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Grass clover swards: A way out for Dutch dairy farms under legislative pressure?

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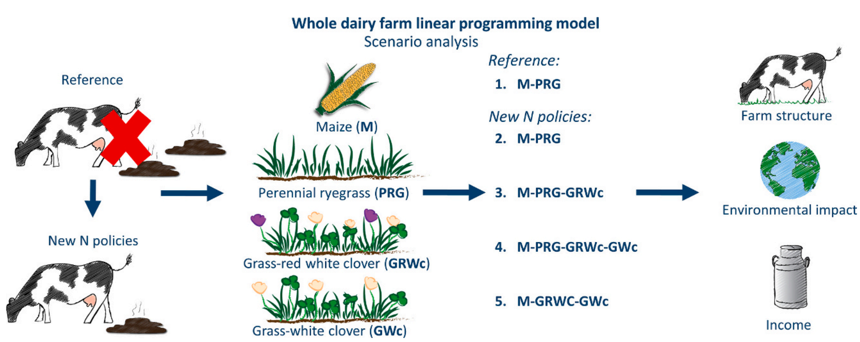
HIGHLIGHTS

- Grass-clover swards might be a strategy for dairy farmers to deal with stricter nitrogen policies in the Netherlands.
- Economic and environmental effects of stricter nitrogen policies were quantified with a whole farm model.
- Number of cows, labour income and nutrient surpluses decreased under stricter policies.
- Grass-clover swards improved labour income and carbon footprint but not always nutrient surpluses.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Policy measures have been taken to improve water quality in the Netherlands. These measures include the abolishment of derogation, which allowed dairy farmers to go beyond the maximum application of 170 kg nitrogen (N) from organic fertiliser per hectare, and additional measures of the 7th Nitrates Action program. Grass-clover swards, known for their symbiotic N fixation, could be a strategy to deal with stricter N policies and can potentially improve the environmental sustainability and economic viability of Dutch dairy farms.
OBJECTIVE: The aim was to assess the effects of stricter N policies on the farm structure, farm income and environmental performance of a representative Dutch dairy farm on a sandy soil, and to assess the effect of incorporating perennial ryegrass-red white clover (GC_{rw}) swards and perennial ryegrass-white clover (GC_w) swards into the grassland management of this farm using a model.
METHODS: A whole-dairy farm linear programming model was used with the objective function to maximize farm income. The model was combined with a farm nutrient balance and life-cycle assessment to determine the impact on nutrient surpluses and greenhouse gas emissions. We modelled a representative Dutch dairy farm with perennial ryegrass (PRG) before and after implementing stricter N policies. Thereafter, the implications of implementing GC_{rw} and GC_w swards was assessed.

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RESULTS AND CONCLUSIONS: Including the policy measures increased the share of maize land (+12%), decreased the number of dairy cows (-9 cows), reduced farm income (€-18,858 yr^{-1}), led to similar greenhouse gas emissions (~800 kg carbon dioxide equivalents (CO_2-eq) per tonne (t) of fat and protein corrected milk (FPCM)), and resulted in a lower N surplus (-65 kg ha^{-1} yr^{-1}) and phosphate surplus (-4.4 kg ha^{-1} yr^{-1}) for a scenario with only PRG. The use of GC_{rw} and GC_w swards could partly compensate for the reduction in farm income (€+9,255 up to +14,706 yr^{-1}). A combination of PRG, GC_{rw} and GC_w resulted in the highest farm income. The use of grass-clover swards only had the most positive effect on greenhouse gas emissions (767 kg CO_2-eq t^{-1} FPCM) and N surplus (113 kg ha^{-1} yr^{-1}). Sensitivity analysis showed the importance of yields and feed characteristics on the obtained farm income.

SIGNIFICIANCE: Grass-clover swards might partly compensate for the negative economic consequences of stricter N policies for Dutch dairy farms. Furthermore, implementing grass-clover swards reduced the GHG emission intensity of milk, but not always nutrient surpluses per hectare of farm land.

1. Introduction

The scientific and political focus of agricultural production has moved from increasing the production efficiency of linear supply chains to optimizing an entire food system in terms of using and reusing available resources and minimizing the environmental impact of production (European Commission, 2020; Ministry of Agriculture Nature and Food Quality, 2018; Springmann et al., 2018). For the Dutch dairy sector this transition involves aspects such as better integrating crop and dairy production systems, improving nutrient cycling within the farm, reducing nitrogen (N) losses, and mitigating greenhouse gas (GHG) emissions while ensuring a viable livelihood for primary producers (Ministry of Agriculture Nature and Food Quality, 2018). One of the recent policy measures that directly affects the Dutch dairy sector is the abolishment of derogation from standard nitrate directive rules from 2023 onwards and additional measures of the 7th Nitrates Action program in order to improve water quality (Ministry of Agriculture Nature and Food Quality and Ministry of Infrastructure and Water Management, 2021; RVO, 2022a). These recent changes in legislation will set the maximum application of organic N to 170 kg N ha^{-1} within a period of three years. In addition, legislation limits the option for continuous maize systems and targets a reduction in the total effective N application on sandy soils (Ministry of Agriculture Nature and Food Quality and Ministry of Infrastructure and Water Management, 2021). These stricter N policies might have an impact on farm structure, which could affect the farmer's income and the environmental impact of production (Splinter and Peerlings, 2023).

Improving grassland management is seen as a strategy with a high potential to improve the environmental and economic performance of a dairy farm. The environmental performance could be improved because grasslands contribute to various provisional and non-provisional ecosystem services (Rodríguez-Ortega et al., 2014). Economic factors, such as variable mineral fertilizer and feedstuff prices, are also driving the current interest in a more efficient grassland management on dairy farms. Producing more home grown protein by using available grasslands can reduce the use of, and dependency on, these external inputs and an efficient conversion of these feed sources into milk could increase farm profitability (Finneran et al., 2010; Kleine et al., 2018). Being characterized by high environmental pressure as well as by favourable environmental conditions for the production and use of grassland and other forages (Taube et al., 2014), the Netherlands offers an interesting case to study the role of grassland management in the transition towards more environmentally sustainable and economically viable dairy production (Reheul et al., 2017).

Grassland management covers a broad spectrum of different practices including fertilization, harvesting and grazing strategies (Vellinga et al., 2001). Among these, the establishment of grass-clover swards is currently seen as a promising grassland management strategy (Lesschen and Sanders, 2023; Lüscher et al., 2014). Expected benefits include mineral N fertilizer savings, increased protein self-sufficiency and reduced GHG emissions (Lüscher et al., 2014). One of the main characteristics of clovers, contributing directly and indirectly to these benefits, is symbiotic N_2 fixation (Lüscher et al., 2014). Grass-clover swards could have a positive effect on DM yields and improve forage quality because of the higher protein content of clover, while simultaneously contributing to various ecosystem services including above- and belowground biodiversity (Beye et al., 2022; de Haas et al., 2019). Hence, grass-clover swards might be a way towards more sustainable production and be able to help dealing with the consequences imposed by expected policy changes.

Pure perennial ryegrass (*Lolium perenne* L.; PRG) swards are commonly used in Dutch dairy production systems. White clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.) are two clover species that could be included in PRG swards. Despite possible benefits of perennial ryegrass-white clover (GC_w) and perennial ryegrass-red white clover (GC_{rw}) swards, consequences of using grass-clover swards need to be evaluated critically. For example, the use of grass-clover swards can affect management practices of the whole farm including the feeding strategy and purchases of external inputs (i.e. concentrates and fertilizers). An integral assessment of these consequences and the economic and environmental implications of using grass-clover swards in combination with the introduction of stricter N policies is missing. Using a whole-farm model offers the potential to consider those consequences. Hence, the aim of this study was to assess the implications of stricter N policies on the farm structure, economic performance and environmental performance of a representative dairy farm on a sandy soil in the Netherlands, and to assess the impact of incorporating perennial ryegrass-red white clover (GC_{rw}) swards and perennial ryegrass-white clover (GC_w) swards into the grassland management of this farm, using a whole-farm linear programming (LP) model.

2. Methods

2.1. The dairy farm model

The whole-dairy-farm LP model described by Klootwijk et al. (2016) was used as a basis in this study, which was originally developed by Berentsen and Giesen (1995). We developed a new version of the model in the R programming language (version 4.2.1) using the lpSolve and lpSolveAPI packages (Berkelaar, 2020; Konis and Schwendinger, 2020). The general structure of the model remained the same as in Klootwijk et al. (2016). The static model represents a typical Dutch dairy farm on sandy soil with input data based on average (annual) values for Dutch dairy farms (Table 1), and output figures reported on an annual basis. The LP model includes all relevant activities and constraints common to Dutch dairy farms. The model uses a matrix format in which the columns describe activities and the rows represent the constraints used to include the technical relations between the activities. Activities of the farm include on-farm feed production (maize silage, grass silage and fresh grass for grazing), related field operations (e.g. manure application and harvesting) and animal production (including dairy cows with youngstock for replacement and for sale). Other activities are purchasing

Table 1
Model input data to describe a representative Dutch dairy farm on sandy soil

Item	Unit	
Farmland[1]	ha	54.7
Barn capacity[1]	No. of cows	108
Labour availability[2]	h	4,000
Milk production[3]	kg cow^{-1} yr^{-1}	9,209
Fat content milk[3]	%	4.43
Protein content milk[3]	%	3.61
Milk price[4]	€ t^{-1}	376.4
Replacement rate[2]	%	26.4
Phosphate quota[4]	kg phosphate yr^{-1}	5099
Manure disposal[4]	€ t^{-1}	15.50
Manure processing[4]	€ t^{-1}	7.50
Mineral N fertilizer[4]	€ kg^{-1} N	0.95
Mineral P_2O_5 fertilizer[4]	€ kg^{-1} P_2O_5	0.87
Extra labour[4]	€ h^{-1}	17.00
Extra barn capacity[5]	€ cow^{-1} yr^{-1}	706.00
Extra phosphate quota[6]	€ kg phosphate yr^{-1}	40.60

[1] Agrimatie (2022), numbers represent the average value for a Dutch dairy farm
[2] CBS (2015)
[3] CRV (2022), numbers represent the average value for a Dutch dairy farm
[4] Blanken et al. (2020).
[5] Blanken et al. (2020) based on a depreciation rate of 5%, maintenance rate of 2% and an interest rate of 3.0%
[6] Anonymous (2018) and van Boxmeer et al. (2021), based on a depreciation period of 5 years and an interest rate of 3.0%

maize silage, concentrates (standard, medium and high levels of protein; Table 2) and mineral fertilizers (i.e. N, fosfor and potassium). Constraints include fixed resources available on the farm (e.g. land area, barn capacity and family labour), environmental policies (e.g. N and phosphate (P_2O_5) application standards) and links between the activities (e.g. to match fertilizer requirements of grassland and available nutrients in manure and mineral fertilizers). Economic incentives are often key in the management of a dairy farm, hence the objective function of the model maximized farm income (i.e. gross returns minus variable and fixed costs).

The model is based on a dairy farm with Holstein-Friesian cows. The dairy herd is represented by one average cow, which is assumed to calve in February. Female young stock is kept for yearly replacement of the dairy herd, whereas male calves and surplus female calves are sold at an age of two weeks. Cows are housed in a cubicle system with slatted floors. A winter and summer period both of 182.5 days was used in the model. Costs of farm inputs, revenues and milk production levels were updated according to long-term expected market prices and national statistics (Table 1). Expanding stable capacity is an optional choice in the model. The total land area is based on the average size of a Dutch dairy farm on sandy soil (54.7 hectares).

Feed requirements (energy and protein) and intake capacity of the average cow were included in the model and determined using the bio-economic model of Groen (1988). Dietary requirements include requirements for net energy for lactation (NE_L), rumen-degradable protein balance (RDP) and intestinal digestible protein (IDP) (Tamminga et al., 1994). Safety margins for requirements of RDP and IDP were set at 100 g cow^{-1} day^{-1}. The concentration of organic N in manure is assumed to be fixed at 2.2 kg m^{3} (Remmelink et al., 2020). Therefore a change in the protein content of the diet results in a change of the mineral N content of manure, assuming a fixed milk and meat production (Berentsen and Giesen, 1995). Feed characteristics of PRG swards depended on the level of mineral N (N_{min}) fertilization, which varied from 100 to 350 kg N ha^{-1} yr^{-1} in the model (Table 2). For 100 kg N_{min}, yields were 50 GJ NE_L ha^{-1} and increased up to 75 GJ NE_L ha^{-1} for 350 kg N_{min}. Maximum grass intake during day grazing was assumed to be 10 kg dry matter (DM) cow^{-1} day^{-1} (Taweel et al., 2004; Abrahamse et al., 2009; Kennedy et al., 2009).

According to the application standards for 2022–2025 (Ministry of Agriculture Nature and Food Quality, Ministry of Infrastructure and Water Management, 2021), the farm average maximum annual amount of N_{min} is 250 kg ha^{-1} for grassland for grazing and mowing. The application standard for maize was set to 112 kg N_{min} ha^{-1} and gross yields are 17 t DM ha^{-1} yr^{-1}, which equals 115 GJ of NE_L ha^{-1} yr^{-1} (Blanken et al., 2020; Ministry of Agriculture Nature and Food Quality, Ministry of Infrastructure and Water Management, 2021). Feed characteristics of purchased concentrates and maize silage are shown in Table 2. For P_2O_5 application, the maximum annual amount is 95 kg ha^{-1} for grasslands and 70 kg ha^{-1} for maize land (Blanken et al., 2020). Atmospheric deposition of N was assumed to be 30 kg N ha^{-1} yr^{-1} (van Dijk et al., 2020).

Under country-specific conditions, such as the prerequisite to use at least 80% of available land as grassland, derogation allowed dairy farmers to go beyond the maximum application of 170 kg of N from organic fertiliser per hectare (up to 250 kg N ha^{-1} on clay soils). This maximum was introduced by the European Nitrates Directive to limit nitrate leaching from agricultural production to ground and surface water (EU., 1991). The maximum annual amount for N from organic fertilizer is 230 kg ha^{-1} with derogation and 170 kg ha^{-1} without derogation, representing a situation on sandy soils in the model. In addition, derogation regulation prescribes that farms are not allowed to use mineral P_2O_5 fertilizers.

The Netherlands is characterized by high livestock density that results in a manure surplus. Dairy farmers have to comply with the so called Dairy Act, to prevent potential negative environmental consequences. The Dairy Act prescribes that excess manure can either be processed or disposed. Manure processing involved treatment so that P_2O_5 is removed from the national manure market, whereas manure disposal is the transport to another farm without processing. The inclusion of the Dutch manure policy in the model is described in detail by Klootwijk et al. (2016), however in this study a maximum of 41% of the reference P_2O_5 surplus could be transported to another farm without manure processing (RVO, 2020).

2.2. Environmental impacts

A farm level nutrient balance and life-cycle assessment (LCA) were linked with the LP model (Klootwijk et al., 2016; van Middelaar et al., 2014a). The nutrient balance is based on an average farm balance, which quantifies N and P_2O_5 surpluses per hectare of on-farm agricultural land. These surpluses can be used as an indicator for the local environmental pressure resulting from farm practices. Concentrates, mineral fertilizer, N deposition and symbiotic N fixation are inputs of N and/or P_2O_5. The outputs of these nutrients are in the form of milk, culled animals, and potentially manure. The nutrient balance was calculated as input minus output, hence a positive nutrient balance implies that these nutrients are potentially lost to the environment (Oenema et al., 2003). In addition, GHG emissions were assessed by using an LCA approach. This LCA approach was used to quantify carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions along the production chain, including all processes from cradle-to-farm gate. Emissions related to the production of farm inputs include those from mineral fertilizers, purchased feeds (concentrates and maize silage), energy sources (diesel and electricity) used on the farm. Emissions from the production of mineral fertilizer, pesticides, tap water, litter and energy were based on Wernet et al. (2016) and van Paassen et al. (2019) (Appendix Table A1). Emissions from the production of concentrates were updated (Appendix Table A2) and based on Feedprint (Feedprint, 2015; Feedprint, 2023). For purchased maize silage the emission factor is based on van Middelaar et al. (2014a) and for milk replacer on Thomassen et al. (2009). Enteric CH_4 emissions from dairy cows are based on empirical relations between the dry matter intake of feed ingredients and feed specific emission factors (Vellinga et al., 2013; Sebek et al., 2016; Appendix Table A3). For young stock, enteric CH_4 emissions are based on the Intergovernmental Panel on Climate Change (IPCC) tier 2

Table 2
Feed characteristics and prices of available feed products.

