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Research Paper

Environmental and economic performance of Dutch dairy farms on peat soil

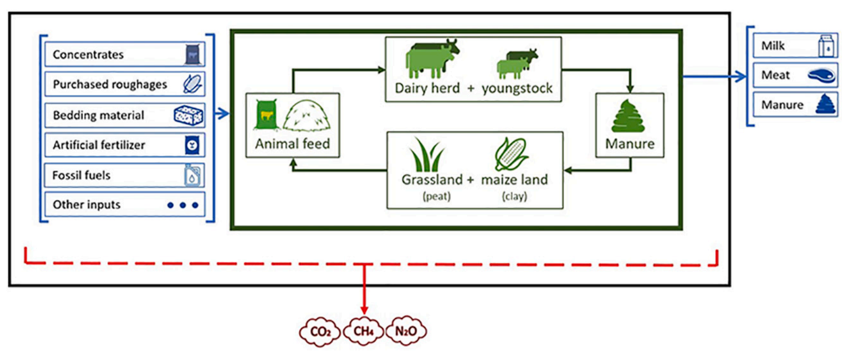
Emma van Boxmeer *, Pablo Modernel, Theo Viets

Animal Production Systems, Wageningen University & Research, De Elst 1, 6706 WD Wageningen, the Netherlands

HIGHLIGHTS

- Peat soils are mainly too wet for arable crop production, however, drainage of the soil causes peat to oxidize and emit CO_2 and N_2O.
- The objective of this study was to evaluate global warming potential and economic performance of Dutch dairy farms on peat compared to sandy soil.
- Dairy farms on peat soil have lower labour income and considerably higher global warming potential compared to sandy soil.
- Higher groundwater table on peat soil decreased greenhouse gas emissions and feeding cattle only grass and by-products increased labour income.
- Improvement of global warming potential of dairy farms on peat soil is possible and can lead to increased labour income.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Global demand for milk is increasing, however, the dairy sector has considerable environmental impact and cattle are large contributors to greenhouse gas (GHG) emissions that lead to global warming. In a circular food system, the role of animals should be to convert biomass that humans cannot or do not want to eat into nutrient-dense products. In this system, dairy cows are only fed with grass from marginal lands and by-products from harvesting and food industries. One example of marginal land are peat areas, since these soils are mainly too wet for arable crop production. However, drainage caused peat to oxidize and emit CO_2 and N_2O.
OBJECTIVE: The objective of this study was to evaluate global warming potential (GWP) and economic performance of Dutch dairy farms on peat compared to sandy soil. Also, two scenarios that might reduce GHG emissions of a dairy farm on peat soil were considered: 1) increased groundwater tables and 2) an adjusted dairy cow diet consisting of grass and by-products only.
METHODS: A whole-farm linear programming (LP) model used for dairy farms on sandy soil was updated and adjusted to simulate structure, management and labour income of a dairy farm on peat soil. The basic LP model is a static year model that includes all relevant activities and constraints that are common to a Dutch dairy farm and the solution generates feeding management, manure application and land use. The objective function maximized labour income. In addition, the linear model was combined with a Life-Cycle Assessment to determine the GWP of the produced milk, economically allocated between milk and meat.

* Corresponding author.
E-mail address: emma.vanboxmeer@hotmail.com (E. van Boxmeer).

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RESULTS AND DISCUSSION: The results of this study showed that dairy farms on peat soil have lower labour income and considerably higher GWP compared to dairy farms on sandy soil. When the groundwater table on peat soil was increased, labour income decreased even more, however GHG emissions were somewhat reduced. Feeding a dairy cow diet with only grass and by-products resulted in higher labour income, but equal GWP compared to a regular dairy farm on peat soil. A sensitivity analysis was performed to explore the effect of grass yield on the economic and environmental performance of dairy farms on peat soil.

SIGNIFICANCE: Dairy farms on peat soils have lower labour income and considerably higher GWP compared to sandy soils. Improvement of GWP is possible and can lead to increased labour income.

