financial performance of a dairy farm.

Soil quality
For soil quality, DairyWise does not provide a full organic matter supply balance but it provides the amount of effective organic matter supplied per ha. Furthermore, it considers the share of permanent grassland in crop rotation which can be considered as a parameter for soil quality. In addition, it includes soil nutrient balances (N, P, K) and considers the P levels in the soil to apply the right legal animal manure application norms.

Nutrient losses
Because the dairy production system is a complex system with several interactions with other production systems like grassland and arable crop production, it is important for dairy models to provide an accurate nutrient flow within the whole production system. DairyWise can simulate internal and external flows (between dairy system, arable system and environment) of nutrients. DairyWise provides detailed overviews of nutrient flows (N, P, K) covering the whole farm, nutrient balances and nutrient use efficiencies are calculated and reported at different levels (whole farm, soil, and animals). DairyWise also estimates the NH_3 emissions from housing and storage, grazing, animal manure and chemical fertiliser application separately.

Nitrate leaching in maize and grassland is included in DairyWise. Water quality (NO_3 concentration groundwater) is not included in DairyWise but the 'KringloopWijzer' outputs of DairyWise can be used as the inputs for 'BedrijfsWaterWijzer' (BWW), a model introduced by Verloop et al. (2018) that considers quantity and quality of water on dairy farms.

Pesticide emissions
DairyWise does not cover the environmental impacts due to application of pesticide.

Resource use
Resource use is covered by DairyWise as the use of mineral fertilisers, energy and water. The energy consumption is divided to direct and embodied energies. Direct energies include diesel, electricity, natural gas, oil, etc. and the embodied energy includes the energy in feed components, machines, etc.

Climate
DairyWise reports detailed information on GHG emissions regarding dairy production. Methane emissions from animal manure storage and enteric fermentation are calculated. Direct N_2O emissions from various sources (such as excreted N during grazing, animal manure application, chemical

fertiliser use, etc.) and indirect N_2O emissions associated with the NO_3 leaching and NH_3 volatilisation are included. Furthermore, GHG emissions associated with purchased feed, chemical fertiliser and energy are included and presented separately.

Biodiversity
DairyWise does not provide specific information on biodiversity. The positive impact of grassland management on nature, however, could be derived indirectly from the amount of 'Beheersgrasland' and other nature conservation packages.

Animal welfare
It is possible to define different grazing systems in DairyWise and therefore calculate the grazing hours for different production systems. It can be considered as an index to quantify the animal welfare in dairy systems. No animal health related issues are modelled in DairyWise.

3.4 CNGRAS

The tool CNGRAS is a dynamic simulation model for grassland management and C and N flows at field scale. This tool offers further details regarding the modelling of fertilisation levels (N) on grassland yield, C and N sequestration and N losses. It was added to the toolbox because it can possibly replace the grass modules in Farmdyn or DairyWise. The tool CNGRAS covers partially a limited number of circular agriculture indicators which are related to the soil quality and nutrient losses. More detailed information about CNGRAS is provided in Appendix 1.

3.5 Nutriëntenbalans akkerbouw (NA)

The NA is a tool that has been developed for calculating N and P surpluses on an arable farm based on the cropping plan, crop yields and the fertilisation of the crops (Schröder and Rutgers, 2018). The motivation for developing the NA is the demand of arable farmers to have a tool that can be used as a proof for farm specific application standards for N and P based on the farm specific N and P surplus, NA calculates the fate of N surplus (in forms of NH_3, NO_3, N_2O, N_2), the GHG emissions and the organic matter supply. For the sake of brevity, more information about the description of NA is provided in Appendix 1.

3.5.1 Circular agricultural indicators covered by NA

NA covers a limited number of the potential indicators regarding circular agriculture defined in Section 2.1, as follows.

Soil quality
The NA calculates the effective organic matter (EOM) supply from crop residues and organic fertilisers. The EOM refers to the organic matter that remains one year after application and is assumed to contribute to the soil organic matter. For crop residues, fixed EOM-values are used.[7] For organic fertilisers, the EOM supply is based on organic matter supply multiplied with the humification coefficient (HC). The HC gives the fraction of the organic matter that remains one year after application. Fixed values are used depending on organic fertiliser type.[8]

The NA also estimates the annual loss of soil organic matter (exogenous parameter) due to mineralisation. However, this only gives a rough indication as a fixed breakdown of 2% is used. The calculated annual breakdown can be compared with the calculated EOM supply to get an indication whether both are in balance. However, this calculation is too rough to quantify effects on soil organic matter and C storage in the soil.

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[7] www.handboekbodemenbemesting.nl
[8] www.handboekbodemenbemesting.nl

Nutrient losses

The model calculates the N and P surpluses and the fate of the N surplus. The N and P surplus are calculated as the sum of N and P inputs with organic and chemical fertilisers, deposition from air and biological N fixation minus the output with harvested crop products. For deposition a national value is used.[9] The output with harvested product is calculated as the product of yield and a fixed N and P content in the harvested product but can also be made dependent on the N supply based on crop-specific response relationships.[10]

Regarding the fate of the N surpluses the NH_3, NO_3 and N_2O emissions are estimated:

- The NH_3 emission refers to the emission from application of organic and chemical fertiliser in the field. The NH_3-emission factors (EF) are derived from the National Environment Management Authority (NEMA) (Van Bruggen et al., 2019). For organic animal manure EF depend on the application technique (input parameter).
- The NO_3 emission is derived from the soil N surplus defined as the N surplus minus the NH_3 losses. Part of the soil N surplus leaches to the ground water. The leaching fraction (LF) depends on soil use (grassland or arable land) and hydrological aspects, e.g., the depth of the groundwater table. The LF values are derived from measurements on farms in the LMM-farmers network (Fraters et al., 2012). The NO_3 concentration in the groundwater is also calculated based on the amount of leached NO_3 (N soil surplus x LF) and the average precipitation surplus.
- The N_2O emissions are calculated based on either IPCC-EF-values (IPCC, 2006) or specific Dutch EF-values based on Velthof and Mosquera (2011).

The model compares the N and P supply with legally allowed application standards for N in animal manure, total P and total N.

Climate

The NA calculates the GHG emissions. For arable farms this is restricted to CO_2 and N_2O emissions. Regarding CO_2 emissions of crop operations, fixed values per crop are used based on an average crop management. Currently, there is no possibility to use farm specific data regarding diesel use. The calculation of the N_2O emissions is already described in the nutrient section.

3.6 Tools for soil health

In circular agriculture good soil quality is an important goal. A major aspect of soil quality is soil health which is determined by the presence of soil-borne pathogens. Especially on arable farms this is an important issue. Indicators for soil health are the number of pathogenic organisms, or more indirectly, the estimated risks based on the crop rotation (see Section 2.2). For the control of soil-borne pathogens different tools have been developed predominantly focusing on nematodes. From these tools especially Aaltjesschema and Nemadecide can be of interest to connect to farm models as these tools provide indicators for soil health that may have an added value for farm models. A short description of both tools is given below. More detailed information regarding soil health tools in general is given in Appendix 1.

Aaltjesschema

The website www.aaltjesschema.nl is a qualitative decision support system (DSS) that estimates the risks of pathogenic nematodes in a crop rotation. It is intended for farmers and advisors and focuses on arable farming, ornamental bulb production and nurseries of perennial plants and trees. It includes 154 crops, 37 nematode species and two viruses that are transmitted by nematodes. Aaltjesschema generates an indication of nematode multiplication on the crops in the rotation and potential crop losses as output.

Regarding circularity indicators Aaltjesschema gives information on the risks of the development of nematode populations in the soil which is a major soil health indicator.

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[9] www.clo.nl

[10] www.handboekbodemenbemesting.nl

NemaDecide
NemaDecide (www.nemadecide.com) is a quantitative Decision Support System that focuses on the management of potato cyst nematodes (*Globodera* spp.) in potato. The system is based on a combination of scientific knowledge and practical experience. It uses models on both the development of nematode populations and on the effect on yield. Population development is predicted based on the choice of crop and potato cultivar and different additional measures that can be selected, such as the application of inundation and the use of crop protection agents. The nematode densities are then used to predict the effect on crop yield. The information can be specified to the level of strips of a field and can be used to minimise the effect of a known infestation on crop yield. The references for the different subparts of the model can be found on the website (www.nemadecide.com).

Regarding the circularity indicators Nemadecide gives information on the population densities of potato cyst nematodes being an indicator for soil health. In addition, effects on yield are given that affects economic indicators.

Aaltjesschema and Nemadecide are separate tools. The scope of Aaltjesschema is wider than that of Nemadecide that only gives information about cyst nematodes in potato. The output of Nemadecide is more quantitative while the output of Aaltjescchema is more qualitative.

3.7 Conclusions

Notwithstanding the strengths and weaknesses of different models and tools, they only partly comply with the conceptual model as described in Chapter 2. Especially the selected models and tools focus mainly on dairy and, arable and arable/vegetable farms, while, e.g., the intensive livestock sector or horticulture is missing. Therefore, e.g., using recycling products in the intensive livestock industry cannot be assessed with the toolbox. Farm level indicators related to soil quality, emission of pesticides, biodiversity and animal welfare are missing from DairyWise and Farmdyn as well. Some can potentially be improved by combined use of BEFMs and tools for soil health. This will be discussed in a more qualitative manner in Chapter 4.

4 Inter-model comparison and possibilities of combined model use

Section 4.1 discusses and gives a justification of the various forms of combined model use that are applied in this chapter. The different approaches for dairy and arable farms are based on the different degrees of overlap between the combined models. Section 4.2 focuses on the combined use of DairyWise, Farmdyn and CNGRAS. Section 4.3 focuses on the combined use of Farmdyn and NA. Section 4.4 discusses in a qualitative manner the possible use of Aaltjesschema, NemaDecide and Best4Soil in combination with the other models.

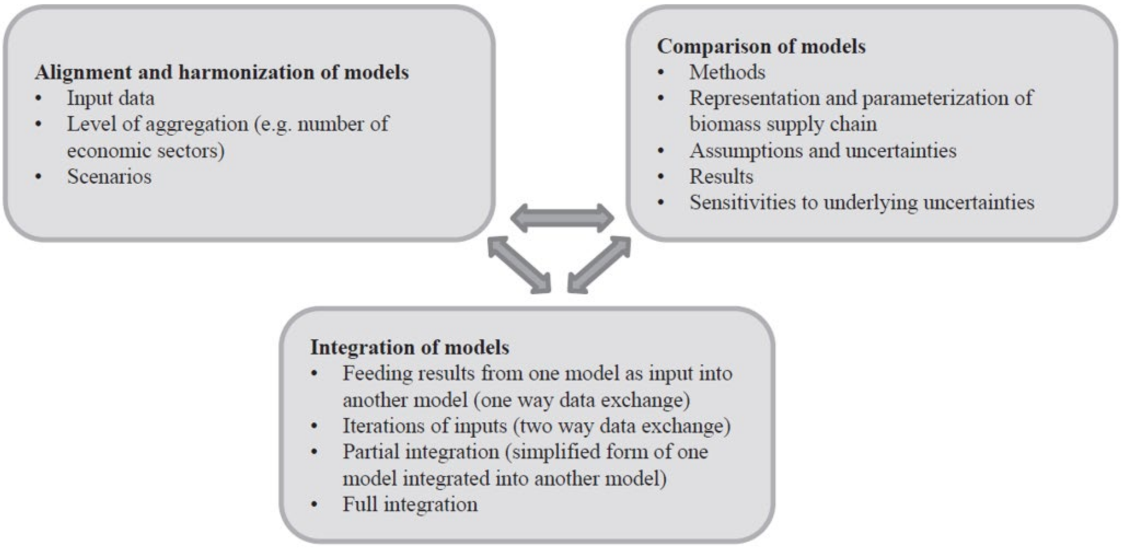

Figure 4.1 *Typology of combined model use*

4.1 Various forms of combined model use

Wicke et al. (2015) identified three general forms of combined model use: 1) alignment and harmonisation of models including model parameters and input data 2) comparison of models and 3) integration of models (Figure 4.1). The arrows show that the three forms are interrelated and that many types of combined model use are possible. In this report the combined use of Farmdyn, DairyWise and CNGRAS is actually a combination of model comparison and alignment and harmonisation of models and scenarios. The combined use of Farmdyn and NA is based on alignment of input data and integration of models, but limited to a one way data exchange.