Feedstuff	NE_L (MJ kg^{-1} of DM)	IDP[1] (g kg^{-1} of DM)	RDP[2] (g kg^{-1} of DM)	Fill value[3] (kg kg^{-1} of DM)	Nitrogen (g kg^{-1} of DM)	Phosphorus (g kg^{-1} of DM)	Market price[4] (€/ton of DM)
Grazed PRG[5,7]							
100 kg N_{min}	6.64	93	18	0.90	27.3	4.1	-
150 kg N_{min}	6.69	95	26	0.90	28.7	4.1	-
200 kg N_{min}	6.75	97	35	0.90	30.1	4.1	-
250 kg N_{min}	6.80	99	43	0.90	31.6	4.1	-
300 kg N_{min}	6.84	100	51	0.90	33.1	4.1	-
350 kg N_{min}	6.87	102	56	0.90	34.7	4.1	-
Grazed GC_w[5,6,7]							
85 kg N_{min}	6.85	93	40	0.82	33.1	4.1	-
Grass silage PRG[5]							
100 kg N_{min}	5.94	69	6	1.10	24.7	4.1	-
150 kg N_{min}	5.98	71	13	1.10	26.5	4.1	-
200 kg N_{min}	6.02	72	20	1.10	28.2	4.1	-
250 kg N_{min}	6.06	74	27	1.10	29.8	4.1	-
300 kg N_{min}	6.09	75	35	1.10	31.4	4.1	-
350 kg N_{min}	6.12	76	44	1.10	32.8	4.1	-
Grass silage GC_w[5,6,7]							
85 kg N_{min}	6.11	76	56	1.06	31.4	4.1	-
Grass silage GC_{rw}[5,6,7]							
85 kg N_{min}	5.93	76	56	1.06	31.4	4.1	-
Concentrates							
Standard protein	7.21	100	6	0.29-0.72	24.1	4.5	225
Medium protein	7.21	133	28	0.29-0.72	32.2	5.0	260
High protein	7.21	200	83	0.29-0.72	48.3	8.0	325
Maize silage	6.76	58	-36	0.87	10.9	1.9	168

[1] True protein digested in the small intestine according to Dutch standards (Tamminga et al., 1994)
[2] Rumen-degradable protein balance according to Dutch standards (Tamminga et al., 1994)
[3] Fill value per kilogram of DM feed expressed in kilogram of a standard reference feed (Jarrige, 1988). The fill value increases with an increase in concentrate intake.
[4] Applies only to purchased feed products (Blanken et al. (2020)
[5] Grazing was applied at 1,700 kg DM ha^{-1} and mowing at 3,500 kg DM ha^{-1}
[6] Feed characteristics are largely based on de Wit et al. (2004), CVB (2018), Schreefel et al. (2022) and adapted based on expert opinion of the co-authors
[7] PRG= perennial ryegrass, GC_{rw} = perennial ryegrass-red white clover, GC_w = perennial ryegrass-white clover

methods and default values (IPCC, 2006). Methods to calculate emissions from manure management, and from fertilizer application to the field, are based on farm specific excretion values in combination with emission factors derived from national reports (e.g. De Mol and Hilhorst, 2003; Van Bruggen et al., 2021) (Appendix Table A4). Greenhouse gases were summed up based on their equivalence factor in terms of CO_2: 1 for CO_2, 27.2 for biogenic CH_4, 29.8 for fossil CH_4, and 273 for N_2O (IPCC, 2022). Emissions of GHG were expressed per tonne of fat- and protein-corrected milk (FPCM) based on economic allocation between milk and meat. Emission calculations have been described in detail by van Middelaar et al. (2014a) and Klootwijk et al. (2016). To monetarize the potential environmental consequences of the strategies we estimated the social costs based on model results and available prices for GHG emissions and nutrient surpluses from the literature. These costs represent the damage to the environment and society caused by a specific pollutant (Kanter et al., 2021). Social costs were set to €0.15 kg^{-1} CO_2-eq, €10 kg^{-1} N and €69 kg^{-1} P (Sampat et al., 2021; The Rockefeller Foundation, 2021; Van Grinsven et al., 2013). In order to calculate the social costs for the farm, we multiplied these values with respective model outcomes for nutrient surpluses and the GHG emissions.

2.3. Description of scenarios

We used the LP model to optimize the farm plan of a dairy farm before the introduction of stricter N policies and using PRG swards to serve as a reference (REF). Thereafter, the LP model was used to determine the new optimal farm plan and to evaluate changes in farm structure, management, farm income and environmental impact with stricter N policies, for a farm with only PRG (NPOL) and three different grass-clover options (+GC_{rw}; +GC_{rw}+GC_w; GC-only)(Table 3). Below a detailed description of the set-up of the scenarios is provided. The option to cultivate maize, used as whole-plant silage, was available in all scenarios. Available farmland was kept constant because obtaining additional farmland is not always practically possible. In addition, keeping the farmland constant allows to compare the different scenarios.

For scenario REF, derogation was included as an option in the model. In this scenario, feed options included grass from grazing (only available during summer), grass silage and maize silage. Feed characteristics are included in Table 2.

For scenario NPOL, the derogation option was removed from the model and adjustments were made to outline a situation with stricter N policies. Legislation prescribes the use of a break crop at least once every four years, preventing the option for continuous maize systems (Ministry of Agriculture Nature and Food Quality, Ministry of Infrastructure and Water Management, 2021). As a result, for all scenarios with the stricter N policies, forage maize produced on the dairy farm is assumed to be cultivated in a ley-arable system reducing N fertilization requirements from 112 to 55 kg N_{min} ha^{-1} yr^{-1} to account for the mineralization of grass residues after the ley phase (Commissie Bemesting Grasland en Voedergewassen, 2022) (Table 3). Furthermore, the farm average

Table 3
Overview of the different scenarios for a representative Dutch dairy farm with perennial ryegrass swards in a scenario without (REF) and with stricter nitrogen policies (NPOL), and for three grass-clover scenarios with stricter nitrogen policies (+GC_{rw}, +GC_{rw}+GC_w,GC-only).

		Stricter nitrogen policies			
	REF	NPOL	+GC_{rw}	+GC_{rw}+GC_w	GC-only
Derogation option	Yes[2]	No	No	No	No
Fresh grass[1]	PRG	PRG	PRG	PRG GC_w	GC_w
Grass silage[1]	PRG	PRG	PRG GC_{rw}	PRG GC_{rw} GC_w	GC_{rw} GC_w
Grassland N_{min}[3]	250	200	200	200	200
Maize system	Continuous	Ley	Ley	Ley	Ley
Maize N_{min}	112	55	55	55	55

[1] PRG= perennial ryegrass, GC_{rw} = perennial ryegrass-red white clover, GC_w = perennial ryegrass-white clover
[2] If derogation is used the N applied from organic fertilizer increased from 170 to 230 kg ha^{-1}, at least 80% of the available farmland must be used as grassland and no mineral P_2O_5 fertilizer could be used
[3] The farm average maximum annual amount of N_{min}

maximum annual amount of N_{min} on grassland was reduced from 250 to 200 kg ha^{-1} yr^{-1} (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2022). The extra costs of resowing of the ley were averaged over three years, attributed to the maize activity and set to €250 ha^{-1} yr^{-1} (Blanken et al., 2020).

For scenario +GC_{rw}, the option to grow GC_{rw} swards was added to the model. Red clover is typically used in cutting only ley (temporary grasslands of 2-5 years) systems because despite their high forage yield potential, they have poor resistance to grazing and poor persistency in general (Eriksen et al., 2014). Here, it was assumed that a three species sward mixture (PRG, red clover and white clover) was used because of the complementarity of such a mixture on both below and aboveground indicators (de Haas et al., 2019). Furthermore, the use of GC_{rw} swards might be relatively easy to implement in practice as only part of the available farmland is used for GC_{rw} leys. Feed production included fresh grass from grazing PRG swards, grass silage from PRG and GC_{rw} swards, and maize silage. The N_{min} fertilization requirements for grass-clover swards can be reduced due to the symbiotic N fixation capacity. The GC_{rw} swards were assumed to be grown for three years in a ley system and the level of N fertilization was set to 85 kg N_{min} ha^{-1} yr^{-1} (Commissie Bemesting Grasland en Voedergewassen, 2022) (Table 2). The percentage of clover was assumed to be 40% with a symbiotic N fixation of 45 kg N t DM^{-1} (Schreefel et al., 2022; van Dijk et al., 2020). The yield of the GC_{rw} leys was 74 GJ of NE_L ha^{-1} yr^{-1}, and feed characteristics are shown in Table 2. Enteric CH_4 emissions factors per kg DM silage intake were assumed to be the same as those for PRG with 225 kg N ha^{-1} (20.74 grams CH_4 per kg DM intake for grass silage).

For scenario +GC_{rw}+GC_w, the option to grow GC_w swards was added to the model. GC_w swards have good persistence, moderate to high yields and are persistent to grazing (Eriksen et al., 2014). In this scenario combinations of all three sward types options could be selected. In contrast to +GC_{rw}, the available farmland could also be used for grazing of GC_w swards. Feed production included the options of fresh grass from grazing PRG and GC_w swards, grass silage from PRG, GC_{rw} and GC_w swards, and maize silage. For GC_wswards, the yearly percentage of grassland improvement was assumed to be 5%, with resowing costs of € 762 ha^{-1} yr^{-1} (Blanken et al., 2020). The level of N fertilization was set to 85 kg N_{min} ha^{-1} yr^{-1} (Commissie Bemesting Grasland en Voedergewassen, 2022) (Table 2). The percentage of clover was assumed to be, on average, 30% with a symbiotic N fixation of 45 kg N t DM^{-1} (Schreefel et al., 2022; van Dijk et al., 2020). The yield of GC_w swards was 65 GJ of NE_L yr^{-1}, and feed characteristics are shown in Table 2. Enteric CH_4 emissions factors per kg DM intake were assumed to be the same as those for PRG with 225 kg N ha^{-1} yr^{-1} (21.74 g CH_4 per kg DM intake for fresh grass and 20.74 g CH_4 per kg DM intake for grass silage).

For scenario GC-only, combinations of both grass-clover sward types could be selected. This scenario was evaluated because of the expected environmental benefits of only using grass-clover swards.

2.4. Sensitivity analysis

A sensitivity analysis was performed to account for uncertainty and variability in feed characteristics (including forage quality and yields) and prices for the scenarios with the stricter N policies (Hoekstra et al., 2018). We examined a 10% decrease and increase the GJ NE_L ha^{-1} yr^{-1} yields, and the NE_L, IDP and RDP per kg DM^{-1} for PRG in the NPOL scenario and for the grass-clover swards (fresh grass and/or grass silage) in the other scenarios. One feeding value was increased or decreased at a time, while all other parameters were kept constant (i.e., the one-at-a-time approach) (Groen et al., 2016). For the +GC_{rw}+GC_w and GC-only scenario, where both grass-clover mixtures are present, values for both sward types were changed simultaneously. A similar approach was used to assess the effect of changes in farm in- and output prices. The effects of a 25% change in concentrate (standard, medium and high protein), mineral N fertilizer, milk, and manure disposal and processing prices on model outcomes were evaluated.

3. Results

3.1. Reference scenario

For the REF scenario, 101 dairy cows and 59 youngstock were kept (Table 4). The number of cows was restricted by the phosphate quota, which means that the revenues of an extra cow did not outweigh the costs of purchasing extra quota. Farmland was divided in 80% grassland and 20% maize land, which allowed for the application of 230 kg of N ha^{-1} yr^{-1} from organic fertilizer under derogation. During the summer period, the maximum amount of fresh grass was fed (i.e. 10 kg DM) because this was the cheapest feed available during the summer period. Maize silage and concentrates were added to meet the requirements for energy and RDP balance. Purchased feed consisted of 127 t DM of maize silage and 206 t DM of concentrates. Furthermore, on-farm production of protein was 56.8% of the total amount of protein fed during the winter and summer period. The external labour requirement was 541 h yr^{-1} and 5,864 kg of mineral N fertilizer was purchased. Manure application was restricted by the amount of N from organic fertilizer and the total amount of P_2O_5 that could be applied on available farmland (Table 4). Farm income was €12,224 yr^{-1} in the REF scenario, where revenues could be attributed primarily to milk sales, and costs to feed purchases and fixed costs for buildings and machinery (Table 5). However, the actual net farm income for this typical dairy farm would be approximately €20,000 yr^{-1} higher due to owner equity, which was not included in the LP model. GHG emission intensity (i.e., from cradle to farm gate) for this scenario was 805 kg CO_2-eq t^{-1} of FPCM (Table 6). The most important contributor was methane from enteric fermentation (54%), followed by emissions from off-farm feed production (19%), on-farm feed production (13%) and manure (13%). The N and P_2O_5 surpluses of the farm in the REF scenario were 183 and 6.9 kg ha^{-1}, respectively.

3.2. Impact of stricter nitrogen policies

Differences in the outcomes of scenarios REF and NPOL reflect the impact of stricter N policies for a representative Dutch dairy farm on sandy soils. Comparing scenario REF with scenario NPOL, the number of dairy cows decreased from 101 to 92 cows (Table 4). The percentage of maize land increased (from 20% to 32% of available farmland) to the point where maize silage per cow was maximized to meet cow requirements for the RDP balance and no maize silage had to be

Table 4
Farm structure and management of a representative Dutch dairy farm with perennial ryegrass swards in the reference scenario (REF) and with stricter nitrogen policies (NPOL) and for the three grass-clover scenarios (+GC_{rw}, +GC_{rw}+GC_{w}, and GC-only)

Item	Unit		Stricter nitrogen policies			
		REF[1]	NPOL[1]	+GC_{rw} [1]	+GC_{rw}+GC_{w} [1]	GC-only[1]
Farm structure						
Dairy cows	No.	101	92	96	98	97
Youngstock	No.	59	54	56	57	57
Total farmland	ha	54.7	54.7	54.7	54.7	54.7
PRG[2]	% total farmland	80	68	47	30	-
GC_{rw} [2]	% total farmland	-	-	22	17	17
GC_{w} [2]	% total farmland	-	-	-	20	50
Maize land	% total farmland	20	32	31	33	33
N_{min} application PRG[2]	kg of N_{min} ha^{-1} yr^{-1}	225	200	250	300	-
N_{min} application GC_{rw} [2]	kg of N_{min} ha^{-1} yr^{-1}	-	-	85	85	85
N_{min} application GC_{w} [2]	kg of N_{min} ha^{-1} yr^{-1}	-	-	-	85	85
N_{min} application maize land	kg of N_{min} ha^{-1} yr^{-1}	112	55	55	55	55
Average N_{min} application	kg of N_{min} ha^{-1} yr^{-1}	202	154	153	140	75
Farm intensity	kg of milk ha^{-1} yr^{-1}	16,935	15,524	16,233	16,429	16,284
On-farm production of protein	% total protein input	56.8	56.6	64.7	64.9	62.1
Diet dairy cows: summer	kg of DM cow^{-1} day^{-1}					
Grass		10.0	10.0	9.0	10.0	9.1
Grass silage		0	0	1.7	0	0
Maize silage		6.4	6.4	5.2	6.4	6.4
Concentrates total		5.2	5.2	5.7	5.1	5.9
Standard protein		3.2	2.7	5.6	4.6	4.8
Medium protein		0	0	0	0	0
High protein		2.0	2.5	0.1	0.5	1.1
Diet restricted by[3]		E,R,G	E,R,G	E,R,T	E,R,T,G	E,T
Diet dairy cows: winter	kg of DM cow^{-1} day^{-1}					
Grass silage		6.2	4.2	4.9	4.8	4.9
Maize silage		6.6	6.7	6.7	6.3	6.7
Concentrates total		5.4	7.0	6.5	6.9	6.5
Standard protein		3.4	3.8	4.9	5.4	4.9
Medium protein		0	0	0	0	0
High protein		2.0	3.2	1.6	1.5	1.6
Diet restricted by[3]		E,R	E,R	E,R,T	E,R,T	E,R,T
External inputs						
Purchased maize silage	t of DM yr^{-1}	127	0	0	0	0
Purchased concentrates	t of DM yr^{-1}	206	218	229	226	232
Purchased mineral nitrogen fertilizer	kg yr^{-1}	5,864	4,643	4,726	3,947	244
Purchased mineral phosphate fertilizer	kg yr^{-1}	-	227	575	650	701
Hired labour	h yr^{-1}	541	218	367	376	338
Manure management						
Manure application restricted by[4]		aN,P	tN, aN	tN, aN	aN	aN
Total excretion	kg of nitrogen yr^{-1}	15,496	14,259	14,284	14,478	14,465
Total excretion	kg of phosphate yr^{-1}	5,099	4,864	4,648	4,606	4,657
Applied on own land	kg of phosphate yr^{-1}	4,923	3,964	4,138	4,119	4,217
Extra phosphate quota	kg of phosphate yr^{-1}	0	0	0	0	0