1. Introduction

Currently, 5% of the average global daily energy intake consist of milk (FAO, 2020). Due to growing human population, wealth and urbanisation, the demand for milk is increasing and is expected to continue increasing in the future (Alexandratos and Bruinsma, 2012). However, expansion of livestock production has been a main driver of the land use change from forest and native grasslands into agriculture, leading to biodiversity losses and carbon emissions (Steinfeld et al., 2006). The global livestock sector emits about 7.1 gigatons of CO_2 equivalents of which 65% is emitted by cattle, equally divided between beef and dairy cattle (Gerber et al., 2013). Therefore, dairy cattle are large contributors to greenhouse gas (GHG) emissions that lead to global warming. Furthermore, 40% of the global arable land is currently used for feed production, although it is more efficient to use that land directly for food production (Foley et al., 2011). Moreover, 13% of the livestock diets consists of human-edible products (Mottet et al., 2017). Therefore, Van Zanten et al. (2014) suggested that the role of animals in the food system should be to convert biomass that humans cannot or do not want to eat into nutrient-dense products like meat, milk and manure. In this circular food system, arable land is used for food production, while dairy cows are fed with grass from marginal lands and by-products from harvesting and food industries.

An example of such marginal lands are peat areas, where partly decomposed organic matter accumulates due to high groundwater tables and related absence of oxygen. These areas cover over 400 million hectares in about 180 countries worldwide and contain 30% of all global soil carbon (Parish et al., 2008). In their natural state, peatlands only have marginal agricultural capability due to the high groundwater table, low bulk density and carrying capacity and low availability of nutrients (Parish et al., 2008; Rieley and Page, 1997). Therefore, farmers have drained these soils to increase the carrying capacity and the nutrient availability through the mineralisation of peat. However, this process also leads to subsidence, which can vary from 3 to 22 mm per year, and emissions of CO_2 and N_2O from the soil (Van den Akker et al., 2008; Schils et al., 2008), especially in summer (Hendriks et al., 2007).

Klootwijk et al. (2016) and Van Calker et al. (2004) used a linear programming (LP) model to calculate economic and environmental sustainability of dairy farms on sandy soil. They both showed that, despite different policies and management strategies, labour income was positive. However, little is known about labour income of dairy farms on peat soil and only a few studies looked at the GHG emissions of farms on peat soil. Some studies investigated CO_2 exchange on drained peat soils, which did not include emissions of other greenhouse gasses (Campbell et al., 2015; Nieveen et al., 2005; Veenendaal et al., 2007). Krimly et al. (2016) calculated the global warming potential (GWP) per hectare of large, small and mixed dairy farms in the South of Germany and confirmed that the GHG emissions from a dairy farm on peat soil are much higher than that of comparable farms without peatland. Additionally, results from a study in Norway showed that the milk carbon footprint of non-organic dairy farms with partial peat soil was higher compared to dairy farms with no peat soil (Schueler et al., 2018).

Highest mineralisation rates on peat soil were observed with groundwater tables of 80–90 cm below soil surface (Joosten and Clarke, 2002) and currently, farmers target groundwater tables of 50–60 cm below soil surface (Querner et al., 2012). The groundwater tables can be raised to a maximum of 35 cm below soil surface and still be suitable for agriculture (Jansen et al., 2009; Rienks et al., 2002). Furthermore, subsurface drains can be used to reduce fluctuations in the groundwater table and thereby prevent subsidence. In summer, subsurface drains prevent falling water levels, while in winter they drain to prevent swampy fields. Besides, to fit into the circular food systems, dairy cow diets should change from maize, concentrates and grass to exclusively grass and by-products from food production (Van Zanten et al., 2018).