As discussed in Chapter 3, Farmdyn is an optimisation model whereas DairyWise is a simulation model. The key difference between optimisation and simulation is that optimisation modelling provides a definite recommendation for action in a specific situation, for example endogenous simulation of the most cost effective mix of abatement measures. This one optimal solution is often based on profit maximisation, but alternative specifications of the objective function (e.g. to include risk preferences) are possible as well. Simulation models can be more detailed and allow users to determine how a system responds to different inputs to better understand how it operates.[11]

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[11] Simulation models such as DairyWise can be and have been used in experiments with farmers to detect farmers' behaviour that, subsequently, can be implemented in an optimisation model. This is another option of combined model use but requires much more time and budget.

Models and tools can be combined in different ways to strengthen each other. In Section 4.2.1 basic input parameters of Farmdyn and DairyWise are aligned and model results are compared. Model comparison is also combined model use. Model comparison contributes to scientific validity of their use and highlights how model and scenario assumptions impact results (Hutchings et al., 2018; Mosnier et al., 2019). This is important information for policy makers and model users. In Section 4.2.2 a specific economic policy scenario is aligned between Farmdyn, DairyWise and CNGRAS. The advantage of optimisation models is the endogenous simulation of cost effective farm management adjustments following economic policies e.g. a tax on N from chemical fertiliser. Both DairyWise and CNGRAS are not able to directly analyse such input price responses, but the one solution from FarmDyn is used as input into the more technically detailed simulation model DairyWise and CNGRAS to limit the number of possible outcomes. Another aspect of combined model use is that Farmdyn presents selected economic results while DairyWise and CNGRAS presents emissions and losses to the environment as these models are more detailed in that respect. This is an example of re-use of models/modules that are not present (or less detailed) in a separate model. CNGRAS is also included in the scenario analysis to investigate consistency of results and to analyse what else it can contribute to grassland modules in Farmdyn and DairyWise.NA is also a simulation model, but different from DairyWise: the overlap with Farmdyn is very limited. The combined use of Farmdyn and NA is based on alignment of input data and integration of models. The integration is limited to a one way data exchange from Farmdyn to NA: output of Farmdyn regarding cropping plan and fertiliser use per arable farm is input to NA to calculate corresponding emissions and losses to the environment. This is another example of the above-mentioned re-use of models/modules.

4.2 Comparison of Farmdyn and DairyWise

This section describes a comparison between the models Farmdyn and DairyWise by means of two selected model farms. The selected dairy farms represent two important types of dairy farms, namely with and without own maize silage production. The basic input data of these two model farms are included in both Farmdyn and DairyWise and the model results are compared (Section 4.2.1). Streamlining the basic input data allow to associate differences in model results with differences in model structures, functions and restrictions (Hutchings et al., 2018). In Section 4.2.2 results of an economic policy scenario are compared. Because the models Farmdyn and DairyWise contain less detailed calculations on N and C sequestration, some additional calculations have been carried out with the CNGRAS model.

4.2.1 Harmonisation of input and output parameters

Input parameters
Table A2.1 (see the Appendix 2) represents the characteristics of two dairy farms initiating further comparison of model outputs. These two selected model farms are representing typical dairy farms in the Netherlands. Dairy farm characteristics were taken from the Dutch FADN database and averaged to the two farms. There is an obvious difference between the two farms in soil type. The soil type of farm 1 is sandy soil and farm 2 has peat soil. The predominant crop on both farms is grass used for grazing or ensilaging. In farm 1, in addition to grass production, 9 ha of land is under maize cultivation. Farms apply a crop rotation for maize cultivation with grass as catch crop.[12] Milk production was considered as an exogenous parameter; therefore, the average milk production was assumed to be 8,600 and 7,800 kg milk per cow per year in farm 1 and 2, respectively. The fat, protein, lactose and P content of the milk were 4.4%, 3.56%, 4.5% and 97 mg per 100 kg of milk in both farms. The grazing system in both farms was limited to day hours (grazing system 'B').[13] Animal manure is stored at the farm (under the barn) for almost 6 months per year in both farms. The excreted slurry during confinement is partly stored in outside silos and applied on grass and maize lands. The slurry is applied on grasslands on sandy soils (farm 1) by shallow injection (in Dutch: 'zodebemesten') and on peat soils (farm 2) by application of diluted animal manure on the soil (in Dutch: 'Verdund uitrijden met sleepslang'). On maize land, animal manure injection is applied. Due to

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[12] Until now catch crop after maize is not a feature in Farmdyn.

[13] Farmdyn distinguishes between full grazing, partial grazing and not grazing.

the fact that DairyWise calculates the usage of N in grassland based on the animal manure legislation, the variable Active N applied on grassland is actually an exogenous variable in DairyWise. In the default situation, the applied amount was 68% of the optimal agricultural N-fertilisation level due to applied animal manure legislation. Farmdyn includes different options for the use of grassland that differ by fertilisation level, times mowing and yield. The highest fertilisation level is determined by the manure legislation, but the actual chosen grassland option is a function of relative prices of inputs and outputs. Yield of silage is a function of total input of N, also constrained by manure legislation.

Output parameters
Results of the comparison of Farmdyn and DairyWise are shown in Table 4.1. Model outputs are classified in different categories including herd characteristics, crop production, feed use by herd, chemical and organic fertilisation, animal excretions, NH_3 emissions, nutrient balances and GHG emissions. Moreover, parameters are identified as endogenous (Y, result of modelling) or exogenous (X, input by the user) parameters. Important exogenous variables in Farmdyn are the urea content (mg/100 ml milk) and animal excretion figures. Concerning crop production, DairyWise calculated a higher total yield of grassland compared to Farmdyn. At the same time Farmdyn does not use all the available grassland on farm 2 for roughage production to feed the animal herd.[14] An important reason is the use of different modelling approaches to model pasturing and production of grass silage, underlying functions for grassland yield (N-response curves) and feed requirement of the dairy herd in DairyWise and Farmdyn. The different approaches regarding optimisation and simulation play a role as well. Full understanding of these differences is difficult because of different feed-back loops within the models. This is also noted by Hutchings et al. (2018). One of the advantages of DairyWise is that detailed information of harvesting, conservation, and feeding losses is included. This allows the model user to calculate the crop yield associated to different stages/processes in a dairy farm. The reported yield of silage maize was almost equal in both models. The milk urea content was significantly higher for DairyWise which can be explained by, among others, the higher consumption of concentrates and by-products compared to Farmdyn.

For feed intake, there was a small difference between the amounts of fresh grass and grass silage calculated by DairyWise and Farmdyn. Generally, DairyWise applies lower levels of energy content to fresh grass and grass silage. Since the amount of animal feed intake is calculated based on the energy requirements, the lower energy content of grass silage in DairyWise leads to higher use of grass silage as feed.

A substantial difference between the outputs of these two models was the amount of concentrates in the diet of farm 1, where the yearly concentrate consumption per farm was calculated to be 257,073 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 and as explained earlier, 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. Farmdyn includes the same mechanisms based on feed requirements and feed content, but the optimal feed ration and land use is a function of relative prices as well. Finally, both models estimated the same level of total energy supplied by the feed.

In the chemical 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 chemical fertiliser was higher. In maize crop, DairyWise calculated a considerably higher amount of N from chemical fertiliser than N from animal manure. Comparing these two models, a high P excretion from the dairy herd was reported by DairyWise. This is mainly caused by the high P content in concentrates (results not presented) in DairyWise and accordingly a higher value for P excretion (Table 4.1 E) was estimated. For N excretion into manure, Farmdyn reported higher values for the farm on sandy soils, whereas DairyWise reported higher values for the farm on peat soils. This could be explained by calculated energy and protein levels of grass in DairyWise, while Farmdyn has

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[14] 46.6 ha of grassland is used to feed the animal herd on farm 2, while about 48.8 ha is available. If we e.g. would allow for selling of silage grass all grassland would be used.

fixed values for urea value and N and P excretion. Also, a part of the differences is due to different approaches applied in DairyWise (simulation) and Farmdyn (optimisation).

Both models reported different figures for NH_3 volatilisation from grazing and animal manure application, but the differences were relatively small. However, NH_3 emissions related to barn and animal manure storages were higher in DairyWise. This difference stresses the importance to check calculation rules and emission parameter settings in DairyWise and Farmdyn. The higher consumption of concentrates in DairyWise can be the reason of the higher NH_3 emissions. Since animal manure content is not affected by the ration in Farmdyn (N excretion is dependent on urea content), Farmdyn reports fewer NH_3 emissions for both farms compared to DairyWise.

The results of the nutrient balances showed similar results for both models. Given that in Farmdyn the optimal feeding plan on farm 1 does not include purchased roughage, the N and P in purchased roughage equals zero. Export of P (and N) in animal manure is rather high. This is due to the relatively high P content of the animal manure. Application of animal manure on the farm is determined by the legal application of P from animal manure on the farm. This is also determined by the share of silage maize, because the legal amount of P from animal manure differs for silage maize and grassland. The last category of results contains the GHG emissions which have been reported explicitly by DairyWise. Since DairyWise is designed to calculate the GHG emissions in a more comprehensive way, this model provides detailed information on GHG emissions in contrast to Farmdyn.