[1] REF = PRG, maize; NPOL = PRG, maize; +GC_{rw} = PRG, maize, GC_{rw}; +GC_{rw}+GC_{w} = PRG, maize, GC_{rw}, GC_{w}; GC-only = maize, GC_{rw}, GC_{w}
[2] PRG= perennial ryegrass, GC_{w} = perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover
[3] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity
[4] Manure application can be restricted by: tN = total mineral N; aN = N from organic manure; P = total P_2O_5

purchased. The N_{min} application on PRG swards decreased from 225 to 200 kg ha^{-1} yr^{-1} as the application standards for total N were limiting in addition to N from organic manure (Table 4). The increase in on-farm maize production and the lower protein content in PRG swards due to a decrease in N_{min} application resulted in an increase in the use of high protein concentrates in kg of DM cow^{-1} day^{-1} during both the summer and winter period increased. During the winter period, the diet contained less grass silage as a result of the reduced areal of grassland and the lower N fertilization rate, slightly more maize silage, and more concentrates compared to REF. Despite the reduction in the number of cows, the total amount of concentrates increased from 206 to 218 t DM and the percentage of on-farm produced protein reduced only slightly (from 56.8 to 56.6% of the total amount of protein fed). The amount of purchased mineral N fertilizer decreased while more mineral P_2O_5 fertilizer was purchased to compensate for the lower amount applied via manure (Table 4). Farm income decreased by €18,858 yr^{-1} compared to REF (Table 5). This was mainly caused by lower milk revenues (€-29,040 yr^{-1}) and increased costs for manure disposal and processing (€+12,328 yr^{-1}), being partly compensated for by a reduction in costs of purchased roughage and hired labour (Table 5). The GHG emission intensity was similar with and without the stricter N policies (Table 6). A reduction in the emissions from purchased maize silage was compensated for by an increase in emissions from production of concentrates. The N surplus decreased by 65 kg N ha^{-1} yr^{-1} (from 183 to 118 kg N ha^{-1} yr^{-1}) and the

Table 5
Economic performance of a representative Dutch dairy farm with perennial ryegrass swards in the reference scenario (REF) and with stricter nitrogen policies (NPOL) and for the three grass-clover scenarios (+GC_{rw}, +GC_{rw}+GC_w, and GC-only)

			Stricter nitrogen policies			
		REF[1]	NPOL[1]	+GC_{rw} [1]	+GC_{rw}+GC_w [1]	GC-only [1]
Revenues	€ yr^{-1}					
Milk		348,671	319,631	334,225	338,251	335,272
Livestock sales-purchases		32,925	30,183	31,561	31,941	31,659
Governmental payments		14,207	14,207	14,207	14,207	14,207
Variable costs	€ yr^{-1}					
Concentrate purchases		62,251	67,443	62,728	62,446	65,478
Roughage purchases		22,084	-	-	-	-
On-farm roughage production		56,701	59,318	64,647	62,025	58,019
Manure disposal and processing		2,313	14,641	15,506	16,568	16,402
Hired labour		11,138	4,495	7,554	7,750	6,958
Other		48,237	44,220	46,239	46,796	46,384
Fixed costs	€ yr^{-1}	180,855	180,538	180,698	180,742	180,709
Farm income[2]	€ yr^{-1}	12,224	-6,634	2,621	8,072	7,188

[1] REF = PRG, maize; NPOL = PRG, maize; +GC_{rw} = PRG, maize, GC_{rw}; +GC_{rw}+GC_w = PRG, maize, GC_{rw}, GC_w; GC-only = maize, GC_{rw}, GC_w
[2] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)

Table 6
Environmental performance of a representative Dutch dairy farm with perennial ryegrass swards in the reference scenario (REF) and with stricter nitrogen policies (NPOL) and for the three grass-clover scenarios (+GC_{rw}, +GC_{rw}+GC_w, and GC-only)

			Stricter nitrogen policies			
		REF[1]	NPOL[1]	+GC_{rw} [1]	+GC_{rw}+GC_w [1]	GC-only [1]
Animal emissions	kg CO_2-eq t^{-1} of FPCM[2]					
Enteric CH_4 dairy cows		368	367	366	359	364
Enteric CH_4 youngstock		66	66	66	66	66
Manure[3]		107	114	109	110	111
Other[4]		11	11	11	11	11
On-farm feed production	kg CO_2-eq t^{-1} of FPCM					
Grassland[5]		81	66	75	59	33
Maize land[6]		21	30	26	27	31
Off-farm feed production	kg CO_2-eq t^{-1} of FPCM					
Concentrates		129	152	138	135	143
Maize		22	-	-	-	-
Total greenhouse gas emissions	kg CO_2-eq t^{-1} of FPCM	805	806	791	767	759
N surplus	kg ha^{-1} yr^{-1}	183	118	137	132	113
P_2O_5 surplus	kg ha^{-1} yr^{-1}	6.9	2.5	0	0	4.3
Social costs greenhouse gas emissions[7]	€ yr^{-1}	119,402	109,594	112,465	110,366	108,178
Social costs N surplus[7]	€ yr^{-1}	100,101	64,546	74,939	72,204	61,811
Social costs P_2O_5 surplus[7]	€ yr^{-1}	11,372	4,120	0	0	7,087
Total social costs	€ yr^{-1}	230,875	178,280	187,404	182,570	177,076

[1] REF = PRG, maize; NPOL = PRG, maize; +GC_{rw} = PRG, maize, GC_{rw}; +GC_{rw}+GC_w = PRG, maize, GC_{rw}, GC_w; GC-only = maize, GC_{rw}, GC_w
[2] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)
[3] Including CH_4 and N_2O emissions from grazing and from manure storage
[4] Includes emissions associated with milk replacer, bedding material, energy sources and tap water
[5] Including N_2O emissions from N application and emissions related to combustion of diesel during field work
[6] Including N_2O emissions from N application and emissions related to combustion of diesel during field work
[7] Prices used are €0.15 kg^{-1} CO_2-eq, €10 kg $^{-1}$ N and €69 kg^{-1} P (Sampat et al., 2021; The Rockefeller Foundation, 2021; Van Grinsven et al., 2013). Total available farmland is 54.7 ha

P_2O_5 surplus decreased by 4.4 kg P_2O_5 ha^{-1} yr^{-1} (from 6.9 to 2.5 kg P_2O_5 ha^{-1} yr^{-1}) after introducing the stricter N policies (Table 6). This resulted in a reduction of €52,595 yr^{-1} for the estimated social costs compared to REF.

3.3. Impact of using grass-clover swards

3.3.1. Impact of adding grass-red and white clover

The impact of adding grass clover swards with stricter N policies is reflected in the differences in outcomes between scenario NPOL on the one hand, and scenarios +GC_{rw}, +GC_{rw}+GC_w and GC-only on the other hand. Comparing scenario NPOL and +GC_{rw}, the number of dairy cows increased from 92 to 96 (Table 4). Farmland was divided into 47% PRG, 22% GC_{rw} and 31% of maize land in scenario +GC_{rw}. Similar to NPOL, the amount of maize silage per cow was maximized and this combination of PRG and GRWc resulted in the lower costs of purchasing concentrates. As a result, on-farm production of protein increased in +GC_{rw} compared with NPOL (from 56.6% to 64.7% of the total amount of protein fed). Furthermore, N_{min} application on PRG swards increased from 200 to 250 kg N ha^{-1} yr^{-1} (Table 4). This was possible due to the application of 85 kg N_{min} ha^{-1} yr^{-1} on the GC_{rw} leys. As a consequence the use of high protein concentrates per cow decreased compared to NPOL in both summer and winter. During summer, the fresh grass intake decreased to 9.0 kg DM, this was the maximum amount available from PRG swards, because GC_{rw} swards could only be used for grass silage. More cows could be kept compared to NPOL, because the change in diet composition resulted in a reduced N intake per cow. Similar to NPOL, maize silage no longer needed to be purchased in +GC_{rw} (Table 4). Mineral N fertilizer use of the total farm increased by 84 kg N compared to NPOL. In addition, mineral P_2O_5 fertilizer was purchased. Manure application was restricted by the maximum of N from organic manure and the total amount of N_{min} that could be applied on available farmland (Table 4). Even though the $+GC_{rw}$ scenario increased farm income compared to NPOL by €9,255 yr^{-1}, it remained below the income of REF (Table 5). The increase was mainly caused by higher revenues from milk production. The GHG emission intensity decreased compared to NPOL mainly due to a reduction in emissions related to purchased concentrates (Table 6). The N surplus increased compared to NPOL (+19 kg ha^{-1} yr^{-1}). This result can be explained by the fact that symbiotic N fixation was accounted for as an input, while N mineral fertilizer use was similar compared to NPOL. Furthermore, the P_2O_5 surplus further decreased (Table 6). Overall, this resulted in an increase of €9,124 yr^{-1} for the estimated social costs compared to NPOL.

3.3.2. Impact of grass-white clover in addition to grass-red and white clover

Comparing scenario $+GC_{rw}$ and scenario $+GC_{rw}+GC_{w}$ subsequently shows the added value of GC_w swards to a scenario that uses PRG and GC_{rw} swards only. For scenario $+GC_{rw}+GC_{w}$, the number of dairy cows increased to 98. All the different sward types were selected (30% PRG, 17% GC_{rw}, 20% GC_w and 33% for maize land). The on-farm production of protein was highest compared to all other scenarios (64.9% of the total amount of protein fed). During the summer period, the combination of PRG and GC_w allowed for feeding the maximum amount of fresh grass. More cows could be kept compared to $+GC_{rw}$ because the change in diet composition resulted in a reduced N intake per cow. The reduced N intake, lowered the N content in manure and as a result more cows could be kept per hectare. The use of mineral N fertilizer decreased while the use of mineral P_2O_5 fertilizer increased compared to the $+GC_{rw}$. Farm income increased by €5,451 yr^{-1} and was with €8,072 yr^{-1} highest for all scenarios with stricter N policies, but it was still lower compared to REF (Table 5). The GHG emission intensity was lower compared to $+GC_{rw}$. The decrease was mainly caused by a reduction in on-farm emissions related to grassland production. The N surplus was 132 kg ha^{-1} yr^{-1}, which was slightly lower compared to $+GC_{rw}$. Overall, this scenario reduced the social costs by €4,834 yr^{-1} compared to $+GC_{rw}$ (Table 6).

3.3.3. Impact of only using grass-clover swards

Scenario GC-only represents a scenario where the option to grow PRG is eliminated from the model and only grass-clover swards are available. Results show that this does not have a large impact on the number of dairy cows (-1 dairy cow) compared to $+GC_{rw}+GC_{w}$. The on-farm production of protein (62.1 of the total amount of protein fed) was lower compared to $+GC_{rw}+GC_{w}$. Because GC_{rw} swards could only be used for grass silage, the maximum of 10 kg DM fresh grass intake per cow could not be met. The total amount of purchased concentrates slightly increased compared to $+GC_{rw}+GC_{w}$ (+6 t of DM yr^{-1}). The use of mineral N fertilizer decreased to a level of only 244 kg yr^{-1}, but mineral P_2O_5 fertilizer use increased. Farm income decreased by €884 yr^{-1} compared to $+GC_{rw}+GC_{w}$. Both the GHG emission intensity (759 kg CO_2-eq t^{-1} FPCM) and the N surplus (113 kg ha^{-1} yr^{-1}) were lower compared to all other scenarios (Table 6). This result can be explained by the fact that mineral N fertilizer use decreased. However, the P_2O_5 surplus increased compared $+GC_{rw}+GC_{w}$. This scenario resulted in the lowest social costs (€177,076 yr^{-1}) compared to all other scenarios (Table 6).

3.4. Sensitivity analysis

A sensitivity analysis was performed for the scenarios with the stricter N policies to assess the change in model output after a 10% decrease or increase in feed characteristics. Results of the sensitivity analysis show that the assumptions on forage quality for both PRG and grass-clover swards are key for the obtained farm income (Fig. 1, Appendix Table A5-A8). However, the feed characteristics that affected the outcome most varied across scenarios. The effect of a change in energy content on farm income was largest for NPOL. The effect of a change in yield the most impact on farm income for $+GC_{rw}$ and $+GC_{rw}+GC_{w}$, while this was the protein content for $+GC_{rw}+GC_{w}$. The results of the sensitivity analysis also show that a change in feed characteristics could result in changes in farm structure and management. For example, for the $+GC_{rw}+GC_{w}$ scenario the share of total farmland used for PRG swards decreased from 30% to 4%, while the share of GC_w swards increased from 20 to 47% (Appendix Table A7) when the IDP value of

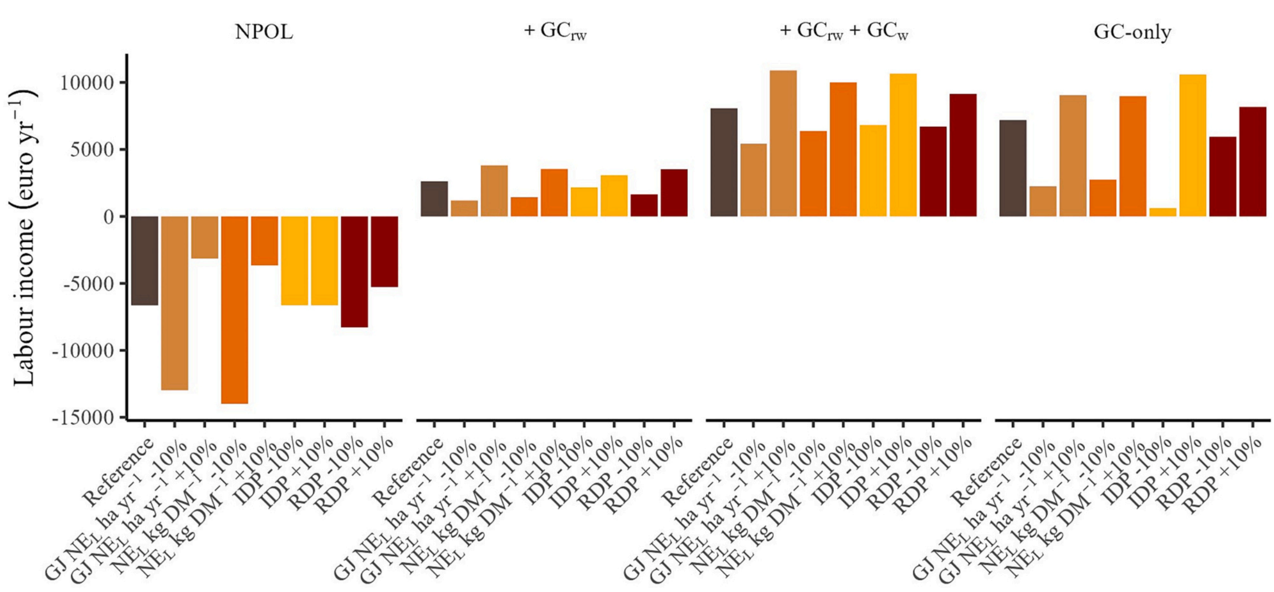

Fig. 1. Farm income (euro yr^{-1}) after a 10% change in the feed characteristics for a representative Dutch dairy farm with perennial ryegrass with stricter nitrogen policies (NPOL) and for the three grass-clover scenarios ($+GC_{rw}$, $+GC_{rw}+GC_{w}$, and GC-only). The results are shown for the total yearly energy yield (GJ NE_L ha^{-1} yr^{-1}), and for the energy (NE_L), rumen-degradable protein balance (RDP) and intestinal digestible protein (IDP) content (kg DM^{-1}). For the $+GC_{rw}+GC_{w}$ and GC-only scenario, where both grass-clover mixtures are present, values for both sward types were changed simultaneously. The reference scenario is the farm income shown in Table 5. Results for the other indicators can be found Appendix Table A5-A8. NPOL = PRG, maize; +GCrw = PRG, maize, GCrw; +GCrw+GCw = PRG, maize, GCrw, GCw; GC-only = maize, GCrw, GCw

clover-swards increases. These changes also affected environmental indicators. For example, for the $+GC_{rw}+GC_w$ scenario the N surplus varied from 107 up to 144 kg N ha^{-1} (Appendix Table A7) across all parameters that were changed.

Changing in- and output prices did not result in major changes for the trends observed across the different scenarios (Appendix Table A9-A12). Among all parameters that were changed, a reduction in milk price (-25%) had the largest impact on the number of dairy cows and on farm income. Results also show that the use of grass-clover swards reduces the dependency on mineral fertilizer prices, with farm income of $+GC_{rw}+GC_w$ scenario being least affected by a change in mineral N fertilizer prices. However, sometimes the results deviated from the observed trend. For example, with a 25% decrease in milk price the GHG emission intensity for the $+GC_{rw}+GC_w$ and GC-only were the same and not only lowest for GC-only. Similarly, in some cases (e.g. -25% for the concentrate price and -25% for the milk price) the lowest N surplus was found for $+GC_{rw}+GC_w$. Here, it deviated from the observed trend in N surplus with the standard parameters due to a reduced N_{min} application on PRG swards.