The objective of this study was to evaluate the differences in GWP and economic performance of Dutch dairy farms on sandy and peat soil. A whole-farm approach was used, since a dairy farm is a complex system with several interacting subsystems (Schils et al., 2007). The LP model used by Klootwijk et al. (2016) was updated and adjusted to simulate structure, management and labour income. In addition, the LP model was combined with a Life-Cycle Assessment (LCA) to determine the GWP of the produced milk. Furthermore, it was analysed whether increasing the groundwater tables and feeding a cattle diet consisting of only grass and by-products will reduce the GWP of dairy farms on peat soil, while still being economically feasible for the farmers.

2. Materials and methods

The dairy farm LP model used in this study was first described by Berentsen and Giesen (1995) and updated by Van Middelaar et al. (2014). Recently, Klootwijk et al. (2016) again updated the model and included stipulations of the Dairy Act. The Dairy Act is a recent Dutch manure policy to limit phosphate production. Each farm is assigned a farm-specific phosphate production quota based on the average number of cows on the farm in July 2015 and standard extraction factors. Increased phosphate surplus on top of the reference surplus needs to be processed (e.g. destruction, treatment or export). The current study updated prices and costs and adjusted the LP model to simulate a Dutch dairy farm on peat soil in 2018.

2.1. Dairy farm model

The basic LP model is a static year model that includes all relevant activities and constraints that are common to a Dutch dairy farm. Activities include on-farm feed production, purchase of maize, concentrates and artificial fertilizer, manure management, field operations and animal production. Constraints were fixed resources such as land area, labour availability, barn capacity, environmental policies and links between these activities. Given these activities and constraints, the solution generates feeding management, manure application and land use. The objective function maximizes labour income, which is the remuneration for labour and management provided by the farmer that remains from the gross returns after all fixed and variable costs have been paid.

The model distinguishes two periods regarding feeding: a summer and winter period of both 182.5 days. Dietary options include grass from grazing (only in summer), grass and maize silage and three types of concentrates (standard, medium and high protein content). Feed characteristics of these dietary options are shown in Appendix Table A1. Grassland yield depends on the level of nitrogen (N_{min}) fertilization, which can vary from 100 to 275 kg N/ha/year. Purchased maize should be ensilaged by the farmer. We assumed that all cows on the farms belonged to the Holstein Friesian breed and that all calves were be born on the 1st of February. Some female youngstock were kept to yearly replace 30% of the dairy herd, while male and surplus female calves were sold at an age of two weeks. The cows were housed in a cubicle system with slatted floors and manure storage under the slats. Farm-specific nitrogen and phosphate excretion was based on inputs and outputs at herd level, represented by the average cow with youngstock.

Furthermore, some links between activities were included in the model as constraints. Animal requirements for energy and protein had to match with on-farm feed production and purchased feed. Moreover, the need for nutrients by grassland had to match with the available nutrients from manure and artificial fertilizer. Environmental policies included limited application of nitrogen and phosphate.

2.2. Environmental impact

Climate change is a global problem and GHG emissions need to be evaluated at chain level (FAO, 2016; Pelletier et al., 2010; Van Middelaar et al., 2013). Therefore, an LCA was used, including extraction of raw materials, production of farm inputs, distribution of these productions and all processes on the dairy farm (Van Middelaar et al., 2013). Land use change was not included (Klootwijk et al., 2016) and processes after the farm gate (e.g. milk processing) were not analysed, since these were assumed to be unaffected by soil type and the highest share of emissions come from the primary production (Opio et al., 2013). The three major GHGs related to agricultural production were considered: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), of which emissions were evaluated from cradle to farm gate. GHGs were summed based on their GWP; 1 for CO_2, 28 for biogenic CH_4, 30 for fossil CH_4 and 265 for N_2O (IPCC, 2013). GWP was expressed in kg CO_2- equivalent per tonne of fat- and protein corrected milk (FPCM) and economically allocated between milk and meat.