Table 4.1 *Results of Farmdyn and DairyWise*

Item	Unit	Type of parameter in the model (Endogenous (Y)/ Exogenous (X))		Farm 1		Farm 2	
		Farm-dyn	Dairy Wise	Farm-dyn	Dairy Wise	Farm-dyn	Dairy Wise
A) Herd characteristics							
Dairy cows	#	X	X	94	94	82	82
Milk production	kg/cow/year	X	X	8,600	8,600	7,800	7,800
Urea content	mg/100 ml milk	X	Y	21.6	28.0	24.5	29.0
B) Crop production							
Grassland	Ha	X	X	37.0	36.9	46.6	48.8
Yield after harvest losses, before conservation and feeding losses	kg dm/ha/year	Y	Y	10240 a)	12223	10,184 a)	12,989
energy content	VEM/kg dm	Y	Y	932	913	916	866
protein content	g CP/kg dm	Y	Y	176	177	174	197
Silage maize	Ha	X	X	9.0	9.0	0.0	0.0
Yield after harvest losses, before conservation and feeding losses	kg dm/ha/year	Y	Y	16,492	16,720	---	---
energy content	VEM/kg dm	Y	Y	937	937	---	---
protein content	g CP/kg dm	Y	Y	74	76	---	---
C) Feed use by herd							
Fresh grass	kg dm/farm/year	Y	Y	168,509	165,819	136,647	145,863
Grass silage	kg dm/farm/year	Y	Y	210,357	234,790	337,436	301,520
Maize silage	kg dm/farm/year	Y	Y	130,617	130,784	4,543	26,978
By-product	kg dm/farm/year		Y	---	29,610	---	25,912
Concentrates	kg/farm/year	Y	Y	257,073	280,356	165,423	155,397
D) Chemical and organic fertilisation							
Grassland							
Applied N from animal manure	kg N/ha/year	Y	Y	254	187	250	219
N from chemical fertiliser	kg N/ha/year	Y	Y	128	135	121	153
P_2O_5 from animal manure	kg P_2O_5/ha/year	Y	Y	89	74	84	77
Silage maize							

Item	Unit	Type of parameter in the model (Endogenous (Y)/ Exogenous (X))		Farm 1		Farm 2	
		Farm-dyn	Dairy Wise	Farm-dyn	Dairy Wise	Farm-dyn	Dairy Wise
Applied N from animal manure	kg N/ha/year	Y	Y	132.9	59.6	0.0	0.0
N from chemical fertiliser	kg N/ha/year	Y	Y	11	83	0.0	0.0
P_2O_5 from animal manure	kg P_2O_5/ha/year	Y	Y	47	24	0.0	0.0
E) Animal excretions							
N before subtraction of any NH_3 emissions (whole herd including young stock)	kg N/farm/year	X	Y	16,000	14,258	13,708	15,331
N based on RVO tables (4 and 6)	kg N/farm/year	X	Y	13,383	15,077	11,465	12,580
P (whole herd including young stock)	kg P_2O_5/farm/year	X	Y	4,963	5,469	4,125	5,063
P based on RVO-tables (4 and 6)	kg P_2O_5/farm/year	X	Y	---	4,884	---	4,028
F) Ammonia emissions							
From barns + animal manure storages	kg NH_3/farm/year	Y	Y	1,173	1,454	1,018	1,543
From grazing	kg NH_3/farm/year	Y	Y	138	110	115	108
From animal manure application	kg NH_3/farm/year	Y	Y	808	882	1,338	1,493
G) Nutrient Balance							
N in purchased roughage	kg N/ha/year	Y	Y	0.0	8.7	1.1	13.1
P in purchased roughage	kg P_2O_5/ha/year	Y	Y	0.0	7.6	0.0	4.8
N in purchased concentrates	kg N/ha/year	Y	Y	175	152	98	81
P in purchased concentrates	kg P_2O_5/ha/year	Y	Y	69	63	40	33
N in disposal/export animal manure	kg N/ha/year	Y	Y	80.3	88.2	0.0	7.9
P in disposal animal manure	kg P_2O_5/ha/year	Y	Y	26.9	34.8	0.0	2.7
N farm surplus	kg N/ha/year	Y	Y	91	108	139	91
P farm surplus	kg P_2O_5/ha/year			---	-10.3	---	-21.5
N soil surplus	kg N/ha/year	Y	Y	95.3	84.0	303.0	264.0
P soil surplus	kg P_2O_5/ha/year	Y	Y	-6.0	-10.0	3.3	-25.0
H) GHG emissions							
GHG rumen fermentation	g $CO_{2\text{-eq}}$/kg FPCM		Y	---	511.0	---	530
GHG animal manure storage	g $CO_{2\text{-eq}}$/kg FPCM		Y	---	137.0	---	152
GHG feed production	g $CO_{2\text{-eq}}$/kg FPCM		Y	---	91	---	335
GHG energy resources	g $CO_{2\text{-eq}}$/kg FPCM		Y	---	50	---	58
GHG imports	g $CO_{2\text{-eq}}$/kg FPCM		Y	---	334	---	304
Total GHG allocated to milk production	g $CO_{2\text{-eq}}$/kg FPCM		Y	---	1,123	---	1,379
Total GHG before allocation	g $CO_{2\text{-eq}}$/kg FPCM		Y	---	1,399	---	1,810

a corrected for storage loss.

4.2.2 Application: Economic and environmental impact on a representative dairy farm with sandy soils of a 100% tax on N from chemical fertilisers

DairyWise, CNGRAS and Farmdyn were used to analyse the impacts of a 100% tax on N from chemical fertilisers. This contributes to circular agriculture as the measure potentially stimulates more efficient use of chemical fertilisers or a switch to alternative technologies. CNGRAS was included in the analysis because it delivers more detailed calculations on N losses and soil organic C balance. The changes in N from chemical fertilisers and resulting changes in grassland yield are also compared to results from DairyWise and Farmdyn.

A 100% tax on N from chemical fertilisers means that the price of N from chemical fertilisers would double. From the literature, it is known that the price (or demand) elasticity, percentage change in use of N from chemical fertiliser per percentage change in price of N from chemical fertiliser, is very low, especially in the short run (Sud, 2020). According to Sud (2020) this is explained by 'lack of knowledge regarding alternative practices amongst farmers, strong risk aversion tendencies, behavioural factors and lack of alternatives'. In the Netherlands a lot of N from animal manure is exported abroad, linked to the phosphate in animal manure surplus and the maximum application of phosphate from animal manure. A potential alternative to N from chemical fertilisers could therefore be high quality manure products with high N and low phosphate content. However, the production costs of these high quality manure products are very high (de Koeijer et al., 2019). It is therefore not included as a real alternative for N from chemical fertilisers in this study.

The scenario allows model comparison with a special focus on the N-response curve and combined model use. The first step was to calibrate the implicit N-response curve between N input from chemical fertilisers and grass output in Farmdyn to econometrically estimates as found in the literature. This allows taking into account empirical estimates of observed behaviour of the farmer as discussed above. Both DairyWise and CNGRAS are not able to directly analyse input price responses. To circumvent this problem a range of changes in N-regime and connected changes in N from chemical fertilisers are simulated with DairyWise and CNGRAS. This allows detailed comparison of the N response between N input from chemical fertilisers and grass output between the calibrated Farmdyn results, DairyWise and CNGRAS (model comparison). The third step (combined model use) was to take the range that most closely reproduced the calibrated Farmdyn outcome as most realistic regarding the behaviour of the dairy farmers under a 100% tax on N from chemical fertilisers.

Farmdyn
A reduction of N from chemical fertiliser use on Dutch dairy farms will result in lower grassland yields, higher roughage yield risks and increased costs for purchased roughage and concentrates. In Farmdyn the extra costs for purchased feed are compared to the avoided tax payments when using less N from chemical fertiliser to minimise income loss. Next to the prices of purchased feed and N from chemical fertiliser, the results are mostly determined by the physical relationship between changes in N from chemical fertilisers and changes in grassland yield; the N-response curve for grassland. To include behavioural aspects in Farmdyn, the linearised N-response curve for grassland was calibrated to econometrically estimated model results using individual farm data (Samson et al., 2017). From an econometrically estimated model using individual farm data and covering the period between 2008 and 2012 it was found that a 1% increase in use of chemical fertiliser increases the roughage production on the farm with only 0.072%. Although the econometric estimates only cover a small period, the price of N from chemical fertiliser fluctuated from about 39 euros per 100 kg in December 2008 to about 16 euros per 100 kg in 2009. Given these price fluctuations we consider the results suitable for calibration of Farmdyn for our 100% tax on N from chemical fertiliser scenario.[15] Farmdyn was calibrated including only a limited number of alternative grassland activity options and a very narrow range of N chemical fertiliser input per grassland activity. N demand can decrease from 250 kg N per ha to 225 kg N per ha both for grazing and silage grassland activities. The data for the N-response curve is based on observed use of chemical fertiliser and grassland yields from Dutch FADN and literature on marginal impacts N input on grassland yield (Samson et al., 2017, Prins et al., 2018; Conijn and Henstra, 2003). The considered parts of the N-response curves for DairyWise, CNGRAS and Farmdyn are presented in Figure 4.2. The differences in the slope of the curve and the range of N reduction considered in the different models will give a range of possible impacts of the scenario on farmers income and emissions. Given the considered range, it can be calculated that per kg N reduction the roughage production decreases by about 0.007, 0.02 and 0.012 tonnes dry matter in Farmdyn, DairyWise and CNGRAS, respectively.

Table 4.2 shows the technical and environmental impacts of the 100% tax on the representative Dutch dairy farm on sandy soil. The acreage of grassland and the acreage of maize silage are kept fixed. In absolute numbers, the use of N from chemical fertiliser decreases from 128 to 113 kg N per ha grassland in baseline and scenario, respectively. This result is affected by the assumed limited range of the N-response curve for grassland. Total effective N decreases from on average 239 kg N per ha to 225 kg N per ha. Income decreases with about 3,800 euros, mainly caused by 3,140 euros of

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[15] Exact calibration is not possible as Farmdyn includes different technologies and restrictions to produce grass. From the Farmdyn output it is calculated that a 1% increase in use of mineral fertiliser increases the roughage production on the farm by 0.082%. We consider this reasonably close to the econometric estimates from Samson et al. (2017).

increased costs of chemical fertiliser and about 780 euro of increased costs of concentrates. These high costs are only partly compensated for by cost savings, e.g., regarding machinery. Without changes in farm management, so the same amount of chemical fertiliser at a 100% higher price, the income decrease would be about 4,200 euros per farm. If the range of N reduction from DairyWise and CNGRAS was considered with the same calibrated N response curve, the impact of the scenario on farmers income would still be considerable, namely around 3,650 euros per farm instead of 3800 euro per farm. If a larger roughage reduction per kg N reduction was considered in combination with the reduction in N from chemical fertilisers in Farmdyn, the income effect would be larger due to higher extra costs for purchased feed.

Table 4.2 *Farmdyn technical and environmental impacts of a 100% tax on chemical fertiliser for the representative Dutch dairy farm on sandy soil (percentages)*

Category	Part of farm	Indicator	Unit	Base	Scenario
Crop figures	Grassland	Yield after harvest losses, before conservation and feeding loss	kg dm/ha/year	10,240 a)	10,142 a)
Feed use by herd	Grass silage	Grass silage	kg dm/farm/year	210,357	206,748
Feed use by herd	Concentrates	Concentrates	kg/farm/year	257,073	260,137
Fertilisation	Grassland	Applied N from animal manure	kg N/ha/year	254	255
Fertilisation	Grassland	N from chemical fertiliser	kg N/ha/year	128	113
Nutrient account	Total Farm	N farm surplus	kg N/ha/year	91	81

a corrected for storage loss.

DairyWise

The approach to mimic the results from Farmdyn was to adjust the exogenous N-regime in DairyWise. The N regime in the default situation was 68% of the agricultural optimal N-fertilisation level due to applied manure legislation. From a range of available results from DairyWise a reduction of the N regime to 60% of the agricultural optimal N-fertilisation level most closely reproduced the optimal situation in Farmdyn after implementation of the tax.[16] Technical and environmental impacts are presented in Table 4.3. The grass yield reduces from 12,223 kg dm per ha to 11,663 kg dm per ha due to the reduction of N application. Ammonia emissions from barns and animal manure storages reduce from 1,454 to 1,373 kg NH_3. For other sources of NH_3 emissions including grazing, and animal manure application, similar reductions were observed. The N and P in the animal excretion were reduced by reduction in N regime. Nitrogen surpluses of farm and soil were reduced by application of less N. This reduction was lower for N soil surplus compared to the N farm surplus, because for the latter also the reduction of NH_3 emissions is included. Results of GHG emissions for different N regimes show small reductions for the alternative scenario. Given that applying less N on grassland leads to a lower grass yield, the feed requirement is supplied by additionally purchased maize and concentrates, resulting in higher GHG emissions from imported feeds. This, however, seems to be counteracted by the reduced import of chemical fertiliser. Furthermore, since grass silage has higher GHG emissions from enteric fermentation compared to maize, GHG emissions associated with enteric fermentation were slightly lower for the scenario with lower N regime. Mainly because the GHG emission associated with feed production was lower for the scenario with lower N regime, the total GHG emission diminished slightly with lower N-regimes. Figure 4.2 shows the considered part of the N-response curve for DairyWise. It can be seen that a larger range of possible N reduction is considered in DairyWise compared to Farmdyn. As a result, the reduction of N from chemical fertiliser in DairyWise exceeds the reduction of the calibrated Farmdyn results (Table 4.3). From that respect, the already small effects presented in Table 4.3 regarding changes in grassland yield and emissions should be seen as upper bounds.