4. Discussion

4.1. Impact of stricter nitrogen policies

This study used an LP model representing a typical Dutch dairy farm on a sandy soil to assess the economic and environmental implications of stricter N policies. After introducing stricter N policies (NPOL) into the model, the share of maize land increased and the number of dairy cows decreased. The share of maize land increased because the farm did not have to comply with the prerequisite for the former derogation regulation in the Netherlands of having at least 80% of the available farmland as grassland. Even though it is economically attractive to increase the share of maize land after derogation abolishment, several policies target the preservation of (permanent) grasslands. For example, subsidies are available that aim to preserve grasslands during the transition of derogation abolishment and the share of permanent grassland cannot decrease with more than 5% compared to the reference year 2012 at the national level (RVO, 2023; RVO, 2022b). Therefore current and future legislation is another important driver in the decision making on dairy farms next to economic considerations. The decrease in the number of cows was also induced by the new legislation. The lower amount of organic fertilizer (170 kg N ha^{-1}) that could be applied on available farmland restricted on-farm manure application and increased the amount of manure exported from the farm. The outlined N policies did not reduce the quantity of purchased concentrates, despite the reduction in the number of dairy cows. Specifically, the use of high protein concentrates in kg of DM cow^{-1} day^{-1} increased. However, the implementation of stricter N policies resulted in mineral N fertilizer savings.

Farm income was considerably reduced, mainly due to lower milk revenues and increased costs for manure disposal and processing. In practice, management decisions might not only be driven by economic incentives (e.g. the aim to maximize farm income). Other objectives related to environmental and societal demands could also play a role in the on-farm decision making and effects of policies. For example, changing the model objective to minimize the GHG emissions per unit of product will result in different model outcomes (van Middelaar et al., 2014a). With the objective used in this study, the GHG emission intensity was similar before and after introducing stricter N policies, a reduction in the emissions from purchased maize silage was compensated for by an increase in emissions from production of concentrates. However, total GHG emissions will be reduced with a reduction in number of cows. Not a large effect on total GHG emissions was predicted by the Commissie Deskundigen Meststoffenwet (2020), who argued that both positive and negative effects are expected to occur simultaneously after derogation abolishment. This net effect was illustrated by an expected decrease in enteric CH_4 emissions with an increased share of maize silage in the diet and by an increase in N_2O emissions due to changes in the applied fertilizer application strategy on grassland and arable land (Commissie Deskundigen Meststoffenwet, 2020). The N policies affected N application on maize land as well because silage maize was assumed to be cultivated in a ley system. Turnover of grass residues in a ley system can increase the availability of soil mineral N and hence can affect N losses via increased N leaching after termination of the sward (Lemaire et al., 2015). Nevertheless, the introduction of leys into a crop rotation can have a positive effect on the measured nitrate levels in groundwater (Kunrath et al., 2015). Management strategies such as the reduction of fertilization levels in the first growing season after a ley down to a level of 0 kg N ha^{-1}, the choice of succeeding crop and the use of cover crops could be efficient strategies to further mitigate N leaching (Eriksen et al., 2008; Kayser et al., 2008). In this study, the reduction in the N application on maize in combination with other modelled N policies showed that both the N surplus (-65 kg N ha^{-1} yr^{-1}) and P_2O_5 surplus (-4.4 kg P_2O_5 ha^{-1} yr^{-1}) could decrease. Overall, this resulted in a reduction of the estimated social costs (€-52,595 yr^{-1}). Beyond the model outcomes, there are other management options to improve the environmental performance such as precision fertilization and manure processing (Lesschen and Sanders, 2023).

4.2. Impact of using grass-clover swards

After introducing the GC_{rw} and GC_w swards (scenarios $+GC_{rw}$, $+GC_{rw}+GC_w$ and GC-only), the number of dairy cows increased but was still lower compared to a situation without stricter N policies. Furthermore, the use of grass-clover swards resulted in a higher protein self-sufficiency because of the relatively high protein content in GC_{rw} and GC_w swards compared to PRG. The implementation of GC_{rw} and GC_w swards might partly compensate for the negative economic consequences caused by the stricter N policies. A combination of the three sward types resulted in the highest farm income, which could be mainly attributed to a decrease of dietary protein content, allowing the number of cows and total farm milk yield to increase within the limitation of the manure policy. In addition, the availability of grass-clover swards resulted in a reduction in the GHG emission intensity. The use of only grass-clover swards resulted in the lowest GHG emission intensity, mainly due to mineral N fertilizer savings. Similar results have been reported by Herron et al. (2021), who demonstrated that the substitution of PRG with GC_w swards has the potential to reduce the GHG emission intensity of milk mainly through mineral N fertilizer savings. The implementation of grass-clover swards might have an additional positive effect on reducing GHG emissions. For example, enteric CH_4 emissions of cows feeding on grass-clover swards might be reduced per kg DM intake due to the a lower fiber content, higher passage rate through the rumen and/or increased dry matter grass intake compared to PRG (Dewhurst et al., 2003; Enriquez-Hidalgo et al., 2014). However, the effect on enteric CH_4 emissions is subject to a complex interaction of factors due to among others changes in diet composition, the effect of secondary compounds (e.g. condensed tannins) and maturity stage (Enriquez-Hidalgo et al., 2014). As these effects are inconclusive the enteric CH_4 emission factors per kg DM intake in this study were assumed to be similar to 225 kg N_{min} fertilized PRG swards for dairy cows. The introduction of stricter N policies might have additional effects on soil carbon stocks. For example, decreasing the amount of organic manure applied, changes in the on-farm share of grassland and arable land, and the use of ley-arable systems could impact soil carbon stocks (Garnett et al., 2017). The transition from an all-arable system (e.g. continuous maize) to a ley-arable system is expected to contribute to soil carbon sequestration (Johnston et al., 2017). In contrast, the conversion of a permanent grassland to a ley-arable system could result in a carbon loss. The net impact on soil carbon stocks (gains and losses) will depend on various factors, including environmental factors like soil type and climate, and managerial factors like fertilization level and ploughing frequency (Vellinga et al., 2004).

The N surplus increased when GC_{rw} and GC_w swards were used in combination with PRG swards compared to using only PRG swards. The relatively low N fertilizer application on grass-clover swards created the option to increase the fertilization level on PRG swards because the N application standard is an average measure on farm level. Furthermore, in practice there is a possibility that the N use efficiency on these plots is reduced and the N surplus and losses from that part of the farm will increase. Therefore, there is the potential to reduce the N surplus if mineral N fertilizer would be saved on PRG swards. Applying a field-level balance might provide additional insights to prevent nutrient losses, especially when there are differences in soil type, negative N balances and/or variation in management across fields (van Leeuwen et al., 2019). The use of only grass-clover swards reduced the N farm surpluses further compared to scenarios where part of the grassland was PRG. In addition, literature is inconclusive about the effect on N losses from grass-clover swards. For example, Lüscher et al. (2014) expected lower N losses compared to PRG swards because the N is fixed symbiotically within the legume nodules and thus is not freely available in the soil in a reactive form. In contrast, changes in the soil structure could enhance N losses (Rochon et al., 2004). The use of only grass-clover swards resulted in the lowest social costs for the three environmental impacts considered. However, the results showed that applying a strategy with the lowest social costs does not necessarily align with the highest obtained farm income, pointing out the trade-off between economic and environmental objectives.

4.3. Uncertainties and limitations

Despite possible advantages of grass-clover swards, results of the sensitivity analysis show that the assumptions on feed characteristics for both PRG and grass-clover swards are key for the obtained results. Nevertheless, even with increased or decreased feeding values using grass-clover swards was economically interesting compared to using PRG only with stricter N policies across all scenarios. However, the impact on results and the parameter with the largest effect varied across scenarios. This emphasizes the importance of feed quality for improving the economic and environmental sustainability of dairy farms, as well as the importance for accurate quality estimates to assess those impacts. Furthermore, a sensitivity analysis was performed to obtain insight in the effects of the different scenarios to volatile market prices. The results showed conclusions for the different scenarios remain similar even when prices for concentrates, mineral N fertilizer, milk, and manure disposal and processing fluctuate.

Legume persistence is one of the main factors influencing the quality and feeding values of grass-clover swards and it is seen as a great challenge related to the implementation of grass-clover swards (Hoekstra et al., 2018). In this study we used clover percentages that are within the range of the optimum proposed inclusion (30-50% of sward biomass) (Lüscher et al., 2014). The legume percentage in a sward, however, fluctuates over time and depends on management and environmental conditions (Suter et al., 2015). For example, the timing and frequency of mowing have an impact on feeding values and indirectly these decisions might have an impact on farm structure, farm income and environmental performance (van Middelaar et al., 2014a). Furthermore, the level of symbiotic N fixation can vary widely depending on factors like soil properties and environmental conditions (Ledgard and Steele, 1992). In this study we assumed an N fixation level of 45 kg N t DM^{-1}, but in practice this could decrease if higher fertilizer N application rates are applied (Thers et al., 2022; van Dijk et al., 2020). A limitation of using this and other LP models is that these dynamics and that of other biological and physical processes cannot be adequately accounted for to incorporate their effects and interactions on farm performance (Rotz et al., 2005).

This study focused on the impact of stricter N policies in the Netherlands, covering an important part of the legislation dairy farmers have to deal with. In addition to those N policies, however, dairy farmers are faced with other upcoming environmental legislation and incentives that could affect farm management. An incentive that promotes the use of grass-clover swards is the national implementation of the new CAP that supports eco-activities. This an additional economic incentive for farmers to assess the potential use of grass-clover swards on their farm (RVO, 2022c). Furthermore, the potential added value of grass-clover swards and exact consequences of stricter N policies are dependent on farm specific characteristics and personal preferences. Therefore, the use of regional and farm specific quantitative environmental targets could be a potential way forward (Ros et al., 2023).

Social costs were used as indicator for the economic effects of environmental pollution. These costs represent the damage to the environment and society caused by a specific pollutant, which could contribute to policy making (Kanter et al., 2021; Sampat et al., 2021). For example, a payment for the avoided social costs might be a way to compensate for the loss of income and to overcome trade-offs between environment and economics. However, it is important to recognize the uncertainty in the monetarization of social costs (Van Grinsven et al., 2013). For example, the economic valuation depends on the type of reactive N, local conditions for transport and exposure to humans and ecosystems (Van Grinsven et al., 2013). Furthermore, grass-clover swards and ley-arable systems are associated with the provisioning of additional ecosystem services, including the preservation of soil quality, water conservation and biodiversity protection, which were not accounted for in this study (de Haas et al., 2019; Martin et al., 2020).

5. Conclusions

Dutch dairy farmers are facing further strengthening of legislation aiming to reduce the environmental impact of production. This study evaluated the impact of stricter N policies and of the implementation of three grass-clover scenarios on farm structure, economic performance and environmental performance on a representative dairy farm on a sandy soil in the Netherlands using a whole-farm optimization model. The outlined legislative scenario with stricter N policies resulted in a vast reduction of farm income. Results showed that the number of dairy cows decreased and the share of maize land on the farm increased. Despite the reduction in the number of cows, the quantity of purchased concentrates increased. In addition, more manure needed to be exported from the farm and in return mineral P_2O_5 fertilizer was purchased. The GHG emission intensity was similar before and after introducing stricter N policies, while the N and P_2O_5 surplus decreased. The use of grass-clover swards could be an economically interesting strategy, which could be mainly attributed to increased revenues from milk sales from extra cows. A combination of perennial ryegrass and grass-clover swards resulted in the highest farm income within the stricter N policies. In general, the use of grass-clover swards improved farm income and reduced the GHG emission intensity but not always nutrient surpluses. The use of grass-clover swards only had the most positive effect on GHG emission intensity and further reduced N surplus, which resulted in the lowest estimated social costs. This study contributed to further understanding of the effects of policy interventions on dairy farms (e.g. number of cows, grassland areal, farm income and nutrient surpluses decreased under stricter policies) and highlights the potential of implementing grass-clover swards with stricter N policies (e.g. improved farm income and GHG emission intensity but not always farm nutrient surpluses).

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A

Table A1
Greenhouse gas emissions from production of farm inputs.[1]

Input		Unit	kg CO_2-eq/unit
Agricultural operations	Application of plant protection products, by field sprayer	Ha	12.66
	Chopping, maize	Ha	37.63
	Fertilizing, by broadcaster	Ha	26.88
	Hoeing	Ha	23.41
	Mowing, by rotary mower	Ha	25.99
	Sowing	Ha	25.69
	Swath, by rotary windrower	Ha	17.79
	Tillage, cultivating, chiselling	Ha	75.16
	Tillage, harrowing, by rotary harrow	Ha	70.20
	Tillage, harrowing, by spring tine harrow	Ha	27.50
	Tillage, ploughing	Ha	124.86
	Tillage, rolling	Ha	28.16
	Fodder loading, by self-loading trailer	M^3	0.71
	Slurry spreading, by vacuum tanker	M^3	1.32
Mineral fertilizer	Calcium ammonium nitrate, as N	Kg N	0.97
	Potassium chloride, as K_2O	Kg K_2O	0.42
	Triple superphosphate, as P_2O_5	Kg P_2O_5	2.06
Pesticides	Insecticides	Kg	13.32
	Herbicides	Kg	17.59
	Fungicides	Kg	12.12
	Unspecified	Kg	10.08
Electricity	Low voltage (i.e. Households & agriculture), at grid	MJ	0.14
Tap water		M^3	0.29
Roughage	Purchased maize silage	Ton DM	182
Milk replacer		Ton DM	1920
Litter	Straw	Ton DM	56.13

[1] Emission factors are based on Eco-invent (2007), Thomassen et al. (2009), van Paassen et al. (2019), Wernet et al. (2016) and include CO_2, CH_4 and N_2O emissions

Table A2
Composition of concentrates with three protein levels (standard, medium and high) and corresponding greenhouse gas (GHG) emissions for production of ingredients.

	Concentrate composition (%)			GHG emissions[1]	Enteric fermentation[1]
Protein level	Standard[2]	Medium[2]	High[3]	total CO_2 equivalent/kg t	gram CH_4/kg DM[2]
Peas	0.00	1.20	0.00	752	26,4
Barley	0.35	0.15	0.95	388	22,1
Soybean meal CF45-70 CP<450[4]	0.07	1.49	0.00	615	20,6
Soybean meal CF45-70 CP>450[4]	0.09	0.48	0.00	636	20,6
Soybean meal Mervobest	0.00	0.015	28.45	632	19,4
Soybean hulls CF 320-360[4]	14.52	19.47	0.00	391	23,01
Sugarane molasses SUG < 475[4]	3.01	3.17	2.10	302	22
Rape seed, expeller	0.17	0.99	0.03	528	19,4
Rye	5.15	1.10	1.84	449	23,3
Wheat	2.05	2.17	0.15	390	23
Palm kernel expeller CF <180[4]	11.80	15.95	19.33	547	20,8
Sugarbeet pulp SUG>200[4]	3.8	4.70	6.33	366	25,6
Maize	15.87	6.57	1.48	595	19,7
Wheat middlings	11.32	2.07	2.62	249	20,6
Soy oil (palm kernel oil)	0.01	0.00	0.00	3,902	−10,95
Maize glutenfeed CP 200-230[4]	8.60	1.65	17.32	1,815	21,4
Sunflower seed meal CF >240[4]	0.67	1.00	0.22	487	18,66
Salt	0.46	0.56	0.00	180	0
Chalk (finely milled)	0.99	1.28	0.00	19	0
Triticale	5.45	6.03	1.32	587	23,29
Palm kernel oil	0.20	0.40	0.00	3,902	−10,95
Rape seed, extruded CP >380[4]	0.18	0.47	0.00	481	19,3
Rape seed, extruded CP 0-380[4]	1.78	5.38	0.00	477	19,4
Rape seed, meal	0.00	0.15	0.00	484	19,4
Premix	1.00	1.00	1.00	4,999	0
Vinasses Sugarbeet CP <250[4]	2.99	3.00	0.00	394	22,69
Magnesium oxide	0.04	0.01	0.00	1,060	0

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Table A2 (*continued*)

Protein level	Concentrate composition (%) Standard[2]	Medium[2]	High[3]	GHG emissions[1] total CO_2 equivalent/kg t	Enteric fermentation[1] gram CH_4/kg DM[2]
Distillers grains and solubles	9.36	17.93	7.47	296	20,6
Citruspulp dehyrdated	0.00	0.00	7.64	747	26,4
Fat animal origin	0.00	0.00	0.04	7,726	−10,94
Urea	0.00	0.00	1,70	1,650	0

[1] Greenhouse gas emissions for production of ingredients were based on Feedprint (2023) and (Sebek et al., 2016)and include CO_2, CH_4 and N_2O emissions from all processes up to farm gate.
[2] Concentrate composition was based on Nevedi (Nevedi, 2015; Nevedi, 2014; Nevedi, 2013; Nevedi, 2012). Standard concentrate was also assumed to be fed to calves and heifers.
[3] Concentrate composition of high protein level was based on Van Middelaar et al. (2014b).
[4] CF = crude fiber, CP= crude protein, SUG = sugar (in g kg^{-1})

Table A3
Emission factors for enteric fermentation of fresh grass, grass silage and maize silage.