Calculations of emissions have been described in detail by Klootwijk et al. (2016) and Van Middelaar et al. (2013). Emissions related to the production of synthetic fertilizer, tap water and pesticides and the production and combustion of energy sources were based on Weidema et al. (2013). Enteric CH_4 emission from dairy cows were based on empirical relations between dry matter intake of feed ingredients and CH_4 emission factors per ingredient (Klootwijk et al., 2016). For youngstock, enteric CH_4 emissions were based on Intergovernmental Panel on Climate Change (IPCC) Tier 2 methods and default values (IPCC, 2006). Calculation of emissions from manure management and fertilizer application were derived from national reports (e.g. De Mol and Hilhorst, 2003).

2.3. Analyses set-up

2.3.1. Dairy farm on sandy and peat soil

The basic scenario for the model was an average Dutch dairy farm on sandy or peat soil. Input data are based on national statistics (CBS, 2018; CRV, 2018; KWIN-V, 2018; Wageningen Economic Research, 2017) and are shown in Table 1. In summer, dairy cows had access to pasture for 10 h a day (Klootwijk et al., 2016). Maximum grass intake during grazing was assumed to be 10 kg DM/day for dairy cows (De Visser et al., 2001; Kennedy et al., 2009; Mattiauda et al., 2013) and 1.9–3.7 kg DM/100 kg of body weight for youngstock (Remmelink et al., 2018). Since peat soil is not suitable for growing maize, farmers produced maize on clay soil. On average 7% of the total farm land was used for maize production (Wageningen Economic Research, 2017) and from this it was assumed that 4 ha of clay soil were available for maize production and the other 52 ha were available for grass production on peat soil. It was assumed that farmers cannot or do not want to expand their farm in terms of farmland, however, expanding barn capacity was optional.

Phosphate quota calculations were based on the average number of dairy cows on a Dutch dairy farm in 2015 (CBS, 2015) and costs for buying extra phosphate quota were €41/kg P_2O_5 (KWIN-V, 2018). On sandy soil, 70% of the reference P_2O_5-surplus in 2013 was allowed to be disposed to another farm without processing, while on peat soil this was 90% (KWIN-V, 2018). Nitrogen and phosphate application standards for grassland and maize land for both soil types are shown in Table 2.

Milk price was calculated using average fat and protein content (respectively 4.37% and 3.56%), including pasture premium (KWIN-V, 2018). Costs for manure processing, purchased maize and concentrates and extra phosphate quota, labour and barn capacity were updated (Table 3). Furthermore, direct costs for maize production on clay soil are €45/ha higher compared to sandy soil (KWIN-V, 2018) and since grassland on peat soil has more ditches than on sandy soil (based on the farm description of Van den Akker et al. (2007)), more labour is required and costs for ditch management increased from €14 to €41 per hectare (KWIN-V, 2018). Also, famers in the Netherlands receive a governmental payment of €415/ha (Ministerie van Economische Zaken, 2014).

The LP model compiles diets for dairy cows and youngstock, where nutritional values of the dietary options should match nutrient requirements of the animal. For dairy cows, this was based on energy content (VEM), true protein digested in the small intestine (DVE) and rumen degradable protein balance (OEB) according to Dutch standards (Tamminga et al., 1994), fill value (VW) per kilogram DM expressed in kilograms of standard reference feed and structure value (SV). Youngstock diets in Klootwijk et al. (2016) were only based on energy content (VEM) and DVE, which resulted in unrealistic diets, where youngstock were only fed with maize and concentrates. Therefore, in this study, restrictions for OEB and fill values were added for youngstock, based on Remmelink et al. (2018).

The energy content of a feedstuff for lactating cows is expressed in VEM (“Voedereenheid melk”, in English: feed unit milk), which is based on the faecal digestibility of the feedstuff (CVB, 2018). Annual maize

Table 1
Model input data to simulate an average Dutch dairy farm on sandy and peat soils.