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[16] The full range of results can be found in Appendix 3.

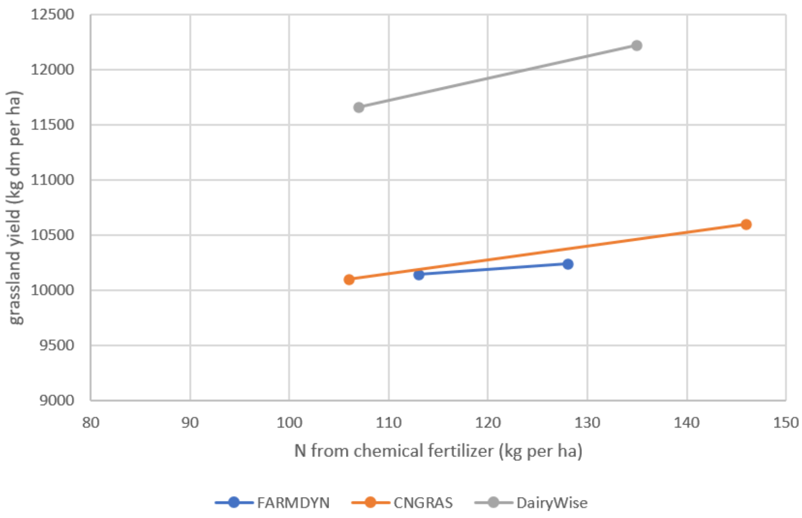

Figure 4.2 *The considered part of the N-response curve in Farmdyn, DairyWise and CNGRAS*

Table 4.3 *DairyWise results for different N fertiliser levels on a simulated dairy farm on sandy soil*

Item			N regime in percent of agricultural optimum	
			Base (68%)	Scenario (60%)
N requirement of grassland	Total	kg N/ha/year	213	185
	Organic fertiliser	kg N/ha/year	78	78
	Chemical fertiliser	kg N/ha/year	135	107
Milk characteristic	Milk urea content	mg/100 gr	28	26
Grass yield a)		kg dm/ha/year	12,223	11,663
Ammonia emissions	From barns+animal manure storages	kg NH_3/farm/year	1,454	1,373
	From grazing	kg NH_3/farm/year	110	103
	From animal manure application	kg NH_3/farm/year	882	851
	Total NH_3 emission	kg NH_3/farm/year	2,445	2,328
	Total NH_3 emission	kg NH_3/ha/year	57	54
Excretions	N before subtraction of any NH_3 emissions (whole herd including young stock)	kg N/farm/year	14,258	13,787
	N based on RVO tables (4 and 6)	kg N/farm/year	15,077	14,748
	P (whole herd including young stock)	kg P_2O_5/farm/year	5,469	5,357
	P based on RVO tables (4 and 6)	kg P_2O_5/farm/year	4,884	4,884
N surplus	N farm surplus	kg N/ha/year	108	97
	N soil surplus	kg N/ha/year	84	76
GHG emissions	GHG rumen fermentation	g $CO_{2\text{-eq}}$/kg FPCM	511	509
	GHG animal manure storage	g $CO_{2\text{-eq}}$/kg FPCM	137	137
	GHG feed production	g $CO_{2\text{-eq}}$/kg FPCM	91	87
	GHG energy resources	g $CO_{2\text{-eq}}$/kg FPCM	50	50
	GHG imports	g $CO_{2\text{-eq}}$/kg FPCM	334	326
	Total GHG allocated to milk production	g $CO_{2\text{-eq}}$/kg FPCM	1,123	1,109
	Total GHG before allocation	g $CO_{2\text{-eq}}$/kg FPCM	1,399	1,382

a Yield after harvest losses, before conservation and feeding losses.

4.2.3 CNGRAS

Table 4.4 shows the CNGRAS results for different N fertiliser levels that most closely mimic the baseline and scenario results of Farmdyn and DairyWise from a range of CNGRAS results. CNGRAS is initially calibrated with data from experimental farm ‘De Marke’ for the years 2006–2015. Table 4.4 gives average annual results after simulating each year separately with CNGRAS (n=10). The input data only differ in the amount of chemical fertiliser per year. All other inputs are assumed equal, such as harvesting management, irrigation and biological N fixation. Results show decreasing grassland yields, N surpluses and N concentrations with lower fertiliser applications. Roughly 50% of the additional fertiliser N is harvested. Total net percolation increases between the baseline and scenario due to lower production and leaf area index of the sward at lower N input levels. Results also suggest a positive relation between N input level and amounts of C and N in the grassland system. Sequestration of C in the soil organic matter decreases due to lower production and related grass residues, whereas the total N balance (total amount of N in the grassland system) decreases from 19.4 kg N/ha to 12.5 kg N/ha. Both C and N results illustrate the dynamic behaviour of the grassland system in CNGRAS. Further analyses are possible, e.g. on the fluctuations among years (which can be important for the farmer) and on the validity of long-term changes in the C and N stocks of the grassland system (which is important for the environmental sustainability of the production system).

From Table 4.4 it can be seen that the reduction of N from chemical fertiliser exceeds the reduction of the calibrated Farmdyn results*.* The reduction in emissions will be even smaller if we would calibrate the scenario results of DairyWise and CNGRAS in Tables 4.3 and 4.4 to the N-response curves found in the literature and the calibrated Farmdyn results.

Table 4.4 *CNGRAS results for different N fertiliser levels of a simulated grassland field on a sandy soil*

	Annual flow	Unit	Base	Scenario
N balance	N deposition	kg N/ha	31.0	31.0
	N fixation	kg N/ha	15.0	15.0
	Organic fertiliser a)	kg N/ha	209	209
	Chemical fertiliser a)	kg N/ha	146	106
Yields	DM yield	t DM/ha	10.6	10.1
	N yield	kg N/ha	287	265
Environment	N surplus b)	kg N/ha	113	94.7
	NO_3 leaching	kg N/ha	47.9	42.6
	NO_3 concentration d)	mg NO_3/l	74	64
	Total N balance c)	kg N/ha	19.4	12.5
	Soil organic C balance e)	t C/ha	1.22	1.18
	Nett percolation f)	mm	274	278

a) Both fertilisers are nett amounts that infiltrate the soil, viz. NH_3 volatilisation has already been subtracted; b) N surplus is calculated as the sum of the four inputs minus the N yield; c) Total N balance is the nett change in the main three N pools of the grassland system (plant, soil (in)organic); d) N concentration refers to the concentration in percolating water below 30 cm soil depth; e) Soil organic C balance gives the average sequestration (positive) or depletion (negative) of the total soil organic C in the upper 30 cm; f) Nett percolation is the amount of water that percolates downwards at a depth of 30 cm, corrected for the amount of water that moved upwards at the same depth through capillary rise.

4.2.4 Conclusions

Comparing the results of DairyWise and Farmdyn in Table 4.1 showed that for most of the studied parameters, almost similar figures were reported. However, for some parameters such as the grassland yield, grass silage uses by the herd, animal excretions, and N and P in purchased roughage, substantial differences were observed. These differences can be explained by the difference in protein and energy content of different feed components, different underlying crop models (N-response curves) and different calculation methods and rules applied in Farmdyn and DairyWise. Full understanding of these differences is difficult because of different feed-back loops within the models and actually require detailed model knowledge. This is also noted by Hutchings et al. (2018). Models are important for ex-ante policy analyses and advice, but are complex by nature although still a simplification of reality. Detailed model documentation and development of tools to transfer knowledge to new model users are recommended to increase the use of these type of models.

Comparison of Farmdyn, DairyWise and CNGRAS shows that the N response of the grassland yield can be quite different between the different models. Econometrically estimates suggest that the position of the average farmer on the N-response curve for grassland is such that changes in fertiliser input have very limited impact on roughage production. Following this, the already small impacts on emission of the tax on N from chemical fertilisers should be considered as upper bounds. We have calibrated and restricted Farmdyn to the above-mentioned econometric estimates of farmers’ behaviour. If we would calibrate Farmdyn to the N-response curve of DairyWise or CNGRAS the effect of the scenario the decrease in N from chemical fertilisers could be larger in Farmdyn, but income losses could be higher due to higher feed costs. The differences in grassland yield and fertilisation levels in the different models in the base and differences in the considered N-responses of the grassland yield, give lower and upper bounds of impacts on farmers’ income and emissions, following reasonable assumptions regarding the considered part of the N-response curve. It is worth keeping the differences in approaches and model features to point at the uncertainties regarding input data and response functions. At the same time, it is worth investing in harmonising definitions of key model variables and input data for key model parameters. The model application in Section 4.2.2 points at the importance to harmonise behavioural aspects to more realistically model allocation of resources. These behavioural aspects should take into account farmers’ behaviour that can deviate from pure profit maximisation. This accounts for both simulation and optimisation models. In this study we use econometric estimates taken from literature to determine the considered part of the N-response curve. An alternative could be organising workshops with farmers or surveys to research the intentions of farmers. It is however known that intended behaviour can deviate from real behaviour (Petrzelka et al., 1996; Hennessy et al., 2016).

Although starting points are different in DairyWise, Farmdyn and CNGRAS, the mechanisms started by the economic incentive work in the same direction. One generic and modular BEFM for dairy farms is therefore not recommended, given among others the different background, objectives, networks of model users and developers, programming language and IT solutions. Much more promising would be to harmonise the key modules regarding feeding and fertilisation.

4.3 Comparison Farmdyn and NA

4.3.1 Harmonisation of input and output parameters

Farmdyn and NA are applied to an average or representative ware potato farm on clay soils in the Netherlands. Farmdyn gives the different crop acreages of the farm (ha), yield per crop (tonnes per ha), chemical fertiliser input per crop (kg per ha) and animal manure input per crop (m^3 per ha). These parameters can directly be used as input in NA that calculates N and P surpluses and losses, organic matter supply and GHG emissions. In this case harmonisation especially means checking whether legal effective N and P supply per crop per ha and the use of animal manure per ha (farm level) in Farmdyn align with the legal N and P standards in NA. The NA results (calculated N and P losses, organic matter supply and GHG emissions) are additional to Farmdyn. The next section presents Farmdyn and NA results of the scenario with a 50% tax on N from chemical fertiliser for this average ware potato farm.

4.3.2 Application: Economic and environmental impact on a representative ware potato farm of a 50% tax on N from chemical fertilisers

Farmdyn

Table 4.5 shows the optimal cropping plan of the representative consumption potato farm on clay soil in Farmdyn.[17] The 50% tax on N from chemical fertiliser has no impact on the optimal cropping plan.