	Enteric fermentation gram CH_4/kg DM[2]
Grazed PRG[1]	
100 kg N_{min}	24.24
150 kg N_{min}	23.24
200 kg N_{min}	22.24
250 kg N_{min}	21.24
300 kg N_{min}	20.24
350 kg N_{min}	19.24
Grazed GC_w[1]	
85 kg N_{min}	21.74
Grass silage PRG[1]	
100 kg N_{min}	23.24
150 kg N_{min}	22.24
200 kg N_{min}	21.24
250 kg N_{min}	20.24
300 kg N_{min}	19.24
350 kg N_{min}	18.24
Grass silage GC_w[1]	
85 kg N_{min}	20.74
Grass silage GC_{rw}[1]	
85 kg N_{min}	20.74
Maize silage	17.50

[1] PRG = perennial ryegrass, GC_w = Perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover
[2] Emission factors for fresh grass and grass silage are based on Vellinga et al. (2013), using a mechanistic model originating from Dijkstra et al. (1992)and updated by Mills et al. (2001) and Bannink et al. (2006). The emission factor of maize silage is based on Sebek et al. (2016).

Table A4
Emission factors for CH_4 and N_2O emissions, NO_3^- leaching, and NH_3 + NO_x volatilization from manure and managed soils.

	Unit	Reference
Manure in stable/storage		
CH_4	0.746 kg/ton manure	De Mol and Hilhorst (2003)
NH_3-N	0.143 kg/kg TAN[1]	Van Bruggen et al. (2021)
NO_x-N	0.002 kg/kg TAN[1]	Van Bruggen et al. (2021)
N_2O-N direct	0.002 kg/kg TAN[1]	Van Bruggen et al. (2021)
N_2-N	0.02 kg/kg TAN[1]	Van Bruggen et al. (2021)
Managed soils (grassland)		
Mineral fertilizer (CAN)		
NH_3-N	0.025 kg/kg N	Van Bruggen et al. (2021)
NO-N	0.008 kg/kg N	Van Bruggen et al. (2021)
N_2O-N direct	0.012 kg/kg N	Van Bruggen et al. (2021)
Slurry spreading		
NH_3-N	0.17 kg/kg TAN	Velthof et al. (2012); Van Bruggen et al. (2021)
NO_x-N	0.21 kg/kg N_2O-direct	Eco-invent (2007)
N_2O-N direct	0.003 kg/kg N	Van Bruggen et al. (2021)
NO-N	0.012 kg/kg N	Van Bruggen et al. (2021)
Crop residues		
N-crop residues perennial ryegrass	40.75 kg N/ha/year	IPCC (2019) (grassland renewal every 5 years Aarts et al. (2002)
N-crop residues perennial ryegrass	50.74 kg N/ha/year	IPCC (2019) (grassland renewal every 3 years)[3]

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Table A4 (*continued*)

	Unit	Reference
N-crop residues grass-white clover	57.94 kg N/ha/year	IPCC (2019) (grassland renewal every 5 years Aarts et al. (2002)
N-crop residues grass-red white clover	96.56 kg N/ha/year	IPCC (2019) (grassland renewal every 3 years)
NOx-N	0.21 kg/kg N_2O-N direct	Eco-invent (2007)
N_2O-direct	0.01 kg/kg N	IPCC (2019))
Manure from grazing		
NH_3-N	0.04 kg/kg TAN	Van Bruggen et al. (2021)
NO_x-N	0.21 kg/kg N_2O-N direct	Eco-invent (2007)
N_2O-N direct	0.025 kg/kg N	Van Bruggen et al. (2021)
Other N inputs		
N-deposition	30 kg N/ha	van Dijk et al. (2020)
N-fixation grass-clover swards	45 kg t/DM	van Dijk et al., 2020)
Leaching NO_3^--N	0.29 kg/kg N surplus[2]	Fraters et al. (2012)
Managed soils (maize land)		
Mineral fertilizer (CAN)		
NH_3-N	0.025 kg/kg N	Van Bruggen et al. (2021)
NO-N	0.008 kg/kg N	Van Bruggen et al. (2021)
N_2O-N direct	0.012 kg/kg N	Van Bruggen et al. (2021)
Slurry spreading		
NH_3-N	0.02 kg/kg TAN	Velthof et al. (2012); Van Bruggen et al. (2021)
NO_x-N	0.21 kg/kg N_2O-direct	Eco-invent (2007)
N_2O-N direct	0.013 kg/kg N	Van Bruggen et al. (2021)
NO-N	0.012 kg/kg N	Van Bruggen et al. (2021)
Crop residues		
N-crop residues	28.39 kg N/ha/year	IPCC (2019)
NO_x-N	0.21 kg/kg N_2O-N direct	Eco-invent (2007)
N_2O-direct	0.01 kg/kg N	IPCC (2019)
Other N inputs		
N-deposition	30 kg N/ha	van Dijk et al. (2020).
Leaching NO_3^--N	0.59 kg/kg N surplus[2]	Fraters et al. (2012)
All		
N_2O-N indirect	0.010 kg/kg NH_3-N + NO_x-N	IPCC (2019)
	0.0075 kg/kg NO_3^--N	IPCC (2019)

[1] Total Ammoniacal Nitrogen
[2] N surplus is calculated as N-inputs minus N-outputs, i.e. (N mineral fertilizer + N manure + N deposition + N fixation) - (N harvested crop products + N emissions)
[3] To account for the ley system used in the NPOL scenario. The difference between N-crop residues between 5 and 3 year renewel of PRG was used and accounted for in the maize activity. For all other scenarios it was assumed that the GC_{rw} swards would be used.

Table A5
Sensitivity analysis for the feed characteristics for the perennial ryegrass scenario with stricter nitrogen policies (NPOL).

			GJ NE_L ha^{-1} yr^{-1}		NE_L kg DM^{-1}		IDP kg DM^{-1}		RDP kg DM^{-1}	
		Reference	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%
Farm structure										
Dairy cows	No.	92	86	93	88	94	92	92	91	92
Youngstock	No.	54	50	54	52	55	54	54	54	54
Total farmland	ha	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7
PRG	% total farmland	68	71	68	70	74	68	68	69	68
GC_{rw}[1]	% total farmland	-	-	-	-	-	-	-	-	-
GC_w[1]	% total farmland	-	-	-	-	-	-	-	-	-
Maize land	% total farmland	32	29	32	30	26	32	32	31	32
N_{min} application PRG	Kg of N ha^{-1} yr^{-1}	200	200	200	200	200	200	200	200	200
N_{min} application GC_{rw}[1]		-	-	-	-	-	-	-	-	-
N_{min} application GC_w[1]		-	-	-	-	-	-	-	-	-
Farm intensity	Kg of milk ha^{-1} yr^{-1}	15,524	14,516	15,651	14,884	15,839	15,524	15,524	15,384	15,524
On-farm production of protein	% of total protein input	56.6	56.3	60.4	61.3	54.1	56.6	56.6	56.7	57.2
Diet dairy cows: summer	Kg of DM cow^{-1} day^{-1}									
Grass		10.0	10.0	10.0	10.0	10.0	10	10	10	10
Grass silage		0	0	1.3	1.9	0	0	0	0	0
Maize silage		6.4	6.0	6.4	6.4	3.4	6.4	6.4	6.4	6.4
Concentrates total		5.2	5.5	4.0	4.7	7.0	5.2	5.2	5.2	5.2
Standard protein		2.7	3.1	2.1	3.0	5.9	2.7	2.7	2.4	2.9
Medium protein		0	0	0	0	0	0	0	0	0
High protein		2.5	2.4	2.0	1.7	1.1	2.5	2.5	2.8	2.3
Diet restricted by[2]		E,R,G	E,R,G	E,R,G	E,R,G	E,R,G	E,R,G	E,R,G	E,R,G	E,R,G

(*continued on next page*)

Table A5 (*continued*)

			GJ NE_L ha^{-1} yr^{-1}		NE_L kg DM^{-1}		IDP kg DM^{-1}		RDP kg DM^{-1}	
		Reference	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%
Diet dairy cows: winter	Kg of DM cow^{-1} day^{-1}									
Grass silage		4.2	4.2	4.2	4.7	3.8	4.2	4.2	4.5	4.2
Maize silage		6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Concentrates total		7.0	7.0	7.0	7.0	7.0	7.0	7.0	6.8	7.0
Standard protein		3.8	3.8	3.8	4.0	3.6	3.8	3.8	3.5	4.0
Medium protein		0	0	0	0	0	0	0	0	0
High protein		3.2	3.2	3.2	3.0	3.4	3.2	3.2	3.3	3.0
Diet restricted by[2]		E,R	E,R	E,R	E,R	E,R	E,R	E,R	E,R	E,R
External inputs										
Purchased maize silage	t of DM yr^{-1}	0	0	0	0	0	0	0	0	0
Purchased concentrates	t of DM yr^{-1}	218	209	200	201	254	218	218	213	218
Purchased mineral N fertilizer	Kg yr^{-1}	4,643	4,737	4,631	4,754	5,016	4,643	4,643	4,672	4,620
Purchased mineral P_2O_5 fertilizer	Kg yr^{-1}	227	313	372	370	268	227	227	205	267
Hired labour	h yr^{-1}	218	58	261	159	278	218	218	199	218
Manure management										
Manure application restricted by[3]		tN, aN	tN,aN	tN,aN	tN,aN	tN,aN	tN,aN	tN,aN	tN, aN	tN,aN
Total excretion	Kg of nitrogen yr^{-1}	14,259	13,330	14,325	14,317	13,886	14,259	14,259	14,311	14,073
Total excretion	Kg of phosphate yr^{-1}	4,864	4,555	4,842	4,855	4,782	4,864	4,864	4,872	4,803
Applied on own land	Kg of phosphate yr^{-1}	3,964	4,068	4,072	4,083	4,047	3,964	3,964	3,935	4,008
Farm income[4]	€ yr^{-1}	-6,634	-12,979	-3,142	-13,994	-3,660	-6,634	-6,635	-8,288	-5,270
Total greenhouse gas emissions	g CO_2-eq t^{-1} of FPCM[5]	806	813	797	834	799	806	807	809	803
N surplus	Kg ha^{-1} yr^{-1}	118	132	105	106	136	118	118	119	117
P_2O_5 surplus	Kg ha^{-1} yr^{-1}	2.5	9.3	0	0	8.5	2.5	2.5	1.9	3.3

[1] PRG= perennial ryegrass, GC_w = perennial ryegrass-white clover, GC_{rw}= perennial ryegrass-red white clover
[2] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity
[3] Manure application can be restricted by: tN = total mineral N; aN = N from organic manure; P = total P_2O_5
[4] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)
[5] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)

Table A6
Sensitivity analysis for the feed characteristics for the perennial ryegrass and perennial ryegrass-red white clover scenario with stricter nitrogen policies (+GC_{rw}).

			GJ NE_L ha^{-1} yr^{-1}		NE_L kg DM^{-1}		IDP kg DM^{-1}		RDP kg DM^{-1}	
		Reference	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%
Farm structure										
Dairy cows	No.	96	94	97	93	98	97	94	93	99
Youngstock	No.	56	55	57	54	58	57	55	54	58
Total farmland	ha	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7
PRG	% total farmland	47	48	46	46	47	46	47	48	45
GC_{rw}[1]	% total farmland	22	23	21	22	23	21	24	23	22
GC_w[1]	% total farmland	-	-	-	-	-	-	-	-	-
Maize land	% total farmland	31	29	33	32	30	33	29	29	33
N_{min} application PRG	Kg of N ha^{-1} yr^{-1}	250	250	250	250	250	250	250	250	250
N_{min} application GC_{rw}[1]		85	85	85	85	85	85	85	85	85
N_{min} application GC_w[1]		-	-	-	-	-	-	-	-	-
Farm intensity	Kg of milk ha^{-1} yr^{-1}	16,233	15,884	16,310	15,635	16,560	16,357	15,850	15,577	16,590
On-farm production of protein	% of total protein input	64.7	64.8	65.5	68.8	62.0	63.0	67.4	67.7	63.0
Diet dairy cows: summer	Kg of DM cow^{-1} day^{-1}									
Grass		9.0	9.6	8.5	9.3	8.8	8.6	9.5	9.8	8.3
Grass silage		1.7	1.5	2.0	2.0	1.5	1.8	1.8	1.6	1.9
Maize silage		5.2	5.0	6.3	6.4	4.7	6.2	5.3	5.1	5.9
Concentrates total		5.7	5.6	4.9	4.3	6.4	5.1	5.2	5.2	5.6
Standard protein		5.6	5.6	4.2	3.9	6.4	4.5	5.2	5.2	5.2
Medium protein		0	0	0	0	0	0	0	0	0
High protein		0.1	0	0.6	0.4	0	0.7	0	0	0.4
Diet restricted by[2]		E, R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T
Diet dairy cows: winter	Kg of DM cow^{-1} day^{-1}									
Grass silage		4.9	4.8	4.9	5.5	4.4	4.4	5.4	5.4	4.4
Maize silage		6.7	6.2	6.7	6.7	6.7	6.7	6.0	6.7	6.7
Concentrates total		6.5	7.0	6.5	6.5	6.5	6.9	6.7	6.1	6.9
Standard protein		4.9	5.6	4.9	5.3	4.6	5.0	5.7	4.4	5.3
Medium protein		0	0	0	0	0	0	0	0	0

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Table A6 (*continued*)

		Reference	GJ NE_L ha^{-1} yr^{-1} -10%	+10%	NE_L kg DM^{-1} -10%	+10%	IDP kg DM^{-1} -10%	+10%	RDP kg DM^{-1} -10%	+10%
High protein		1.6	1.4	1.6	1.2	1.9	1.9	1.0	1.6	1.6
Diet restricted by[2]		E, R, T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T
External inputs										
Purchased maize silage	t of DM yr^{-1}	0	0	0	0	0	0	0	0	0
Purchased concentrates	t of DM yr^{-1}	229	230	214	196	247	227	217	202	239
Purchased mineral N fertilizer	Kg yr^{-1}	4,726	4,845	4,523	4,584	4,779	4,559	4,816	4,785	4,568
Purchased mineral P_2O_5 fertilizer	Kg yr^{-1}	575	483	669	732	450	541	624	635	528
Hired labour	h yr^{-1}	367	318	369	279	409	367	323	279	403
Manure management										
Manure application restricted by[3]		tN, aN	tN, aN	tN,aN	tN,aN	tN,aN	tN, aN	tN,aN	tN,aN	tN,aN
Total excretion	Kg of nitrogen yr^{-1}	14,284	14,008	14,320	13,931	14,423	14,430	13,901	13,893	14,417
Total excretion	Kg of phosphate yr^{-1}	4,648	4,558	4,642	4,471	4,733	4,715	4,483	4,458	4,731
Applied on own land	Kg of phosphate yr^{-1}	4,138	4,047	4,218	4,249	4,040	4,115	4,159	4,156	4,116
Farm income[4]	€ yr^{-1}	2,621	1,187	3,812	1,433	3,543	2,168	3,077	1,643	3,529
Total greenhouse gas emissions	g CO_2-eq t^{-1} of FPCM[5]	791	794	783	787	790	789	788	786	790
N surplus	Kg ha^{-1} yr^{-1}	137	140	133	132	141	135	138	136	136
P_2O_5 surplus	Kg ha^{-1} yr^{-1}	0	0	0	0	0	0	0	0	0

[1] PRG= perennial ryegrass, GC_w = perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover

[2] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity

[3] Manure application can be restricted by: tN = total mineral N; aN = N from organic manure; P = total P_2O_5

[4] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)

[5] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)

Table A7

Sensitivity analysis for feed characteristics for the perennial ryegrass, perennial ryegrass-white clover and perennial ryegrass-red white clover scenario with stricter nitrogen policies (+GC_{rw}+GC_w).