Item	Unit	Sandy soil	Peat soil
Farm land	ha	50[1]	56[1]
Barn capacity	No. animals	139[2]	136[2]
Labour availability	hour	3960[2]	3960[2]
Milk production*	kg/cow/year	8498[3]	8,451[1]
Phosphate quota	kg P_2O_5/year	4352[2,4]	4192[2,4]

[1] Wageningen Economic Research (2017).
[2] CBS (2018).
[3] CRV (2018).
[4] KWIN-V (2018).
* 4.37% fat and 3.56% protein.

Table 2
Application standards for grass and maize land on sandy[1] and peat soil[2].

	Sandy soil	Peat soil
N_{min}-application (kg N/ha)		
Grassland	250	265
Maize land		
With derogation*	140	160**
Without derogation	140	185**
N from animal manure (kg N/ha)		
With derogation	230	250
Without derogation	170	170
Phosphate application (kg P_2O_5/ha)		
Grassland	80	80
Maize land	50	50**

*The Netherlands is one of the EU member states that is allowed to go beyond the 170 kg N/ha limit, due to relative high proportion of grassland and long growing season **on clay soil.
[1] Klootwijk et al. (2016).
[2] Nitraatrichtlijn (2017).

Table 3
Prices and costs from 2015 to 2018.

Item	Unit	2015[1]	2018[2]
Prices			
Milk price	€/ton	355	371
Purchased maize	€/KVEM	177	141
Purchased concentrates			
High protein	€/kg	315	325
Medium protein	€/kg	250	260
Standard protein	€/kg	215	225
Costs			
Extra phosphate quota	€/kg P_2O_5/year	2.10	41
Manure processing	€/ton/year	13	18
Extra labour	€/hour	17	20
Extra barn capacity	€/cow place/year	558	646

[1] Klootwijk et al. (2016).
[2] KWIN-V (2018).

yields were on average 13,531 and 16,104 kVEM/ha/year on sandy soil and peat soil respectively. Annual grass yields were based on averages and differed per soil type and N_{min}-application level. For grass production on peat soil, it was assumed that the trend between kVEM/ha grassland and N_{min} application on the fields was the same as on sandy soil (Fig. 1). However, the starting point (in terms of kVEM/ha) was higher on peat soil, based on Remmelink et al. (2018). In contrast to sandy soil, no grassland renewal took place on peat soils, since a lot of nitrogen will be lost and grassland renewal generally has a negative effect on soil quality and carrying capacity (Schils et al., 2008).

N-deposition on peat soil is 31 kg of N/ha compared to 49 kg of N/ha on sandy soil, due to the absence of intensive animal farms (like pigs and poultry) in peat regions in the Netherlands. Due to oxidation of peat, organic matter is decomposed and nitrogen is mineralized, becoming available for grass. Annual N-mineralisation in peat soil is 180 kg N/ha (Van den Eertwegh and Van Beek, 2004), but peat oxidation also causes emission of 19 tons of CO_2 and 7.4 kg of N_20 per hectare of grassland per year (Kuikman et al., 2005). Parameters for (de)nitrification on peat soil for grassland and clay soil for maize land were based on Hendriks (1991) and Van Calker et al. (2004). Higher NO_3^- content in peat soil increased denitrification rates compared to sandy soil. A large fraction of the ammonium from mineralisation will be nitrified to NO_3^-, which increases NO_3^- content in peat soil and results in higher denitrification rates compared to sandy soil (Van Beek et al., 2007).

2.3.2. *Increased groundwater table*

In this scenario, the groundwater table was increased to 35 cm below soil surface and subsurface drains were installed on the farmland on peat soil. Costs for subsurface drains were €107/ha/year, based on construction costs (€1800/ha), 1% insurance and maintenance costs, a depreciation period of 33 years and an interest rate of 3.5% (KWIN-V, 2018; Valuta voor Veen, 2014). Higher groundwater tables decrease grassland yield with 4.4% (Holshof et al., 2011). No additional grass was assumed to be lost due to trampling on the wetter soil when cows are moved to other lots of grassland every 4–5 days or due to extra damage of agricultural vehicles (Holshof et al., 2011). Compared to groundwater tables of 60 cm below soil surface, the increased groundwater tables reduced CO_2 emissions by 35% (Hendriks et al., 2007). While increasing the groundwater table increases CH_4 emissions, this amount is negligible (Hendriks et al., 2007; Langeveld et al., 1997).