Table 4.5 *Total acreage (ha) and optimal cropping plan (ha) on a representative consumption potato farm on clay soil in the Netherlands in the base scenario and in the 50% tax on chemical fertiliser scenario. Share in cropping plan between brackets*

	Base	50% tax on N from chemical fertiliser
Winter Wheat	23 (38)	23
Potatoes	19 (31)	19
Sugar beet	9 (15)	9
Onions	10 (16)	10
Total acreage	61	61

Source: calculations with Farmdyn.

Table 4.6 shows the fertilisation plan. In the base situation N-fertiliser levels of almost all crops are equal to N advice and the legal fertiliser allowance. Only fertilisation level of winter wheat is 80% of the normal N advice. Given the relative prices of fertiliser and winter wheat, the savings on chemical fertiliser exceeds the loss in revenue.

The '50% tax on N from chemical fertiliser' scenario decreases total input of N from chemical fertiliser by about 14%, from about 10,200 kg N per farm to about 8,780 kg N per farm. This results in a price elasticity of N from chemical fertiliser for this specific farm of -0.28. Table 4.6 shows that use of N from chemical fertiliser decreases on winter wheat, namely from 167 kg N per ha to 100 kg N per ha and on sugar beet from 150 kg N per ha to 120 kg N per ha. To further optimise the N input from chemical fertiliser and following from the internal logic of the model, some animal manure is shifted from consumption potatoes to winter wheat. This explains the increase in N input from chemical fertiliser on consumption potato. (The changes in the allocation of the animal manure could come from changes in the ratio between the N:P ratio in the animal manure and the optimal N:P ratio per crop.)

Table 4.6 *Application of N and P2O5 from chemical fertiliser and application of pig animal manure per crop in the base and in the 50% tax on chemical fertiliser scenario*

	Base	50% tax on N from chemical fertiliser
N from chemical fertiliser (kg N per ha)		
WinterWheat	167	100
Potatoes	173	197
Sugarbeet	150	120
Onions	170	170
P from chemical fertiliser		
Sugarbeet	73	73
Onions	37	37
Pig manure (m3 per ha)		
WinterWheat	8	13
Potatoes	20	14

Source: calculations with Farmdyn.

The lower fertilisation levels on winter wheat and sugar beet result into lower yields per ha, see Table 4.7. Given the very flat N to yield response curve, the yield impact is rather limited. Income loss

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[17] The total share of consumption potato, sugar beet and onions in the cropping plan exceeds the observed shares for the average consumption potato farm, see Table A4.2 in the Appendix. This shows the tendency to increase the share of high margin crops in the cropping plan in the Netherlands.

from the 50% tax on chemical fertiliser scenario equals about 4,000 euros per farm. This consists of a lower revenue of about 1,500 euros and extra costs of chemical fertiliser of about 2,500 euros. This result could be compared to an income loss that would occur without changes in farm management as described above. This so-called direct impact of the tax would result in an income loss of about 4,330 euros, so only about 330 euros more than with farm management changes included. This shows again that at least in the short term, there are limited alternatives to mitigate the use and demand of N from chemical fertilisers. In the long-term investments in fertilisation technologies might increase mitigation options, but these investments are also costly and maybe only feasible in combination with other labour-saving technologies.

Table 4.7 *Crop yield per scenario (tonnes per ha)*

	Base	50% tax on N from chemical fertiliser
WinterWheat	9.5	9.2
Potatoes	52.1	52.1
Sugarbeet	104.1	103.0
Onions	52.9	52.9

Source: calculations with Farmdyn.

Nutriëntenbalans akkerbouw (NA)

In Table 4.8 the results of the run with NA for the two scenarios are given. In the baseline scenario, the N input with animal manure and chemical fertiliser is 65 and 167 kg N per ha, respectively. For P these amounts are 39 and 17 kg P_2O_5 per ha, respectively. The offtake with harvested products is 179 kg N per ha and 68 kg P_2O_5 per ha. This results in a surplus of 83 kg N per ha and -11 kg P_2O_5 per ha. Putting a tax on chemical N fertiliser results in a decreased chemical N fertiliser use and a lower N surplus. The P surplus increases as the crop offtake decreases due to a lower yield level because of suboptimal N rates for wheat and sugar beet.

For the baseline scenario the N surplus was 83 kg N per ha from which 14 and 24 kg N per ha were lost by ammonia volatilisation and NO_3 leaching, respectively. The remaining part of the N surplus must have been lost by N_2, N_2O and NO_x emissions that are not separately calculated. The leached NO_3 results in a concentration of 30 mg NO_3 per litre in the leached water. Due to the lower N surplus in the 50% tax scenario the NO_3 leaching decreased to 18 kg N per ha resulting in a NO_3 concentration of 23 mg per liter. The NH_3 emission increased a little due to a shift of animal manure use from potato to winter wheat. Compared to potato, animal manure application in wheat is done with more shallow injection techniques characterised with a higher NH_3 emission factor

In the baseline scenario, total EOM supply was 1,810 kg per ha, 1,545 kg per ha is from crop residues and 265 kg EOM per ha is from the pig animal manure. Putting a tax on chemical N fertiliser did not affect the EOM supply.

The total GHG emissions in the base scenario amount to about 2,900 CO_2-eq per ha of which about 45% resulting from CO_2 emission and for about 55% resulting from N_2O emission. The direct CO_2 emissions refer to fuel consumption, the indirect CO_2 emissions mainly to fertiliser production. The indirect N_2O emission refers to emissions occurring outside the farm due to NH_3 volatilisation and NO_3 leaching. Putting a tax on the chemical N fertiliser reduced its use resulting in a decrease of the GHG emissions of about 200 kg CO_2-eq per ha due to a lower indirect CO_2 emission level and a lower direct N_2O emission level.

Table 4.8 *Results NA baseline scenario and the scenario with 50% tax on chemical N fertiliser for the ware potato farm on clay*

Indicator	Base scenario	50% tax on N from chemical fertiliser
N balance		
Total N input (kg N/ha) of which	262	239
Animal manure (kg N/ha)	65	65
Chemical fertiliser (kg N/ha)	167	144
Deposition (kg N/ha)	30	30
N outputs		
N-offtake in harvested product (kg N/ha)	179	171
N surplus (kg N/ha) of which	83	68
NH_3-N (kg N/ha)	13	14
NO_3-N (kg N/ha)	24	18
N_2-N + N_2O-N (kg N/ha)	46	36
NO_3 concentration leached water (mg NO_3/l)	30	23
P balance		
Total P-input (kg P_2O_5/ha) of which	56	56
Animal manure (kg P_2O_5/ha)	39	39
Chemical fertiliser (kg P_2O_5/ha)	17	17
Deposition (kg P_2O_5/ha)	1	1
P outputs		
P offtake in harvested product (kg P_2O_5/ha)	68	64
P-surplus (kg P_2O_5/ha)	-11	-8
Organic matter:		
EOM supply (kg/ha)	1,810	1,810
GHG emissions:		
Total (kg CO_2-eq/ha)	2,941	2,730
CO_2 direct (kg CO_2-eq/ha)	601	601
CO_2 indirect (kg CO_2-eq/ha)	906	783
N_2O direct (kg CO_2-eq/ha)	1,307	1,230
N_2O indirect (kg CO_2-eq/ha)	127	116

4.4 Use of soil health tools and CNGRAS in combination with other models

The soil health tools as mentioned in Chapter 3 are not taken into account in the model comparisons. Hereunder a short outline is given how they can support the BEFM models:

- Aaltjesschema and Best4Soil can use the crops that are part of the cropping plan in Farmdyn. With Aaltjesschema and Best4Soil, the most optimal order of crops in the rotation can be determined, so that a crop that is sensitive to damage will not be grown after a crop that generates a high multiplication of the nematodes. Further, an estimate is given of the effect of nematode (both models) or fungal (Best4Soil) species, when present in high densities, on crop growth. The indication of crop loss can be used as input for Farmdyn or NA.
- Nemadecide can be used to manage potato cyst nematodes (Globodera spp.) and therewith the production of potatoes in case of an infestation. As the other models (Aaltjesschema and Best4Soil), it can make use of the cropping plan of Farmdyn. The information can be used to determine the effect on an infestation with cyst nematodes, and the consequences for growth of the potato crop.

Different options can be investigated, for example the number of years in a rotation between potato crops, cultivar choice and the cost effectiveness of control measures like nematicides. The program determines the effect on potato crop production, which can be used as input for Farmdyn or NA.

In Section 4.2.3 the CNGRAS results are presented. The model can have an added value to the BEFM models Farmdyn and Dairywise:

- Farmdyn and DairyWise can provide input on several parameters for CNGRAS like fertilisation levels and number of cuts. Next, CNGRAS executes detailed calculations concerning many processes in the soil of which C sequestration and C emission (as CO_2) are very important in light of GHG emissions. These CNGRAS-results (C sequestration and C emission) complement Farmdyn and DairyWise.
- The tool CNGRAS potentially could replace all or parts of the grass growth modules in Farmdyn and/or DairyWise. Projects focusing, e.g., on impacts of climate change on farm level, could use an analysis of variation among years (such as due to dry and wet periods within growing seasons), which is simulated by CNGRAS.

5 General conclusions and recommendations

The main objective of this project was to develop a conceptual model and a toolbox able to evaluate circularity at farm level. From the start we focussed on the two available BEFMs within Wageningen Research, namely DairyWise and Farmdyn. The conceptual framework as described in Chapter 2 stresses the importance of a farm level approach to analyse the large number of aspects related to circular agriculture and their interrelationships. As discussed in Chapter 3, Dairywise and Farmdyn do not cover all research and policy questions and indicators of circular agriculture. For example, farm level indicators related to soil quality, emission of pesticides, biodiversity and animal welfare are missing. Some can be improved by combined use of BEFMs and tools for soil health, but this is only discussed in a qualitative manner in this report. It is therefore recommended to further integrate the identified tools for predicting risks regarding soil health, namely Aaltjesschema and Nemadecide, into the BEFMs.

DairyWise and Farmdyn and the selected tools mainly focus on dairy and arable farming, while, e.g., the intensive livestock and horticulture sectors are missing. Therefore, it is recommended to build, or extend already existing technical/economic farm models for the above mentioned farm types, to make it possible to model, e.g., the use of recycling products in the intensive livestock industry. Very important for the transition to circular agriculture is that behavioural aspects other than pure profit maximisation are not automatically taken into account in DairyWise and Farmdyn. This is also because behavioural data regarding farmers' preferences, attitudes and beliefs are missing. In this study econometric analyses taken from literature are used to more closely include observed behaviour in the model results. It is recommended to invest in econometric models to be added to the toolbox. Notwithstanding possible differences in intended behaviour and real behaviour it is also recommended to invest in experiments or surveys among farmers to resolve the lack of behavioural data.

From the model descriptions, we concluded that there is overlap between DairyWise and Farmdyn, but there is also complementarity e.g. regarding implementation of economic policies and environmental modules. Combined model use also contributes to scientific validity of their use and highlights how model and scenario assumptions impact results (Hutchings et al., 2018; Mosnier et al.,2019). When the results of DairyWise are compared to Farmdyn (Section 4.2), it became clear that model results differ. As also experienced by Hutchings et al. (2018), full understanding of these differences is difficult because of different feed-back loops within the models. Additional reasons include the difference in protein and energy content of different feed components and using different underlying crop models (N-response curves) which has been discussed in Section 4.2.2. Technically speaking, this could be improved by harmonisation of input parameters, e.g., emission parameters and by sharing modules, e.g. feed modules or grassland yield modules. It is recommended to keep different models and tools and modelling teams as they have their own network of model developers and users. Sharing and harmonising modules is recommended as this would be supportive to this. It also contributes to combined models to improve scientific quality of the individual models and for efficient policy impact assessments. Models covering a large number of farm branches and farm management activities are important tools for ex-ante policy assessment but are complex by nature. It is recommended to invest in model documentation and tools to transfer knowledge to new model users in order to increase the network of model developers and users.