		Reference	GJ NE_L ha^{-1} yr^{-1} −10%	+10%	NE_L kg DM^{-1} −10%	+10%	IDP kg DM^{-1} −10%	+10%	RDP kg DM^{-1} −10%	+10%
Farm structure										
Dairy cows	No.	98	98	98	97	100	97	96	97	98
Youngstock	No.	57	57	57	57	59	57	56	57	58
Total farmland	ha	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7
PRG	% total farmland	30	31	15	18	19	35	4	33	23
GC_{rw}[1]	% total farmland	17	19	15	17	17	17	18	18	15
GC_w[1]	% total farmland	20	17	36	32	29	15	47	16	28
Maize land	% total farmland	33	33	34	33	35	33	31	33	34
N_{min} application PRG	Kg of N ha^{-1} yr^{-1}	300	325	175	200	300	300	250	325	275
N_{min} application GC_{rw}[1]		85	85	85	85	85	85	85	85	85
N_{min} application GC_w[1]		85	85	85	85	85	85	85	85	85
Farm intensity	Kg of milk ha^{-1} yr^{-1}	16,429	16,512	16,412	16,246	16,909	16,371	16,195	16,361	16,579
On-farm production of protein	% of total protein input	64.9	63.1	64.2	65.5	59.7	64.4	64.9	66.0	62.7
Diet dairy cows: summer	Kg of DM cow^{-1} day^{-1}									
Grass		10	8.8	10	9.9	8.4	10	9.4	9.6	9.6
Grass silage		0	0.4	0	0	0	0.2	0	0	0
Maize silage		6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Concentrates total		5.1	5.9	5.1	6.0	6.3	4.9	5.6	5.4	5.5
Standard protein		4.6	5.5	4.2	5.8	5.3	4.5	5.4	5.0	4.9
Medium protein		0	0	0	0	0	0	0	0	0
High protein		0.5	0.4	0.9	0.2	1.0	0.4	0.2	0.4	0.6
Diet restricted by[2]		G,E,R,T	E,R,T	G,E,R,T	E,R,T	E,R,T	G,E,R,T	E,R,T	E,T	E,R,T
Diet dairy cows: winter	Kg of DM cow^{-1} day^{-1}									
Grass silage		4.8	4.8	4.9	5.4	4.4	4.4	5.3	5.4	4.4
Maize silage		6.3	6.3	6.7	6.7	6.7	6.7	5.8	6.7	6.7
Concentrates total		6.9	6.9	6.5	6.5	6.5	6.9	6.9	6.0	6.9
Standard protein		5.4	5.4	4.9	5.3	4.6	5.0	6.2	4.4	5.3
Medium protein		0	0	0	0	0	0	0	0	0
High protein		1.4	1.4	1.6	1.2	1.9	1.9	0.8	1.6	1.6
Diet restricted by[2]		E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T
External inputs										
Purchased maize silage	t of DM yr^{-1}	0	0	0	0	0	0	0	0	0

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Table A7 (*continued*)

		Reference	GJ NE_L ha^{-1} yr^{-1}		NE_L kg DM^{-1}		IDP kg DM^{-1}		RDP kg DM^{-1}	
			−10%	+10%	−10%	+10%	−10%	+10%	−10%	+10%
Purchased concentrates	t of DM yr^{-1}	226	242	220	233	249	223	235	217	236
Purchased mineral N fertilizer	Kg yr^{-1}	3,947	4,570	1,066	1,267	2,625	4,535	409	4,544	2,609
Purchased mineral P_2O_5 fertilizer	Kg yr^{-1}	650	519	625	642	325	626	498	734	520
Hired labour	h yr^{-1}	376	377	372	355	414	361	342	367	384
Manure management										
Manure application restricted by[3]		aN	tN, aN	aN	aN	aN	tN, aN	aN	tN, aN	aN
Total excretion	Kg of nitrogen yr^{-1}	14,478	14,483	14,458	14,478	14,435	14,487	13,983	14,567	14,443
Total excretion	Kg of phosphate yr^{-1}	4,606	4,623	4,673	4,706	4,693	4,611	4,488	4,572	4,666
Applied on own land	Kg of phosphate yr^{-1}	4,119	4,000	4,155	4,206	3,876	4,095	4,009	4,164	4,044
Farm income[4]	€ yr^{-1}	8,072	5,425	10,899	6,372	10,004	6,821	10,665	6,709	9,142
Total greenhouse gas emissions	CO_2-eq t^{-1} of FPCM[5]	767	777	758	776	757	772	752	768	765
N surplus	Kg ha^{-1} yr^{-1}	132	144	108	107	131	137	111	139	123
P_2O_5 surplus	Kg ha^{-1} yr^{-1}	0	0	0	0	0	0	0	0	0

[1] PRG,GC_w = perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover
[2] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity
[3] Manure application can be restricted by: tN = total mineral N; aN = N from organic manur; P = total P_2O_5
[4] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)
[5] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)

Table A8
Sensitivity analysis for feed characteristics for the perennial ryegrass-white clover and perennial ryegrass-red white clover scenario with stricter nitrogen policies (GC-only)1, 2, 3, 4, 5

		Reference	GJ NE_L ha^{-1} yr^{-1}		NE_L kg DM^{-1}		IDP kg DM^{-1}		RDP kg DM^{-1}	
			-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%
Farm structure										
Dairy cows	No.	97	95	96	94	100	95	96	96	97
Youngstock	No.	57	55	46	55	59	55	56	56	57
Total farmland	ha	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7
PRG[1]	% total farmland	-	-	-	-	-	-	-	-	-
GC_{rw}[1]	% total farmland	17	18	15	16	17	15	18	18	15
GC_w[1]	% total farmland	50	49	52	52	49	53	51	49	51
Maize land	% total farmland	33	33	33	32	34	32	31	33	33
N_{min} application PRG	Kg of N ha^{-1} yr^{-1}	-	-	-	-	-	-	-	-	-
N_{min} application GC_{rw}[1]		85	85	85	85	85	85	85	85	85
N_{min} application GC_w[1]		85	85	85	85	85	85	85	85	85
Farm intensity	Kg of milk ha^{-1} yr^{-1}	16,284	15,918	16,153	15,777	16,866	15,911	16,158	16,244	16,352
On-farm production of protein	% of total protein input	62.1	59.0	64.4	65.8	56.7	59.1	64.8	62.3	61.8
Diet dairy cows: summer	Kg of DM cow^{-1} day^{-1}									
Grass		9.1	8.0	10	10	7.5	9.0	9.4	8.7	9.4
Grass silage		0	0	0	0	0	0	0	0	0
Maize silage		6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Concentrates total		5.9	7.0	5.1	6.0	6.7	5.9	5.6	6.3	5.6
Standard protein		4.8	6.0	4.0	5.9	5.0	0.2	5.4	5.2	3.6
Medium protein		0	0	0	0	0	5.7	0	0	1.4
High protein		1.1	1.0	1.1	0.1	1.7	0	0.2	1.1	0.6
Diet restricted by[2]		E,T	E,T	G,E,T	G,E,T	E,T	E,T	E,R,T	E,T	E,T
Diet dairy cows: winter	Kg of DM cow^{-1} day^{-1}									
Grass silage		4.9	4.9	4.9	5.5	4.4	4.4	5.3	5.4	4.4
Maize silage		6.7	6.7	6.7	6.7	6.7	6.7	5.8	6.7	6.7
Concentrates total		6.5	6.5	6.5	6.5	6.5	6.9	7.0	6.0	6.9
Standard protein		4.9	4.9	4.9	5.3	4.6	5.0	6.1	4.4	5.3
Medium protein		0	0	0	0	0	0	0	0	0
High protein		1.6	1.6	1.6	1.2	1.9	1.9	0.9	1.6	1.6
Diet restricted by[2]		E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T
External inputs										
Purchased maize silage	t of DM yr^{-1}	0	0	0	0	0	0	0	0	0
Purchased concentrates	t of DM yr^{-1}	232	247	216	227	256	235	234	231	235
Purchased mineral N fertilizer	Kg yr^{-1}	244	251	257	277	215	267	290	242	252
Purchased mineral P_2O_5 fertilizer	Kg yr^{-1}	701	531	692	724	608	569	617	734	682
Hired labour	h yr^{-1}	338	262	330	285	393	269	336	335	345

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Table A8 (*continued*)

		Reference	GJ NE_L ha^{-1} yr^{-1}		NE_L kg DM^{-1}		IDP kg DM^{-1}		RDP kg DM^{-1}	
			-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%
Manure management[3]										
Manure application restricted by[3]		aN	aN	aN	aN	aN	aN	aN	aN	aN
Total excretion	Kg of nitrogen yr^{-1}	14,465	13,939	14,502	14,489	14,406	14,535	13,971	14,478	14,477
Total excretion	Kg of phosphate yr^{-1}	4,657	4,563	4,612	4,630	4,733	4,556	4,475	4,460	4,627
Applied on own land	Kg of phosphate yr^{-1}	4,217	4,115	4,162	4,212	4,199	3,983	4,119	4,252	4,167
Farm income[4]	€ yr^{-1}	7,188	2,248	9,050	2,742	8,981	626	10,593	5,948	8,172
Total greenhouse gas emissions	CO_2-eq t^{-1} of FPCM[5]	759	768	752	780	749	754	754	760	754
N surplus	Kg ha^{-1} yr^{-1}	113	121	110	110	120	118	114	144	113
P_2O_5 surplus	Kg ha^{-1} yr^{-1}	4.3	7.5	1.3	1.2	8.8	3.3	2.2	4.7	3.7

[1] PRG = perennial ryegrass, GC_w = perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover

[2] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity

[3] Manure application can be restricted by: tN = total mineral N; aN = N from organic manure; P = total P_2O_5

[4] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)

[5] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)

Table A9

Sensitivity analysis in- and output prices for perennial ryegrass scenario with stricter nitrogen policies (NPOL)1, 2, 3, 4, 5

Item	Unit	Reference	Concentrates		Mineral N fertilizer		Milk price	Manure disposal and processing		
			-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%
Farm structure										
Dairy cows	No.	92	92	85	92	92	85	92	92	92
Youngstock	No.	54	54	50	50	54	50	54	54	54
Total farmland	ha	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7
PRG	% total farmland	68	69	71	69	68	71	68	69	68
GC_{rw}^1	% total farmland	-	-	-	-	-	-	-	-	-
GC_w^1	% total farmland	-	-	-	-	-	-	-	-	-
Maize land	% total farmland	32	31	29	31	32	29	32	31	32
N_{min} application PRG[1]	Kg of N ha^{-1} yr^{-1}	200	200	200	200	200	200	200	200	200
N_{min} application GC_{rw}[1]		-	-	-	-	-	-	-	-	-
N_{min} application GC_w[1]		-	-	-	-	-	-	-	-	-
Farm intensity	Kg of milk ha^{-1} yr^{-1}	15,524	15,570	14,296	15,570	15,524	14,297	15,570	15,570	15,524
On-farm production of protein	% of total protein input	56.6	56.5	62.9	56.5	56.6	62.9	56.5	56.5	56.6
Diet dairy cows: summer	Kg of DM cow^{-1} day^{-1}									
Grass		10	10	10	10	10	10	10	10	10
Grass silage		0	0	0	0	0	0	0	0	0
Maize silage		6.4	6.2	6.4	6.2	6.4	6.4	6.2	6.2	6.4
Concentrates total		5.2	5.3	5.2	5.3	5.2	5.2	5.3	5.3	5.2
Standard protein		2.7	2.9	2.7	2.9	2.7	2.7	2.9	2.9	2.7
Medium protein		0	0	0	0	0	0	0	0	0
High protein		2.5	2.5	2.5	2.4	2.5	2.5	2.4	2.4	2.5
Diet restricted by[2]		E,R,G	E,R,G	E,R,G	E,R,G	E,R	E,R	E,R	E,R	E,R
Diet dairy cows: winter	Kg of DM cow^{-1} day^{-1}									
Grass silage		4.2	4.2	6.4	4.2	4.2	6.4	4.2	4.2	4.2
Maize silage		6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Concentrates total		7.0	7.0	5.1	7.0	7.0	5.1	7.0	7.0	7.0
Standard protein		3.8	3.8	2.8	3.8	3.8	2.8	3.8	3.8	3.8
Medium protein		0	0	0	0	0	0	0	0	0
High protein		3.2	3.2	2.3	3.2	3.2	2.3	3.2	3.2	3.2
Diet restricted by[2]		E,R	E,R	E,R	E,R	E,R	E,R	E,R	E,R	E,R
External inputs										
Purchased maize silage	t of DM yr^{-1}	0	0	0	0	0	0	0	0	0
Purchased concentrates	t of DM yr^{-1}	218	221	171	221	218	171	221	221	218
Purchased mineral N fertilizer	Kg yr^{-1}	4,643	4,664	4,690	4,664	4,643	4,690	4,664	4,664	4,643
Purchased mineral P_2O_5 fertilizer	Kg yr^{-1}	227	220	378	220	227	378	220	220	227
Hired labour	h yr^{-1}	218	226	55	226	218	55	226	226	218
Manure management										
Manure application restricted by[3]		tN, aN	tN,aN	tN,aN	tN,aN	tN,aN	tN, aN	tN,aN	tN,aN	tN,aN
Total excretion	Kg of nitrogen yr^{-1}	14,259	14,299	13,053	14,299	14,259	13,055	14,299	14,299	14,258
Total excretion	Kg of phosphate yr^{-1}	4,864	4,881	4,384	4,881	4,864	4,385	4,881	4,881	4,864
Applied on own land	Kg of phosphate yr^{-1}	3,964	3,960	4,076	3,960	3,964	4,076	3,960	3,960	3,964
Extra phosphate quota	Kg of phosphate yr^{-1}	0	0	0	0	0	0	0	0	0

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Table A9 (*continued*)

Item	Unit	Reference	Concentrates		Mineral N fertilizer		Milk price	Manure disposal and processing		
			-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%
Farm income[4]	€ yr^{-1}	-6,634	9,473	-21,744	-5,534	-7,738	-82,872	73,499	-2,930	-10,296
Total greenhouse gas emissions	g CO_2-eq t^{-1} of FPCM[5]	806	808	795	808	807	775	821	808	807
N surplus	Kg ha^{-1} yr^{-1}	118	119	114	119	118	114	118	119	118
P_2O_5 surplus	Kg ha^{-1} yr^{-1}	2.5	2.4	4.2	2.4	2.5	4.2	2.4	2.4	2.5

[1] PRG = perennial ryegrass, GC_{GCw} = perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover

[2] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity

[3] Manure application can be restricted by: tN = total mineral N; aN = N from organic manure; P = total P_2O_5

[4] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)

[5] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)

Table A10

Sensitivity analysis for in- and output prices for the perennial ryegrass and perennial ryegrass-red white clover scenario with stricter nitrogen policies (+GC_{rw})

Item	Unit	Reference	Concentrates		Mineral N fertilizer		Milk price		Manure disposal and processing	
			-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%
Farm structure										
Dairy cows	No.	96	97	88	96	96	82	97	97	94
Youngstock	No.	56	57	52	56	57	48	57	57	55
Total farmland	ha	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7
PRG	% total farmland	47	48	48	47	47	45	46	46	46
GC_{rw}[1]	% total farmland	22	22	22	22	22	23	22	22	22
GC_w[1]	% total farmland	-	-	-	-	-	-	-	-	-
Maize land	% total farmland	31	30	30	31	31	32	32	32	32
N_{min} application PRG	Kg of N ha^{-1} yr^{-1}	250	250	225	250	250	175	250	250	250
N_{min} application GC_{rw}[1]		85	85	85	85	85	85	85	85	85
N_{min} application GC_w[1]		-	-	-	-	-	-	-	-	-
Farm intensity	Kg of milk ha^{-1} yr^{-1}	16,233	16,406	14,856	16,233	16,231	13,816	16,407	16,407	15,784
On-farm production of protein	% of total protein input	64.7	64.1	69.3	64.7	64.7	71.1	64.1	64.1	66.4
Diet dairy cows: summer	Kg of DM cow^{-1} day^{-1}									
Grass		9.0	9.1	10	9.0	9.0	10	9.0	9.0	9.0
Grass silage		1.7	1.7	2.3	1.7	1.7	3.3	1.7	1.7	1.9
Maize silage		5.2	5.0	6.4	5.2	5.2	6.4	5.0	5.0	6.4
Concentrates total		5.7	6.0	3.4	5.7	5.7	2.5	6.0	6.0	4.6
Standard protein		5.6	6.0	2.8	5.6	5.6	1.7	6.0	6.0	4.0
Medium protein		0	0	0	0	0	0	0	0	0
High protein		0.1	0	0.6	0.1	0.1	0.8	0	0	0.6
Diet restricted by[2]		E,R,T	E,R,T	G,E,R,T	E,R,T	E,R,T	G,E,R,T	E,R,T	E,R,T	E,R,T
Diet dairy cows: winter	Kg of DM cow^{-1} day^{-1}									
Grass silage		4.9	4.9	4.9	4.9	4.9	4.9	4.8	4.8	4.9
Maize silage		6.7	6.5	6.7	6.7	6.7	6.7	6.5	6.5	6.7
Concentrates total		6.5	6.7	6.5	6.5	6.5	6.5	6.7	6.7	6.5
Standard protein		4.9	5.2	4.9	4.9	4.9	4.9	5.2	5.2	4.9
Medium protein		0	0	0	0	0	0	0	0	0
High protein		1.6	1.5	1.6	1.6	1.6	1.6	1.5	1.5	1.6
Diet restricted by[2]		E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T
External inputs										
Purchased maize silage	t of DM yr^{-1}	0	0	0	0	0	0	0	0	0
Purchased concentrates	t of DM yr^{-1}	229	240	171	229	229	146	240	240	202
Purchased mineral N fertilizer	Kg yr^{-1}	4,726	4,793	4,301	4,726	4,725	2,992	4,793	4,793	4,553
Purchased mineral P_2O_5 fertilizer	Kg yr^{-1}	575	570	547	575	574	365	569	569	591
Hired labour	h yr^{-1}	367	397	155	367	366	2	397	397	287
Manure management										
Manure application restricted by[3]		tN, aN	tN,aN	aN	tN,aN	tN,aN	aN	tN,aN	tN,aN	tN,aN
Total excretion	Kg of nitrogen yr^{-1}	14,284	14,440	13,115	14,284	14,283	12,195	14,441	14,440	13,881
Total excretion	Kg of phosphate yr^{-1}	4,648	4,713	4,220	4,649	4,648	3,972	4,713	4,714	4,482
Applied on own land	Kg of phosphate yr^{-1}	4,138	4,142	4,083	4,138	4,138	3,959	4,141	4,141	4,130
Extra phosphate quota	Kg of phosphate yr^{-1}	0	0	0	0	0	0	0	0	0
Farm income[4]	€ yr^{-1}	2,621	17,888	-9,828	3,744	1,498	-73,481	87,036	6,672	-769
Total greenhouse gas emissions	g CO_2-eq t^{-1} of FPCM[5]	791	794	777	791	791	755	807	794	781
N surplus	Kg ha^{-1} yr^{-1}	137	138	131	137	137	120	138	138	134
P_2O_5 surplus	Kg ha^{-1} yr^{-1}	0	0	0	0	0	0	0	0	0