2.3.3. *Feeding only grass and by-products*

In this scenario, cows and youngstock were only fed with grass and some additional by-products, so no concentrates and maize silage were purchased. Additional land on clay soil was not required, since no maize was grown on-farm and therefore, all 56 ha of farmland were used for grass production. Available grazing time in summer was maximized to 18 h/day (whole day minus milking time) and therefore, the amount of manure in the stable reduced from 60 to 10%.

To meet the nutritional requirements of the dairy cows and their youngstock, several by-products, available in the Netherlands, were added to the model: wheat straw (from wheat grain production), potato pulp (from potato starch extraction), breadcrumb meal (from unsold bread from supermarkets and bakeries), brewers' grains (from beer brewing), sunflower meal (from oil extraction) and beet pulp (from sugar extraction). Nutritional values and prices of these by-products are shown in Appendix Table A2. Youngstock received a fixed amount of milk replacer and calf concentrates, however some additional roughage was available. By-products available for youngstock in summer were potato pulp, breadcrumb meal and brewers' grains and in winter also wheat straw was available. For dairy cows, available by-products were potato pulp, breadcrumb meal, brewers' grains, sunflower meal and beet pulp, both in summer and winter. GHG emissions from by-products were allocated to the main product and therefore GHG emissions of the production of by-products was assumed to be zero. Lastly, some labour was required to ensilage brewers' grains, potato pulp and beet pulp.

2.3.4. *Combination: Increased groundwater table and feeding only grass and by-products*

This scenario is a combination of increased groundwater tables with subsurface drains and feeding an adjusted cattle diet containing only grass and by-products. Groundwater tables were increased to 35 cm below soil surface and subsurface drains were installed. Cows and

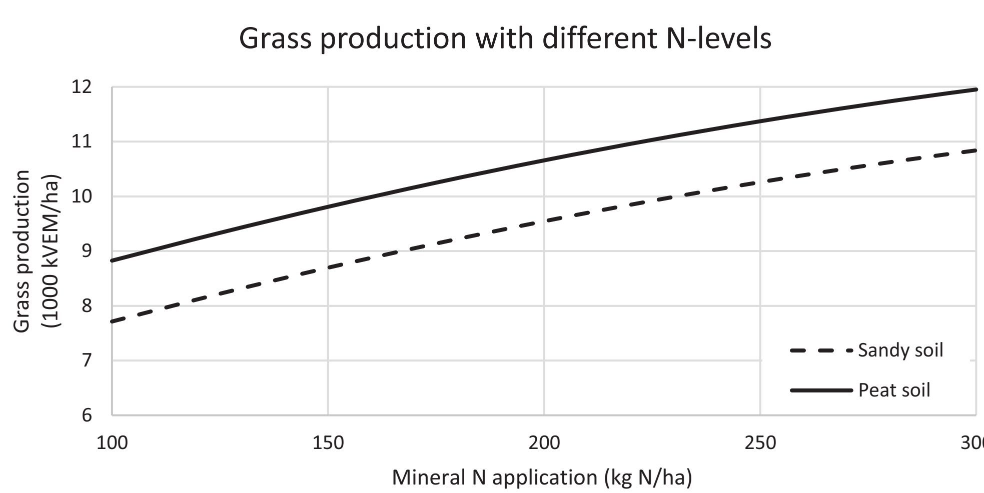

Fig. 1. Grass production with different mineral nitrogen application levels (from manure and artificial fertilizer) in kg N/ha for sandy soil (Klootwijk et al., 2016) and peat soil (Remmelink et al., 2018) in 1000 kVEM/ha.

youngstock were only fed with grass and some additional by-products. Additional land on clay soil was not required and therefore, all 56 ha of farm land were used to produce grass and available grazing time in summer was increased to 18 h/day.