Regarding arable farming, we compared Farmdyn and the tool NA that provides information about nutrient surpluses, the fate of the N surplus and GHG emissions (Section 4.3). These two models are complementary to each other, Farmdyn is providing economic and farm management data and NA is providing information about nutrient losses. It shows that combined use and/or the integration of farm level models and tools describing parts of the farm system is promising. It is recommended to include NA as a module directly in Farmdyn.

In principle, the approaches of combined models presented in this report can be applied to many combinations of models but of course the degree of success will vary widely. It is not enough to know which models exist in a certain field of interest, e.g., capable to analyse the effects of a tax on chemical fertiliser. A library of models, as currently developed by the Wageningen Modelling Group,[18] should include more detailed information about inputs and outputs of the models to allow knowledge transfer to new model users. Furthermore, the library should include literature references to existing combined model use of models and tools that are included in the library.

Based on our experiences, regarding combined use of models and tools in a toolbox, to answer more complex questions and widening the scope of the analysis, the following recommendations for researchers and modelers can be provided:

- In this study research teams were quite experienced and could start from pre-selected models and tools, otherwise it is recommended to search intensively for existing models in the above mentioned library of models and involve the respective contact persons.
- Try to detect which answers the discovered models can provide separately.
- Explore if useful combinations of the discovered models can improve the answers:
  - If so, set up a combined use between those models and run the combined set of models.
- If a new model has to be built:
  - Build it modularly and incorporate already existing modules from other models (re-use of models/modules).
  - Take into account the ability to integrate micro and macro levels: from, e.g., soil level (e.g., NemaDecide) to parts of the farm level (e.g., NA), further to farm level (e.g., Farmdyn and DairyWise) and then to regional, national and international level.

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[18] https://modelgallery.wurnet.nl

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Appendix 1 General description of models

Farmdyn

Farmdyn is a bio-economic, mixed-integer programming model at individual farm level, that simulates farmer’s decisions regarding agricultural production and investments in a comparative static or dynamic setting.[19] 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 has been 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 (KWIN)),[20] such that it becomes applicable to analyse representative arable and dairy farms in the Netherlands, incorporating Dutch legislation on fertiliser applications and N balances.

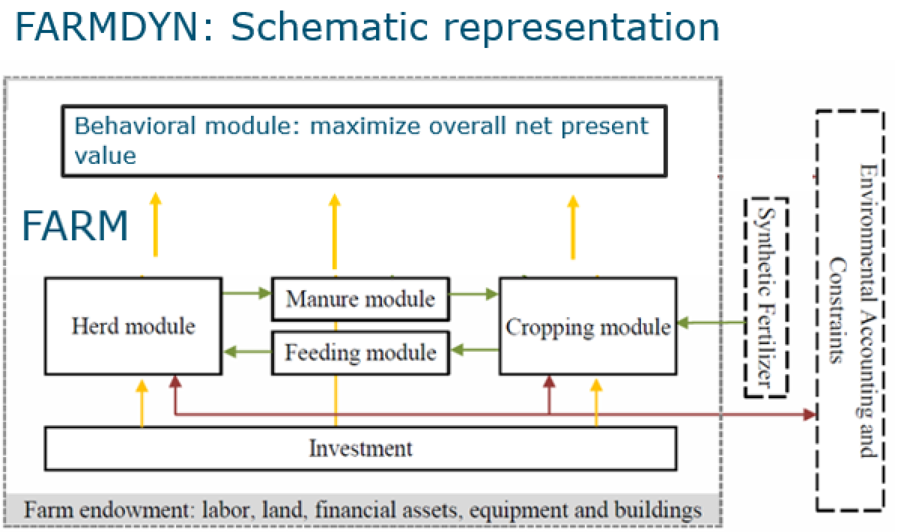

Figure A1.1 *Farmdyn: schematic representation*
Source: http://www.ilr.uni-bonn.de/em/rsrch/Farmdyn/FarmdynDoku/

General description (taken from Britz et al., 2021)
The Dutch version of the single farm model Farmdyn allows simulating optimal farm management and investment decisions under changes in boundary conditions such as prices, technology or policy instruments for arable and dairy farms. It is based on a model template for a fully dynamic or comparative-static bio-economic simulation, building on Mixed-Integer Programming. Farm branches and other elements such as fertilisation and animal manure policy restrictions can be added in a modular fashion to the core model. The model is capable to run 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) (Figure A1.1). 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.

The farming branches for dairy and cattle farming differentiate raising and fattening processes by month, grazing share and weight gains, and, in case of dairy cows, by month of calving and lactation period. These options interact with multiple, seasonally differentiated grassland management options.

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[19] http://www.ilr.uni-bonn.de/em/rsrch/Farmdyn/FarmdynDoku

[20] Kwantitatieve Informatie Veehouderij (KWIN-Veehouderij).

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 and intra-year feeding periods (energy, protein, dry matter) for each cattle herd. Farmdyn allows to define up to 10 different types of grassland management options by the following two attributes: 1. total dry matter output, 2. distribution of fresh grass and grass silage over months. The different types of grassland management each produce three types of fresh grass (early, middle and late). Each type of fresh grass has different nutrient and dry matter contents. 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 endogenous choice of 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. The crops can be differentiated by tillage (ploughing, minimal tillage, no tillage) and intensity level (normal and reduced fertilisation in 20% steps). As stated above, machinery use is linked to field working-day requirements depicted with a bi-weekly resolution during the relevant months. Operation and machinery data are taken from above mentioned management handbooks. Crop rotational constraints are modelled as simple maximal shares. The model can capture plots which are differentiated by soil and land type (arable land and grassland with both mowing and grazing, only mown or with only grazing (pasture)) and size.

DairyWise

DairyWise (Schils et al., 2007) is a whole-farm dairy model that empirically simulates technical, environmental, and financial processes. It calculates technical and economic indicators based on a combination of farm-specific and normative input values. Based on these technical and economic indicators, strengths and weaknesses of a farm can be detected and consequences of changes can be assessed. DairyWise can be used for integrated scenario development and evaluation by scientists, policy makers, extension workers, teachers and farmers.

General description

The structure of DairyWise is depicted in Figure A1.2. This model integrates all the main subsystems of a dairy farm into a farm model. 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 is used as input for several technical, environmental, and economic sub-models. The sub-models simulate a range of farm aspects such as N and P cycling, NO_3 leaching, NH_3 emissions, GHG emissions, energy use, and a financial farm budget. The final output is a farm plan describing all material and nutrient flows and the consequences for the environment and economy.

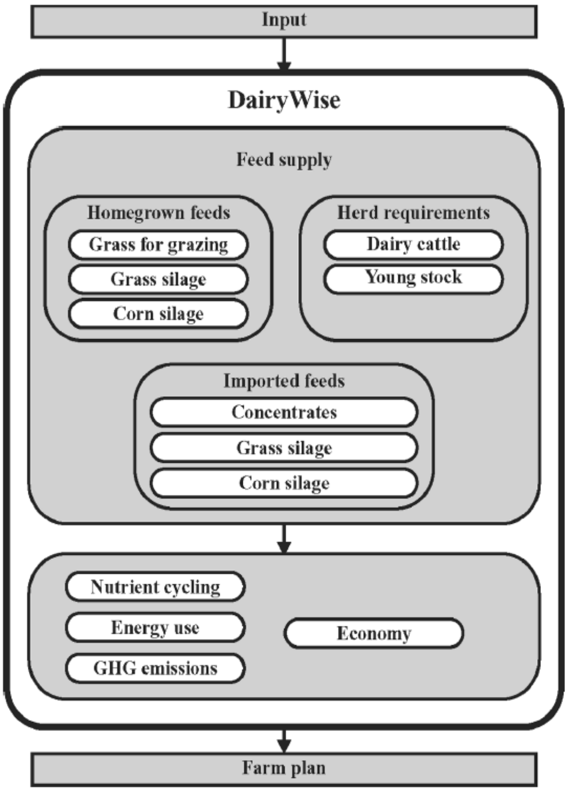


Figure A1.2 *Modular structure of DairyWise. The model input consists of user-defined traits that describe a dairy farm. The Feed Supply model balances the herd requirements with homegrown and imported feeds. The output of the FeedSupply model is the input of several sub-models. The final model output consists of a farm plan containing the technical, environmental, and economic data of the defined farm*
Source: Schils et al. (2007).

DairyWise is a whole-farm dairy model, aimed at modelling at farm level and includes dairy farming, including its young stock and home-grown grass, maize as silage or corn cob mix (CCM), triticale, lucerne and fodder beets. Feed and chemical fertiliser can be imported, and milk and meat (live animals) can be exported from the modelled farm. Animal feed requirements and production as well as animal manure production and its utilisation in crop growth are modelled.

DairyWise is a flexible model which can be run with different levels of inputs. It provides different input options depending on the data availability. At the minimal level, data of livestock and feed management, land and crop management and some other variables should be provided. Livestock and feed management categories consist of data related to the number of dairy cows, the grazing system and feeding strategy. Land and crop management categories include the soil types, the land area (grass, maize and other forage crops), and the fertiliser application rates. In each step it is possible to extend the list of inputs to change the default values.

As it is seen in Figure A1.2 and discussed previously, DairyWise applies various models. For crop models DairyWise applies GrassGrowth and maize models. Three models are used in DairyWise as animal models: for dairy cows (DairyCow model), for young stock (YoungStock model) and for herd characteristics (DairyHerd model). Also, for feed, the FeedSupply model is applied to balance the herd energy and protein requirements with the supply from the homegrown feeds and imported ones.

Besides the applied models, a wide range of calculations are done by DairyWise, including the nutrient cycling, energy assessment, GHG emission calculations and economic evaluation. All the detailed information about the applied methods can be found in De Haan et al. (2007) and Schils et al. (2007).

DairyWise provides a long list of outputs including economic evaluation, feed supply details, nutrient cycling, mineral balance, energy balance, GHG emissions, labour demand, and consequences from animal manure policies. Some of the generated outputs are based on the 'Annual Nutrient Cycle Assessment' (in Dutch: 'KringLoopWijzer Melkveehouderij' (KLW)) calculations.

CNGRAS

The tool CNGRAS is a dynamic simulation model for grassland management and C and N flows at field scale. Increasing concern over the last few decades about the adverse effects of agriculture on the environment has led to imposing various restrictions on grassland management in order to protect the human population and the environment. Many of these restrictions will also have an effect on grassland productivity. However, the relation between (changing) abiotic conditions, grassland productivity/management and environmental quality is very complex and a dynamic model that integrates the main processes is a helpful tool to disentangle trade-offs and synergies, linked to the (long-term) effects of grassland management. Furthermore, CNGRAS explicitly incorporates the 'hidden' or non-harvestable part of total grass production and nutrient uptake. Special attention is given to incorporating various management options into the model in order to mimic closely actual and possible alternative management options. These requirements resulted in a dynamic model, operating with small time steps (i.e. one day) for the simulation of the effects of (daily) weather/climate conditions and grassland management on productivity, C sequestration, N and water flows. Daily weather data are needed as input for CNGRAS. However, the model is also suitable for use on a time scale of several decades to simulate long-term effects (Conijn, 2005) (note: large part of this text has been published earlier in Conijn, 2005).