[1] PRG = perennial ryegrass, GC_w = perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover

[2] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity

[3] Manure application can be restricted by: tN = total mineral N; aN = N from organic manure; P = total P_2O_5

[4] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)

[5] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)

Table A11

Sensitivity analysis for in- and output prices for the perennial ryegrass, perennial ryegrass-white clover and perennial ryegrass-red white clover scenario with stricter nitrogen policies (+GC_{rw}+GC_w)

Item	Unit	Reference	Concentrates		Mineral N fertilizer	Milk price			Manure disposal and processing	
			-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%
Farm structure										
Dairy cows	No.	98	100	97	98	98	88	100	98	97
Youngstock	No.	57	58	57	57	57	52	58	57	57
Total farmland	ha	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7
PRG	% total farmland	30	19	30	30	11	58	20	22	22
GC_{rw}[1]	% total farmland	17	16	17	17	17	15	17	17	17
GC_w[1]	% total farmland	20	31	20	20	38	27	31	20	20
Maize land	% total farmland	33	34	33	33	34	32	32	32	32
N_{min} application PRG	Kg of N ha^{-1} yr^{-1}	300	125	300	300	250	100	150	300	300
N_{min} application GC_{rw}[1]		85	85	85	85	85	85	85	85	85
N_{min} application GC_w[1]		85	85	85	85	85	85	85	85	85
Farm intensity	Kg of milk ha^{-1} yr^{-1}	16,429	16,769	16,283	16,445	16,461	14,822	16,778	16,445	16,283
On-farm production of protein	% of total protein input	64.9	57.8	65.4	64.8	61.9	63.9	58.7	64.8	65.4
Diet dairy cows: summer	Kg of DM cow^{-1} day^{-1}									
Grass		10	8.0	10	10	9.0	10	8.0	10	10
Grass silage		0	0	0	0	0	0	0	0	0
Maize silage		6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Concentrates total		5.1	7.0	5.1	5.1	6.0	5.1	7.0	5.1	5.1
Standard protein		4.6	6.0	4.6	4.6	5.1	4.1	6.0	4.6	4.6
Medium protein		0	0	0	0	0	0	0	0	0
High protein		0.5	1.0	0.5	0.5	0.9	1.0	1.0	0.5	0.5
Diet restricted by[2]		G,E,R,T	E,R,T	G,E,R,T	G,E,R,T	E,R,T	G,E,R,T	E,R,T	G,E,R,T	G,E,R,T
Diet dairy cows: winter	Kg of DM cow^{-1} day^{-1}									
Grass silage		4.8	4.6	4.9	4.8	4.9	4.9	4.9	4.8	4.9
Maize silage		6.3	6.4	6.7	6.3	6.7	6.7	6.5	6.3	6.7
Concentrates total		6.9	7.0	6.5	6.9	6.5	6.5	6.7	6.9	6.5
Standard protein		5.4	5.4	4.9	5.5	4.9	4.9	5.2	5.5	4.9
Medium protein		0	0	0	0	0	0	0	0	0
High protein		1.4	1.6	1.6	1.4	1.6	1.6	1.5	1.4	1.6
Diet restricted by[2]		E,R,T	E,R	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T
External inputs										
Purchased maize silage	t of DM yr^{-1}	0	0	0	0	0	0	0	0	0
Purchased concentrates	t of DM yr^{-1}	226	269	218	227	237	199	264	227	218
Purchased mineral N fertilizer	Kg yr^{-1}	3,947	607	3,906	3,952	1,114	541	806	3,951	3,906
Purchased mineral P_2O_5 fertilizer	Kg yr^{-1}	650	158	654	650	463	153	141	650	654
Hired labour	h yr^{-1}	376	397	351	379	365	116	401	379	351
Manure management										
Manure application restricted by[3]		aN	aN	aN	aN	aN	aN	aN	aN	aN
Total excretion	Kg of nitrogen yr^{-1}	14,478	14,402	14,347	14,492	14,445	12,813	14,425	14,492	14,347
Total excretion	Kg of phosphate yr^{-1}	4,606	4,851	4,553	4,612	4,682	4,285	4,828	4,612	4,553
Applied on own land	Kg of phosphate yr^{-1}	4,119	3,868	4,117	4,120	4,003	3,824	3,921	4,120	4,117
Extra phosphate quota	Kg of phosphate yr^{-1}	0	0	0	0	0	0	0	0	0
Farm income[4]	€ yr^{-1}	8,072	24,743	-6,110	9,487	7,199	-70,540	93,847	12,233	4,110
Total greenhouse gas emissions	g CO_2-eq t^{-1} of FPCM[5]	767	770	765	767	762	734	780	769	765
N surplus	Kg ha^{-1} yr^{-1}	132	109	132	133	114	103	111	133	132
P_2O_5 surplus	Kg ha^{-1} yr^{-1}	0	0	0	0	0	1.0	0.4	0	0

[1] PRG = perennial ryegrass, GC_w = perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover

[2] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity

[3] Manure application can be restricted by: tN = total mineral N; aN = N from organic manure; P = total P_2O_5

[4] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)

[5] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)

Table A12
Sensitivity analysis for in- and output prices for the perennial ryegrass-white clover and perennial ryegrass-red white clover scenario with the stricter nitrogen policies (GC-only)

Item	Unit	Reference	Concentrates		Mineral N fertilizer		Milk price		Manure disposal and processing	
			-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%
Farm structure										
Dairy cows	No.	97	97	93	97	97	89	97	97	93
Youngstock	No.	57	57	55	57	57	52	57	57	55
Total farmland	ha	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.7
PRG	% total farmland	-	-	-	-	-	-	-	-	-
GC_{rw}[1]	% total farmland	17	17	16	17	17	15	17	17	16
GC_w[1]	% total farmland	50	50	52	50	50	54	50	50	52
Maize land	% total farmland	33	33	32	33	33	32	33	33	32
N_{min} application PRG	Kg of N ha^{-1} yr^{-1}	-	-	-	-	-	-	-	-	-
N_{min} application GC_{rw}[1]		85	85	85	85	85	85	85	85	85
N_{min} application GC_w[1]		85	85	85	85	85	85	85	85	85
Farm intensity	Kg of milk ha^{-1} yr^{-1}	16,284	16,284	15,737	16,284	16,284	15,008	16,284	16,284	15,737
On-farm production of protein	% of total protein input	62.1	62.1	64.4	62.1	62.1	64.4	62.1	62.1	64.4
Diet dairy cows: summer	Kg of DM cow^{-1} day^{-1}									
Grass		9.1	9.1	10	9.1	9.1	10	9.1	9.1	10
Grass silage		0	0	0	0	0	0	0	0	0
Maize silage		6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Concentrates total		5.9	5.9	5.1	5.9	5.9	5.1	5.9	5.9	5.1
Standard protein		4.8	4.8	4.0	4.8	4.8	4.0	4.8	4.8	4.0
Medium protein		0	0	0	0	0	0	0	0	0
High protein		1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Diet restricted by[2]		E,T	E,T	G,E,T	E,T	E,T	G,E,T	E,T	E,T	E,T
Diet dairy cows: winter	Kg of DM cow^{-1} day^{-1}									
Grass silage		4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
Maize silage		6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Concentrates total		6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Standard protein		4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
Medium protein		0	0	0	0	0	0	0	0	0
High protein		1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Diet restricted by[2]		E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T	E,R,T
External inputs										
Purchased maize silage	t of DM yr^{-1}	0	0	0	0	0	0	0	0	0
Purchased concentrates	t of DM yr^{-1}	232	232	211	232	232	200	233	232	210
Purchased mineral N fertilizer	Kg yr^{-1}	244	244	273	482	244	300	244	244	273
Purchased mineral P_2O_5 fertilizer	Kg yr^{-1}	701	701	624	464	701	385	701	701	624
Hired labour	h yr^{-1}	338	338	263	338	338	145	338	338	263
Manure management										
Manure application restricted by[3]		aN	aN	aN	aN	aN	aN	aN	aN	aN
Total excretion	Kg of nitrogen yr^{-1}	14,465	14,465	14,129	14,465	14,467	13,474	14,465	14,465	14,129
Total excretion	Kg of phosphate yr^{-1}	4,657	4,657	4,493	4,657	4,657	4,285	4,657	4,657	4,493
Applied on own land	Kg of phosphate yr^{-1}	4,217	4,217	4,099	3,980	4,217	3,870	4,217	4,217	4,099
Extra phosphate quota	Kg of phosphate yr^{-1}	0	0	0	0	0	0	0	0	0
Farm income[4]	€ yr^{-1}	7,188	22,612	-7,005	7,284	7,132	-73,819	91,009	11,290	3,380
Total greenhouse gas emissions	Kg CO_2-eq t^{-1} of FPCM[5]	759	758	753	760	758	734	771	758	753
N surplus	Kg ha^{-1} yr^{-1}	113	113	112	117	113	117	113	113	112
P_2O_5 surplus	Kg ha^{-1} yr^{-1}	4.3	4.3	2.1	0	4.3	1.3	4.3	4.3	2.0

[1] PRG = perennial ryegrass, GC_w = perennial ryegrass-white clover, GC_{rw} = perennial ryegrass-red white clover
[2] Diet can be restricted by: E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = intestinal digestible protein, I = intake capacity
[3] Manure application can be restricted by: tN = total mineral N; aN = N from organic manure; P = total P_2O_5
[4] The net farm income would be approximately € 20.000 yr^{-1} higher because of owner equity (Klootwijk et al., 2016)
[5] Fat- and protein-corrected milk (FPCM) was calculated using the equation: 1 kg FPCM = (0.337 + 0.116 × fat% + 0.06 × protein%) × 1 kg milk (International Dairy Federation, 2010)

References

Aarts, H.F.M., Bussink, D.W., Hoving, I.E., van der Meer, H.G., Schils, R.L.M., Velthof, G. L., 2002. Mileutechnische en landbouwkundige effecten van graslandvernieuwing. Een verkenning aan de hand van praktijksituaties. Rapport 41A.

Abrahamse, P.A., Tamminga, S., Dijkstra, J., 2009. Effect of daily movement of dairy cattle to fresh grass in morning or afternoon on intake, grazing behaviour, rumen fermentation and milk production. J. Agric. Sci. 147, 721–730. https://doi.org/10.1017/S0021859609990153.

Agrimatie, 2022. Areaal cultuurgrond op melkveebedrijven toegenomen in 2021 [WWW Document]. URL. https://www.agrimatie.nl (accessed 7.18.22).

Anonymous, 2018. Kwantitatieve Informatie Veehouderij 2018–2019. Wageningen UR Livestock Research, Wageningen.

Bannink, A., Kogut, J., Dijkstra, J., France, J., Kebreab, E., Van Vuuren, A.M., Tamminga, S., 2006. Estimation of the stoichiometry of volatile fatty acid production in the rumen of lactating cows. J. Theor. Biol. 238, 36–51. https://doi.org/10.1016/j.jtbi.2005.05.026.