The tool CNGRAS consists of five main modules, in which the calculations on C, N and water cycling in the grassland ecosystem are performed. These are: (1) grass production, (2) grassland management, (3) soil organic C and N, (4) soil inorganic N, and (5) soil water balance. Four plant compartments are distinguished for the simulation of grass production: root, stem, leaf and a reserve pool (Figure A1.3). Dry matter production depends on the amount of radiation absorbed by the green leaf area index and is influenced by air temperature, leaf N content and transpiration status. The death rates are added to pools of dead root, stem and leaf dry matter, which are input for the soil organic matter model. The C dynamics of the grass sward have been correlated to the dry matter dynamics by applying C concentrations (g C / g DM) (Conijn, 2005).

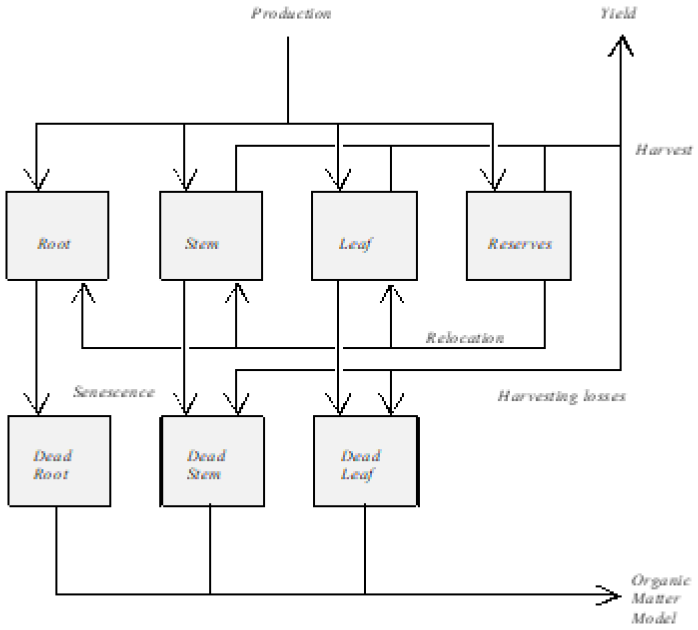


Figure A1.3 The four plant biomass compartments (root, stem, leaf and reserves) and their main flows in modelling grass dry matter dynamics in CNGRAS
Source: Conijn (2005).

For the partitioning of N, the same compartments are used. The amount of inorganic N taken up from the soil has been modelled as a function of N demand, which depends on the difference between attainable and actual N contents in each plant compartment, while correcting for the relocation of N from senescent plant parts. Nitrogen concentrations are not constant and vary depending on the growing conditions. In CNGRAS, low N concentrations in leaf tissue negatively affect dry matter production, change the partitioning of dry matter in favour of the roots, and accelerate the senescence of the aboveground plant parts.

Via an input file a model user can enter different sets of input parameters for each harvest, which provides flexibility to operate CNGRAS. Various options can be defined separately for each harvest event: harvest timing and method, intake levels during grazing, harvest losses, fertiliser application (type, timing and amounts), irrigation events and amounts. If an organic fertiliser is used, the organic N is distributed among the pools of soil organic N, from which N is released in inorganic form through decomposition of organic matter. Information on irrigation can be supplied either by an irrigation calendar, consisting of dates and amounts of water applied or at a certain soil water deficit during the calculations. This tool can thus be used for situations with a known past management calendar as well as for scenario studies where management depends on the actual state of the grassland system which may be different from year to year.

The model component on soil organic C and N integrates inputs and outputs of organic C and N in soil organic matter at each time step. Inputs are derived from grass residues, organic fertilisers and faeces deposition during grazing, outputs are given by C and N mineralisation, i.e. the transformation of organic C and N into inorganic C and N. Total organic C and N in the soil is subdivided into three different pools, mainly to account for differences in mineralisation rates between various soil organic matter fractions. Soil biomass, such as living microbes, earthworms, etc. (but excluding plant roots), is not simulated separately, but is included in each organic matter pool. Because soil organic matter is found at various depths in the soil, inputs are - for reasons of simplicity - directly distributed over soil depth by using constant distribution functions. Movement of organic matter in the soil is thus not explicitly simulated but is included in the soil depth distribution functions. The transformation of organic C into CO_2 (C mineralisation rate) has been described as a process with first order kinetics and is influenced by (a) soil temperature, (b) water content in the soil, and (c) clay content of the soil. The N mineralisation rate is calculated as a function of the relative C mineralisation rate and two other parameters, viz. the microbial growth efficiency and the C:N ratio of the microbes.

A simple soil water balance (‘tipping bucket’ or ‘storage-overflow’) is the standard option in CNGRAS. The user defines a number of soil layers, and their characteristics related to water contents at saturation, field capacity, wilting point and air-dry. Water percolates vertically from the top towards the bottom after subtracting possible runoff. Water that percolates through the lower boundary of the bottom layer is assumed to be lost for the grassland system. Plant transpiration and soil evaporation are simulated, both depending on evapotranspiration demand and leaf area index.

The soil balance of inorganic N is closely linked to the soil water balance. Dissolved N moves with the soil water through the soil until it can be lost at the bottom. Simple equations are used for the loss of N via denitrification. Nitrogen is taken up by the grass as a function of availability in the soil solution, the N demand of the grass and the water uptake by the roots. It is also possible to replace the simple balances in CNGRAS by soil models with a higher complexity (see e.g. Conijn and Henstra, 2003).

Nutriëntenbalans Akkerbouw

The Nutriëntenbalans Akkerbouw (NA) is a tool that has been developed for calculating N and P surpluses on an arable farm based on the cropping plan, crop yields and the fertilisation of the crops (Schröder and Rutgers, 2018). The motivation for developing the NA is the demand from arable farmers to have a tool that can be used as a proof for farm specific application standards for N and P. The current application standards are based on an average situation regarding animal manure use and crop yields. Especially on farms with high yield levels, farmers claim that higher application standards are necessary to maintain these high yields. The NA is a potential tool for underpinning this claim. Next to the nutrient surpluses, the NA also calculates the fate of the N surplus (in form of NH_3, NO_3, N_2O, N_2), the GHG emissions (CO_2 and N_2O) and the organic matter supply.

In the NA, a registration mode and a forecast mode are distinguished. In the registration mode, the nutrient surpluses are calculated based on the registration of the fertilisation and yield data for a selected year. The forecast mode offers the possibility to evaluate alternative measures regarding cropping plan, fertilisation levels, animal manure type, growing catch crops and application method of chemical fertilisers (broadcast or row application).

Some of the restriction of NA are:

- The model is developed for arable farmers. It also includes vegetables and some flower bulb crops that are frequently grown on arable farms. Grass is not included in the model.
- With regard to nutrients, NA is restricted to N and P. Other nutrients, like K, are not included.
- The calculations are restricted to nutrient parameters, organic matter supply and GHG emissions. Economic parameters are not included.

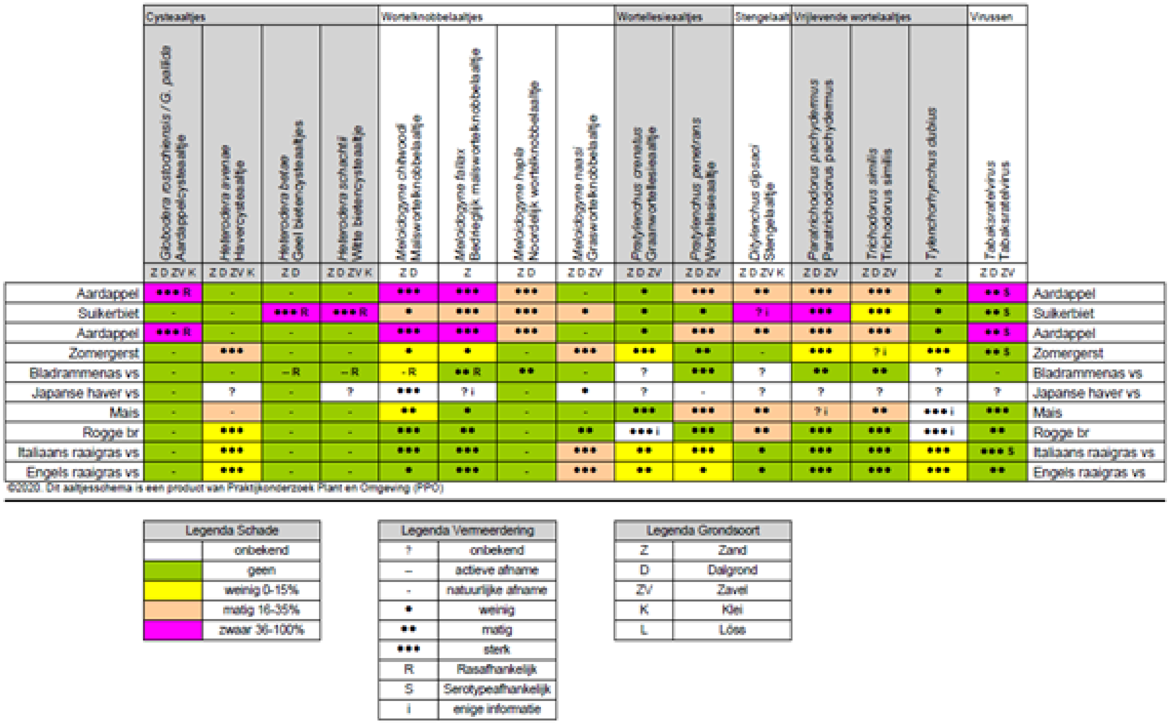
The NA requires the fertilisation and crop yields per crop/field as inputs. The fertilisation data refer to amount, time and application method of organic as well as chemical fertilisers. For organic fertilisers a default composition (organic matter, N_{total}, NH_4-N, P) is available per organic fertiliser type, but users can adjust these values to farm specific values.

The NA also requires a couple of soil parameters: organic matter content and P soil content.

Soil health models

Aaltjesschema
The website www.aaltjesschema.nl is a qualitative Decision Support System (DSS) that estimates the risks of pathogenic nematodes in a crop rotation. It is intended for farmers and advisors and focuses on arable farming, ornamental bulb production and nurseries of perennial plants and trees. It includes 154 crops, 37 nematode species and two viruses that are transmitted by nematodes.

Aaltjesschema generates an indication of nematode multiplication and potential crop losses as output. For each of the selected combinations of nematodes and plants, the host plant status is presented in five levels: no, low, intermediate or high multiplication, or active decline (Figure A1.4). In addition, information about the availability of resistant cultivars is indicated with ‘R’. A question mark indicates that no information on host status is known. The sensitivity of the crop is presented in colour determining four levels: no, low, intermediate or severe damage, or damage unknown. Damage to a crop may be quantitative or qualitative. The presented information is based on data from at least three field experiments. The presence of additional information that has been judged insufficient but indicative, such as data from greenhouse experiments, is indicated with ‘i’. Clicking on the field opens a tab with background information.



	Cysteaaltjes				Wortelknobbelaaltjes				Wortellesieaaltjes		Stengelaaltj	Vrijlevende wortelaaltjes			Virussen	
	Globodera rostochiensis / G. pallida Aardappelcysteaaltje	Heterodera avenae Havercysteaaltje	Heterodera betae Geel bietencysteaaltjes	Heterodera schachtii Witte bietencysteaaltje	Meloidogyne chitwoodi Maïswortelknobbelaaltje	Meloidogyne fallax Bedrieglijk maïswortelknobbelaaltje	Meloidogyne hapla Noordelijk wortelknobbelaaltje	Meloidogyne naasi Graswortelknobbelaaltje	Pratylenchus crenatus Graanwortellesieaaltje	Pratylenchus penetrans Wortellesieaaltje	Ditylenchus dipsaci Stengelaaltje	Paratrichodorus pachydermus Paratrichodorus pachydermus	Trichodorus similis Trichodorus similis	Tylenchorhynchus dubius	Tabaksratelvirus Tabaksratelvirus	
	Z D ZV K	Z D ZV K	Z D	Z D ZV K	Z D	Z	Z D	Z D ZV	Z D ZV	Z D ZV	Z D ZV K	Z D ZV	Z D ZV	Z	Z D ZV	
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Zomergerst	🟩 -	🟧 •••	🟩 -	🟩 -	🟨 •	🟨 •	🟩 -	🟧 •••	🟨 •••	🟩 ••	🟩 -	🟨 •••	🟨 ? i	🟨 •••	🟩 •• S	Zomergerst
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Japanse haver vs	🟩 -	?	🟩 -	?	•••	? i	🟩 -	•	?	-	?	?	?	?	?	Japanse haver vs
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Legenda Schade	
	onbekend
🟩	geen
🟨	weinig 0-15%
🟧	matig 16-35%
🟪	zwaar 36-100%

Legenda Vermeerdering	
?	onbekend
–	actieve afname
-	natuurlijke afname
•	weinig
••	matig
•••	sterk
R	Rasafhankelijk
S	Serotypeafhankelijk
i	enige informatie

Legenda Grondsoort	
Z	Zand
D	Dalgrond
ZV	Zavel
K	Klei
L	Löss

Figure A1.4 *Example of a scheme of nematode multiplication and damage on crops that was made with Aaltjesschema (www.aaltjesschema.nl)*

Regarding circularity indicators these tools give information on the risks of the development of nematode populations in the soil. In addition, effects on yield are given that affects economic indicators.

NemaDecide

NemaDecide (www.nemadecide.com) is a quantitative DSS that focuses on the management of potato cyst nematodes (*Globodera* spp.) in potato. The system is based on a combination of scientific knowledge and practical experience. It uses models on both the development of nematode populations and on the effect on yield. Population development is predicted based on the choice of crop and potato cultivar and different additional measures that can be selected, such as the application of inundation and the use of crop protection agents. The nematode densities are then used to predict the effect on crop yield. The information can be specified to the level of strips of a field and can be used to minimize the effect of a known infestation on crop yield. The references for the different subparts of the model can be found on the website (www.nemadecide.com).

Regarding the circularity indicators Nemadecide gives information on the population densities of potato cyst nematodes being an indicator for soil health. In addition effects on yield are given that affects economic indicators.

Aaltjesschema and Nemadecide are separate tools. The scope of Aaltjesschema is wider than that of Nemadecide that only gives information about cyst nematodes in potato. The output of Nemadecide is more quantitative while the output of Aaltjescchema is more qualitative.

Best4Soil

Best4Soil (www.Best4Soil.eu/database) is inspired by Aaltjesschema and has become available in 22 European languages in October 2020. It only covers a selection of the crops that are available in Aaltjesschema, but also provides information on plant parasitic nematodes that are important in European countries with a Mediterranean climate. More important for the Netherlands, it includes information on plant pathogenic soil-borne fungi that previously only was available as a static scheme for a lower number of fungi. It includes 69 crop species (19 arable crops, 29 vegetables and 21 green animal manure crops), 32 nematodes and 137 pathogens. Best4Soil has an approach that is similar to Aaltjesschema. It needs a choice of crops and soil type, and, if available, presence of certain nematodes as input. It assumes that conditions for nematode multiplication are optimal and considers the worst-case scenario for effect on crop growth. Best4Soil generates an indication of nematode multiplication and potential crop losses as output.

Akkerweb

Akkerweb (www.akkerweb.eu) is an open service platform that can be used for different precision farming applications. It provides maps, services, data, decision support and connections. It provides background maps, services for weather data, satellite images, soil maps, but also a task map generator and crop growth models. The applications that are available are focused tools for crop protection such as nematode and weed management, Phytophthora, but also on nutrient management and grass production. The advantage of Akkerweb is that data only need to be added once and then can be used in different applications.

Appendix 2 Characteristic of two model dairy farms

Table A2.1 *Characteristics (input data) of two model dairy farms*

Parameter	Unit	Farm 1	Farm 2
Number of dairy cows	Number	94	82
Replacement rate of dairy cows	%	30	33
Soil type of grassland		Sandy soil	Peat soil
Ground water level for grassland		V	II
N yielding capacity of grassland	kg/ha	138	246
Grassland renewal percentage	%	10	5
Total Pasture area	Ha	37	49
Pasture area for dairy cows	ha	26	34
Pasture area for calves	Ha	4.4	5.8
Pasture area for heifers	Ha	6.6	8.8
Total silage maize area	Ha	9	0
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	32
Total lease area	Ha	16	17
Fat percentage of milk	%	4.42	4.36
Protein percentage of milk	%	3.56	3.56
Lactose percentage of milk	%	4.51	4.51
P content of milk	mg P/100 g	97	97
Milk production	kg/cow per year	8,600	7,800
Grassland use system		B	B
Additional roughage in summer	kg dry matter/cow/day	6	6
Barn type - dairy barn		Barn with cubicles and slatted floor	Barn with cubicles and slatted floor
Animal manure storage under barn	Month	3	3
Barn type - young cattle barn		Barn with cubicles and slatted floor	Barn with cubicles and slatted floor
Animal manure storage under young stock barn	Month	3	3
Type of animal manure storage outside the barn		silo	silo
Content of animal manure storage outside the barn	m^3	1,000	900
Slurry application method on grassland		shallow injection	application of diluted animal manure on the soil
Slurry application method on silage maize		Injection	
P rights	kg P_2O_5	4,000	3,300

Appendix 3 DairyWise results for different N fertiliser levels on a simulated dairy farm on sandy soil

Item			**N regime**					
			68% (base)	**60% (scenario)**	**50%**	**40%**	**30%**	**25%**
Nitrogen requirement of grassland	Total	kg N/ha/year	213	185	145	112	81	65
	Organic fertiliser	kg N/ha/year	78	78	75	72	62	57
	Chemical fertiliser	kg N/ha/year	135	107	70	40	19	8
Milk characteristic	Milk urea content	mg/100 gr	28	26	22	20	17	16
Grass yield*		kg dm/ha/year	12,223	11,663	10,900	10,190	9,330	8,601
Ammonia emissions	From barns+animal manure storages	kg NH_3/year	1,454	1,373	1,309	1,263	1,177	1,152
	From grazing	kg NH_3/year	110	103	99	92	81	75
	From animal manure application	kg NH_3/year	882	851	810	780	692	633
	Total NH_3 emission	kg NH_3/year	57	54	50	48	43	41
Excretions	Nitrogen before subtraction of any ammonia losses(whole herd including young stock)	kg N/farm/year	14,258	13,787	13,417	12,986	12,293	12,067
	Nitrogen based on RVO tables (4 and 6)	kg N/farm/year	15,077	14,748	14,137	13,855	13,385	13,197
	Phosphorus (whole herd including young stock)	kg P_2O_5/farm/year	5,469	5,357	5,291	5,234	5,001	4,891
	Phosphate based on RVO tables (4 and 6)	kg P_2O_5/farm/year	4,884	4,884	4,884	4,884	4,884	4,884
Nitrogen surplus	Nitrogen farm surplus	kg N/ha/year	108	97	88	79	71	64
	Nitrogen soil surplus	kg N/ha/year	84	76	71	66	63	58
GHG emissions	GHG rumen fermentation	g $CO_{2\text{-eq}}$/kg FPCM	511	509	508	507	504	503
	GHG animal manure storage	g $CO_{2\text{-eq}}$/kg FPCM	137	137	138	138	139	140
	GHG feed production	g $CO_{2\text{-eq}}$/kg FPCM	91	87	81	75	70	67
	iHG energy resources	g $CO_{2\text{-eq}}$/kg FPCM	50	50	49	48	47	47
	iHG imports	g $CO_{2\text{-eq}}$/kg FPCM	334	326	331	336	332	336
	Total GHG allocated to milk production	g $CO_{2\text{-eq}}$/kg FPCM	1,123	1,109	1,106	1,104	1,092	1,093
	Total GHG before allocation	g $CO_{2\text{-eq}}$/kg FPCM	1,399	1,382	1,378	1,375	1,361	1,362

* Yield after harvest losses, before conservation and feeding losses.

Appendix 4 Farmdyn representative ware potato input data and assumptions

Average economic and technical statistics for the representative ware potato farm on clay soil were constructed from a group of individual farms as found in the Dutch FADN, bookkeeping year 2017. This group was constructed using cluster analysis. The total crop acreage of the farm is 61 ha. The average cropping plan and the revenue (yield x price) minus seed, crop protection and other direct costs per crop as found in the Dutch FADN, bookkeeping year 2017 are presented in Table A4.1. The fertilisation costs are not included but added later on.

Table A4.1 *Cropping plan and revenue minus seed, crop protection and other direct costs (euros per ha) for average consumption potato farm on clay soil in the Netherlands, bookkeeping year 2017*

Crops	Share in cropping plan (%)	revenue 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	

Source: Dutch FADN, bookkeeping year 2017.

Typically, this way of constructing an average or representative arable farm results in a cropping plan with a large number of individual crops. This is not realistic and to solve the problem, only crops with a share of more than 7.5% in the total cropping plan were selected for the optimisation in Farmdyn. To respect crop rotation restrictions, 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. Costs for chemical fertiliser, animal manure, hired labour and machinery costs (based on machinery needs, depreciation rates and maintenance costs) are added in Farmdyn to enrich the income calculation. Existing machinery inventory is taken from the Dutch FADN, while 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 consumption potato 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 A4.2. Farmdyn also allows to include autonomous developments. In this study, it is important that we assume a decrease of the price of sugar beet to the minimum price of 32.5 euros per tonne.

Table A4.2 *Three year (2015-2017) average price of selected arable products (euros per 100 kg)*

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

Source: price statistics

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 chemical 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 A4.3). These standards apply to effective nutrients, i.e. the amount that is available for crop uptake. For reason of simplicity in this study 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 paid to accept animal manure, but the total amount of animal manure that can be applied on the farm is limited by animal manure legislation. To further control the application of animal manure per crop, an upper limit of 120, 250 and 67 kg N per ha from animal manure is included for winter wheat, consumption potatoes and catch crops, respectively. It is assumed that animal manure is not applied to sugar beets and onions.

Table A4.3 *N-advice/N application standards for the selected arable crops on clay soils*

	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 van Dijk et al. (2007). The yield coefficient for winter wheat is taken from de Koeijer et al. (1995). Results are presented in Table A4.4. 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 are not harvested. The extra N input from catch crops incorporated into the soil is not accounted for. It is assumed that crops harvested in summer are always followed by a catch crop.

Table A4.4 *Yield coefficients (relative reduction of the yield in relation to the yield achieved at recommended N fertilisation level) of the response relationship between nitrogen fertilisation and crop yield*

	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

Source: van Dijk et al. (2007), de Koeijer et al. (1995), own extrapolation.

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Wageningen Economic Research
REPORT
2021-095

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the potential
of nature to
improve the
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Report 2021-095
ISBN 978-94-6447-030-7

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