Berentsen, P.B.M., Giesen, G.W.J., 1995. An Environmental-Economic Model at Farm Level to Analyse Institutional and Technical Change in Dairy Farming. Ekevier Science Limited.
Berkelaar, M., 2020. Package "lpSolve" Interface to "Lp_solve" v. 5.5 to Solve Linear/Integer Programs.
Beye, H., Taube, F., Lange, K., Hasler, M., Kluß, C., Loges, R., Diekötter, T., 2022. Species-enriched grass–clover mixtures can promote bumblebee abundance compared with intensively managed conventional pastures. Agronomy 12 (5). https://doi.org/10.3390/agronomy12051080.
Blanken, K., de Buisonje, F., Evers, A., Ouweltjes, W., Verkaik, J., Vermeij, I., Wemmenhove, H., 2020. Kwantitatieve Informatie Veehouderij 2020–2021.
CBS, 2015. CBS StatLine [WWW Document]. URL. https://opendata.cbs.nl/statline/#/CBS/en/ (accessed 7.5.15).
Commissie Bemesting Grasland en Voedergewassen, 2022. Adviesbasis bemesting grasland en voedergewassen.
Commissie Deskundigen Meststoffenwet, 2020. Milieueffecten bij geen derogatie van de Nitraatrichtlijn.
CRV, 2022. International Dutch cattle improvement co-operative. Bedrijven en koeien in cijfers - Nederland 2021 [WWW Document]. URL. https://www.cooperatie-crv.nl/downloads/stamboek/bedrijven-en-koeien-in-cijfers/ (accessed 7.18.22).
CVB, 2018. CVB Feed Table 2018.
de Haas, B.R., Hoekstra, N.J., van der Schoot, J.R., Visser, E.J.W., de Kroon, H., van Eekeren, N., 2019. Combining agro-ecological functions in grass-clover mixtures. AIMS Agriculture Food 4, 547–567. https://doi.org/10.3934/agrfood.2019.3.547.
De Mol, R.M., Hilhorst, M.A., 2003. Methaan-, lachgas- en ammoniakemissies bij productie, opslag en transport van mest. Emissions of methane, nitrous oxide and ammonia occuring during production, storage and transport of manure. Report 2003–03. Institute of Agricultural and Environmental Engineering, Wageningen, the Netherlands, pp. 1–252.
de Wit, J., van Dongen, M., van Eekeren, N., Heeres, E., 2004. Handboek grasklaver.
Dewhurst, R.J., Evans, R.T., Scollan, N.D., Moorby, R.M., Merry, R.J., Wilkins, R.J., 2003. Comparison of grass and legume silages for milk production. 2. In vivo and in sacco evaluation of rumen function. J. Dairy Sci. 86, 2612–2621.
Dijkstra, J., Neal, H.D.S.C., Beever, D.E., France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: Model description. J. Nutr. 122, 2239–2256.
Eco-invent, 2007. Ecoinvent Data v2.0 Final Reports Ecoinvent 2007.
Enriquez-Hidalgo, D., Gilliland, T., Deighton, M.H., O'Donovan, M., Hennessy, D., 2014. Milk production and enteric methane emissions by dairy cows grazing fertilized perennial ryegrass pasture with or without inclusion of white clover. J. Dairy Sci. 97, 1400–1412. https://doi.org/10.3168/jds.2013-7034.
Eriksen, J., Askegaard, M., Søegaard, K., 2008. Residual effect and nitrate leaching in grass-arable rotations: Effect of grassland proportion, sward type and fertilizer history. Soil Use Manag. 24, 373–382. https://doi.org/10.1111/j.1475-2743.2008.00178.x.
Eriksen, J., Askegaard, M., Søegaard, K., 2014. Complementary effects of red clover inclusion in ryegrass-white clover swards for grazing and cutting. Grass Forage Sci. 69, 241–250. https://doi.org/10.1111/gfs.12025.
EU. (1991). *Council Directive concerning the protection of waters against pollution caused by nitrates from agricultural sources. In Official Journal of the European Communities. Document 91/676/ EEC*.
European Commission, 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system COM/2020/381 final.
Feedprint, 2015. FeedPrint: calculate CO2 per kilogram meat, milk or eggs [WWW Document]. URL. http://www.wageningenur.nl/en/show/Feedprint.htm (accessed 12.9.15).
Feedprint, 2023. FeedPrint: calculate CO2 per kilogram meat, milk or eggs [WWW Document]. URL. http://www.wageningenur.nl/en/show/Feedprint.htm (accessed 3.2.23).
Finneran, E., Crosson, P., O'Kiely, P., Shalloo, L., Forristal, P.D., Wallace, M.T., 2010. Simulation Modelling of the cost of producing and utilising feeds for ruminants on Irish farms.
Fraters, B., Boumans, L.J.M., van Leeuwen, T.C., Reijs, J.W., 2012. De uitspoeling van het stikstofoverschot naar grond- en oppervlaktewater op landbouwbedrijven.
Garnett, T., Godde, C., Muller, A., Röös, E., Smith, P., De Boer, I., Zu Ermgassen, E., Herrero, M., Van Middelaar, C., Schader, C., Van Zanten, H., 2017. Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question – and what it all means for greenhouse gas emissions.
Groen, A.E., 1988. Derivation of economic values in cattle breeding: a model at farm level. Agric. Syst. 27, 195–213.
Groen, E.A., Van Zanten, H.H.E., Heijungs, R., Bokkers, E.A.M., De Boer, I.J.M., 2016. Sensitivity analysis of greenhouse gas emissions from a pork production chain. J. Clean. Prod. 129, 202–211. https://doi.org/10.1016/j.jclepro.2016.04.081.
Herron, J., Hennessy, D., Curran, T.P., Moloney, A., O'Brien, D., 2021. The simulated environmental impact of incorporating white clover into pasture-based dairy production systems. J. Dairy Sci. 104, 7902–7918. https://doi.org/10.3168/jds.2020-19077.
Hoekstra, N.J., De Deyn, G.B., Xu, Y., Prinsen, R., Van Eekeren, N., 2018. Red clover varieties of Mattenklee type have higher production, protein yield and persistence than Ackerklee types in grass–clover mixtures. Grass Forage Sci. 73, 297–308. https://doi.org/10.1111/gfs.12307.
International Dairy Federation, 2010. A common carbon footprint approach for the dairy sector: the IDF guide to standard life cycle assessment methodology.
IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. In: Volume 4: Agriculture, Forestry and Other Land Use. Kanagawa, Japan.
IPCC, 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use Task Force on National Greenhouse Gas Inventories.
IPCC, 2022. Mitigation of Climate Change Climate Change 2022 Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
Jarrige, R., 1988. Alimentation des bovins, ovins et caprins. Feeding of cattle, sheep and goats.
Johnston, A.E., Poulton, P.R., Coleman, K., Macdonald, A.J., White, R.P., 2017. Changes in soil organic matter over 70 years in continuous arable and ley–arable rotations on a sandy loam soil in England. Eur. J. Soil Sci. 68, 305–316. https://doi.org/10.1111/ejss.12415.
Kanter, D.R., Wagner-Riddle, C., Groffman, P.M., Davidson, G.E., Galloway, J.N., Gourevitch, J.D., van Grinsven, H.J.M., Houlton, B.Z., Keeler, B.L., Ogle, S.M., Pearen, H., Rennert, K.J., Saifuddin, M., Sobota, D.J., Wagner, G., 2021. Improving the social cost of nitrous oxide. Nat. Clim. Chang. 11, 1006–1008. https://doi.org/10.1038/s41558-021-01221-4.
Kayser, M., Seidel, K., Müller, J., Isselstein, J., 2008. The effect of succeeding crop and level of N fertilization on N leaching after break-up of grassland. Eur. J. Agron. 29, 200–207. https://doi.org/10.1016/j.eja.2008.06.002.
Kennedy, E., McEvoy, M., Murphy, J.P., O'Donovan, M., 2009. Effect of restricted access time to pasture on dairy cow milk production, grazing behavior, and dry matter intake. J. Dairy Sci. 92, 168–176. https://doi.org/10.3168/jds.2008-1091.
Kleine, J., Ruiter, S., van Velde, A., Zonderland, H., Bolscher, K., Oerlemans, N., van der Weijden, W., Hendrix, L., van Dijk, J., Loman, T., 2018. Grond gebondenheid als basis voor een toekomstbestendige melkveehouderij als basis voor een toekomstbestendige melkveehouderij.
Klootwijk, C.W., Van Middelaar, C.E., Berentsen, P.B.M., de Boer, I.J.M., 2016. Dutch dairy farms after milk quota abolition: Economic and environmental consequences of a new manure policy. J. Dairy Sci. 99, 8384–8396. https://doi.org/10.3168/jds.2015-10781.
Konis, K., Schwendinger, F., 2020. lpSolveAPI: R Interface to "lp_solve" Version 5.5.2.0.
Kunrath, T.R., de Berranger, C., Charrier, X., Gastal, F., de Faccio Carvalho, P.C., Lemaire, G., Emile, J.C., Durand, J.L., 2015. How much do sod-based rotations reduce nitrate leaching in a cereal cropping system? Agric. Water Manag. 150, 46–56. https://doi.org/10.1016/j.agwat.2014.11.015.
Ledgard, S.F., Steele, K.W., 1992. Biological nitrogen fixation in mixed legume/grass pastures. Plant Soil 141, 137–153.
Lemaire, G., Gastal, F., Franzluebbers, A., Chabbi, A., 2015. Grassland–cropping rotations: an avenue for agricultural diversification to reconcile high production with environmental quality. Environ. Manag. 56, 1065–1077. https://doi.org/10.1007/s00267-015-0561-6.
Lesschen, J.P., Sanders, J., 2023. Options to improve the nitrogen use efficiency in the Dutch agriculture sector. Wageningen.
Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M., Peyraud, J.L., 2014. Potential of legume-based grassland-livestock systems in Europe: a review. Grass Forage Sci. https://doi.org/10.1111/gfs.12124.
Martin, G., Durand, J., Duru, M., Gastal, F., Julier, B., Litrico, I., Louarn, G., Médiène, S., Moreau, D., Valentin-morison, M., Novak, S., Parnaudeau, V., Paschalidou, F., Vertès, F., Voisin, A., Cellier, P., Jeuffroy, M., Martin, G., 2020. Role of ley pastures in tomorrow ' s cropping systems. A review. Agron. Sustain. Dev. 40, 1–25. https://doi.org/10.1007/s13593-020-00620-9.
Mills, J.A.N., Dijkstra, J., Bannink, A., Cammell, S.B., Kebreab, E., France, J., 2001. A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation, and application. J. Anim. Sci. 79, 1584–1597.
Ministerie van Landbouw Natuur en Voedselkwaliteit, 2022. Regeling van de Minister van Landbouw, Natuur en Voedselkwaliteit van 11 november 2022, nr. WJZ/22482839, houdende wijziging van de Uitvoeringsregeling Meststoffenwet in verband met de uitvoering voor het jaar 2022 van de derogatiebeschikking 2022–2025.
Ministry of Agriculture Nature and Food Quality, 2018. Agriculture, nature and food: valuable and connected. In: The Netherlands as a Leader in Circular Agriculture.
Ministry of Agriculture Nature and Food Quality, Ministry of Infrastructure and Water Management, 2021. 7e Nederlandse actieprogramma betreffende de Nitraatrichtlijn (2022-2025).
Nevedi, 2012. De Nederlandse Vereniging Diervoederindustrie. The Dutch Feed Industry Association. Lineaire programmeringen rundvee-, varkens en pluimveevoerders. Linear programming cattle-, pig, and poultry feed.
Nevedi, 2013. De Nederlandse Vereniging Diervoederindustrie. The Dutch Feed Industry Association. Lineaire programmeringen rundvee-, varkens en pluimveevoerders. Linear Programming cattle-, pig, and poultry feed.
Nevedi, 2014. De Nederlandse Vereniging Diervoederindustrie. The Dutch Feed Industry Association. Lineaire programmeringen rundvee-, varkens en pluimveevoerders. Linear programming cattle-, pig, and poultry feed.
Nevedi, 2015. De Nederlandse Vereniging Diervoederindustrie. The Dutch Feed Industry Association. Lineaire programmeringen rundvee-, varkens en pluimveevoerders. Linear programming cattle-, pig, and poultry feed.
Oenema, O., Kros, H., De Vries, W., 2003. Approaches and uncertainties in nutrient budgets: Implications for nutrient management and environmental policies. Eur. J. Agron. 20, 3–16. https://doi.org/10.1016/S1161-0301(03)00067-4.
Reheul, D., Cougnon, M., Kayser, M., Pannecoucque, J., Swanckaert, J., De Cauwer, B., van den Pol-van Dasselaar, A., De Vliegher, A., 2017. Sustainable intensification in

the production of grass and forage crops in the Low Countries of north-west Europe. Grass Forage Sci. 72, 369–381. https://doi.org/10.1111/gfs.12285.
Remmelink, G., van Middelkoop, J., Ouweltjes, W., Wemmenhove, H., 2020. Handboek melkveehouderij 2020/21. https://doi.org/10.18174/529557.
Rochon, J.J., Doyle, C.J., Greef, J.M., Hopkins, A., Molle, G., Sitzia, M., Scholefield, D., Smith, C.J., 2004. Grazing legumes in Europe: A review of their status, management, benefits, research needs and future prospects. Grass Forage Sci. https://doi.org/10.1111/j.1365-2494.2004.00423.x.
Rodríguez-Ortega, T., Oteros-Rozas, E., Ripoll-Bosch, R., Tichit, M., Martín-López, B., Bernués, A., 2014. Applying the ecosystem services framework to pasture-based livestock farming systems in Europe. Animal 8, 1361–1372. https://doi.org/10.1017/S1751731114000421.
Ros, G.H., De Vries, W., Jongeneel, R., Van Ittersum, M., 2023. Gebieds-en bedrijfsgerichte handelingsperspectieven voor een duurzame landbouw in Nederland.
Rotz, C.A., Taube, F., Russelle, M.P., Oenema, J., Sanderson, M.A., Wachendorf, M., 2005. Whole-farm perspectives of nutrient flows in grassland agriculture. Crop Sci. 45, 2139–2159. https://doi.org/10.2135/cropsci2004.0523.
RVO, 2020. Mestverwerkingsplicht veehouder [WWW Document]. URL. https://www.rvo.nl/onderwerpen/mest/mvp-veehouder (accessed 7.26.22).
RVO, 2022a. Derogatie in 2022 en daarna [WWW Document]. URL. https://www.rvo.nl/onderwerpen/mest/derogatie (accessed 9.15.22).
RVO, 2022b. Blijvend grasland 2022 [WWW Document]. URL. https://www.rvo.nl/onderwerpen/vergroeningsbetaling-2022/blijvend-grasland-2022 (accessed 1.16.23).
RVO, 2022c. Het nieuwe GLB: de eco-regeling [WWW Document]. URL. https://www.rvo.nl/subsidies-financiering/eco-regeling (accessed 9.12.22).
RVO, 2023. Subsidie Behoud grasland bij afbouw derogatie [WWW Document]. URL. https://www.rvo.nl/subsidies-financiering/behoud-grasland (accessed 6.16.23).
Sampat, A.M., Hicks, A., Ruiz-Mercado, G.J., Zavala, V.M., 2021. Valuing economic impact reductions of nutrient pollution from livestock waste. Resour. Conserv. Recycl. 164 https://doi.org/10.1016/j.resconrec.2020.105199.
Schreefel, L., van Zanten, H.H.E., Groot, J.C.J., Timler, C.J., Zwetsloot, M.J., Schrijver, A. P., Creamer, R.E., Schulte, R.P.O., de Boer, I.J.M., 2022. Tailor-made solutions for regenerative agriculture in the Netherlands. Agric. Syst. 203 https://doi.org/10.1016/j.agsy.2022.103518.
Sebek, L.B., Mosquera, J., Bannink, A., 2016. Rekenregels voor de enterische methaan-emissie op het melkveebedrijf en reductie van de methaan-emissie via mesthandling, het handelings-perspectief van het voerspoor inzichtelijk maken met de Kringloopwijzer. https://doi.org/10.18174/391726.
Splinter, M.A.B.S., Peerlings, J.H.M., 2023. Examining the trade-offs between agri-environmental and manure policies in Dutch dairy farming. NJAS Impact Agricult. Life Sci. 95 https://doi.org/10.1080/27685241.2023.2194261.
Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0.
Suter, M., Connolly, J., Finn, J.A., Loges, R., Kirwan, L., Sebastià, M.T., Lüscher, A., 2015. Nitrogen yield advantage from grass-legume mixtures is robust over a wide range of legume proportions and environmental conditions. Glob. Chang. Biol. 21, 2424–2438. https://doi.org/10.1111/gcb.12880.
Tamminga, S., Van Straalen, W.M., Subnel, C., Meijer, R.G.M., Steg, A., Wever, C.J.G., Blok, M.C., 1994. The Dutch protein evaluation system: the DVE/OEB-system. Livest. Prod. Sci. 40, 139–155. https://doi.org/10.1016/0301-6226(94)90043-4.
Taube, F., Gierus, M., Hermann, A., Loges, R., Schönbach, P., 2014. Grassland and globalization - challenges for north-west European grass and forage research. Grass Forage Sci. 69, 2–16. https://doi.org/10.1111/gfs.12043.
Taweel, H.Z., Tas, B.M., Dijkstra, J., Tamminga, S., 2004. Intake regulation and grazing behavior of dairy cows under continuous stocking. J. Dairy Sci. 87, 3417–3427. https://doi.org/10.3168/jds.S0022-0302(04)73477-3.
The Rockefeller Foundation, 2021. The True Cost of Food in the United States Technical Appendix.
Thers, H., Jensen, J.L., Rasmussen, J., Eriksen, J., 2022. Grass-clover response to cattle slurry N-rates: Yield, clover proportion, protein concentration and estimated N2-fixation. Field Crop Res. 287 https://doi.org/10.1016/j.fcr.2022.108675.
Thomassen, M.A., Dolman, M.A., van Calker, K.J., de Boer, I.J.M., 2009. Relating life cycle assessment indicators to gross value added for Dutch dairy farms. Ecol. Econ. 68, 2278–2284. https://doi.org/10.1016/j.ecolecon.2009.02.011.
van Boxmeer, E., Modernel, P., Viets, T., 2021. Environmental and economic performance of Dutch dairy farms on peat soil. Agricultural Systems 193. https://doi.org/10.1016/j.agsy.2021.103243.
Van Bruggen, C., Bannink, A., Groenestein, C.M., Huijsmans, J.F.M., Lagerwerf, L.A., Luesink, H.H., Ros, M.B.H., Velthof, G.L., Vonk, J., Van Der Zee, T., 2021. Emissies naar lucht uit de landbouw berekend met NEMA voor 1990-2019.
van Dijk, W., de Boer, J., de Haan, M.H.A., Mostert, P., Oenema, J., Verloop, J., 2020. Rekenregels van de KringloopWijzer 2021 : achtergronden van BEX, BEA, BEN, BEP en BEC: actualisatie van de 2020-versie. https://doi.org/10.18174/557803.
Van Grinsven, H.J.M., Holland, M., Jacobsen, B.H., Klimont, Z., Sutton, M.A., Jaap Willems, W., 2013. Costs and benefits of nitrogen for europe and implications for mitigation. Environ. Sci. Technol. 47, 3571–3579. https://doi.org/10.1021/es303804g.
van Leeuwen, M.M.W.J., van Middelaar, C.E., Oenema, J., van Dam, J.C., Stoorvogel, J. J., Stoof, C.R., de Boer, I.J.M., 2019. The relevance of spatial scales in nutrient balances on dairy farms. Agric. Ecosyst. Environ. 269, 125–139. https://doi.org/10.1016/j.agee.2018.09.026.
van Middelaar, C.E., Berentsen, P.B.M., Dijkstra, J., van Arendonk, J.A.M., de Boer, I.J. M., 2014a. Methods to determine the relative value of genetic traits in dairy cows to reduce greenhouse gas emissions along the chain. J. Dairy Sci. 97, 5191–5205. https://doi.org/10.3168/jds.2013-7413.
Van Middelaar, C.E., Dijkstra, J., Berentsen, P.B.M., De Boer, I.J.M., 2014b. Cost-effectiveness of feeding strategies to reduce greenhouse gas emissions from dairy farming. J. Dairy Sci. 97, 2427–2439. https://doi.org/10.3168/jds.2013-7648.
van Paassen, M., Braconi, N., Kuling, L., Durlinger, B., Gual, P., 2019. Agri-footprint 5.0 Part 1: Methodology and basic principles.
Vellinga, T.V., Van Der Putten, A.H.J., Mooij, M., 2001. Grassland management and nitrate leaching, a model approach. NJAS 49, 229–253. https://doi.org/10.1016/S1573-5214(01)80009-9.
Vellinga, T.V., Van Den Pol-Van Dasselaar, A., Kuikman, P.J., 2004. The impact of grassland ploughing on CO 2 and N 2 O emissions in the Netherlands.
Vellinga, T.V., Blonk, H., Marinussen, M., Van Zeist, W.J., De Boer, I.J.M., Starmans, D., 2013. Methodology used in FeedPrint: a tool quantifying greenhouse gas emissions of feed production and utilization.
Velthof, G.L., van Bruggen, C., Groenestein, C.M., de Haan, B.J., Hoogeveen, M.W., Huijsmans, J.F.M., 2012. A model for inventory of ammonia emissions from agriculture in the Netherlands. Atmos. Environ. 46, 248–255. https://doi.org/10.1016/j.atmosenv.2011.09.075.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.