2.4. Sensitivity analyses

A sensitivity analysis was performed to account for N fertilizer application and climate variability on grass yield of the farm on peat soil. Two sensitivity analyses were performed: grass yield was increased and decreased by 10% from the baseline dairy farm on peat soil.

3. Results

3.1. Farm structure, management and labour income

3.1.1. Dairy farm on sandy and peat soil

The lower phosphate quota and barn capacity on the farm on peat soil resulted in 3 dairy cows with youngstock less compared to the farm on sandy soil (Appendix Table A3). This resulted in 30 ton/year fewer milk production and together with 6 ha more available farmland, to a lower farm intensity (kg of milk/ha) on peat soil. On both farms, the maximum amount of fresh grass (10 kg DM/day) was fed, since this was the cheapest food resource (Appendix Table A1). Dairy cows on peat soil were fed with more concentrates in summer, more grass silage in winter and less maize silage throughout the year compared to the farm on sandy soil. This is mainly caused by lower costs for grass production on peat soil, since no grassland renewal takes place on peat soil. Since less maize silage was fed to both cows and youngstock, less maize silage had to be purchased on the farm on peat soil. Furthermore, more maize was produced on-farm, since more farmland was used for maize production and costs for producing maize on clay soil were lower than on sandy soil, since no catch crop had to be grown after maize harvest. More labour was hired on the farm on peat soil, because more labour was required for ditch management. Total phosphate excretion of the dairy farm on peat soil was 4415 kg/year and therefore, phosphate quota was reached and 222 kg phosphate had to be processed.

Total revenues of the dairy farm on peat soil were lower than on sandy soil, mainly due to lower milk production and lower number of animals. Variable costs were higher, due to higher costs for manure application, ditch management and labour. Furthermore, more phosphate was produced than the phosphate quota allowed, leading to extra costs for manure processing. Less extra barn capacity was purchased on the farm on peat soil and therefore fixed costs were lower compared to the farm on sandy soil. In total, labour income on the dairy farm on peat soil was €12,903, which was about half of the labour income of the dairy farm on sandy soil (Fig. 2).

3.1.2. Increased groundwater tables

Farm structure and management of the dairy farm on peat soil with subsurface drains and increased groundwater table was comparable with a regular dairy farm on peat soil, resulting in comparable revenues and fixed costs. Only small differences in dairy cows' diets were shown, due to lower grass production. However, there was a difference in labour income due to higher variable costs for installation and maintenance of the subsurface drains (Appendix Table A3). Therefore, the labour income of the dairy farm on peat soil with the increased groundwater table was €5330, which was 41% lower compared to a regular dairy farm on peat soil (Fig. 2).

3.1.3. Feeding only grass and by-products

The dairy farm on peat soil, feeding an adjusted diet of only grass and by-products, had 3 cows less compared to the dairy farm on peat soil feeding a regular diet (Appendix Table A3). No maize silage was fed and therefore, all the farmland was used to produce grass. Milk production was lower due to lower number of dairy cows and thus farm intensity was lower. N_{min} application was lower on the dairy farm with adjusted diets compared to a regular dairy farm.

The adjusted summer diet for dairy cows consisted of more fresh grass, since the number of grazing hours was increased from 10 to 12 h/day. Concentrates, grass silage and maize silage were replaced by beet pulp and brewers' grains. In winter, dairy cows received more grass silage with additional beet pulp and brewers' grains. Adjusted summer diets for youngstock consisted of less grass compared to the regular diet, which was compensated with breadcrumb meal. In winter, youngstock were fed with breadcrumb meal, brewers' grains and wheat straw. In the

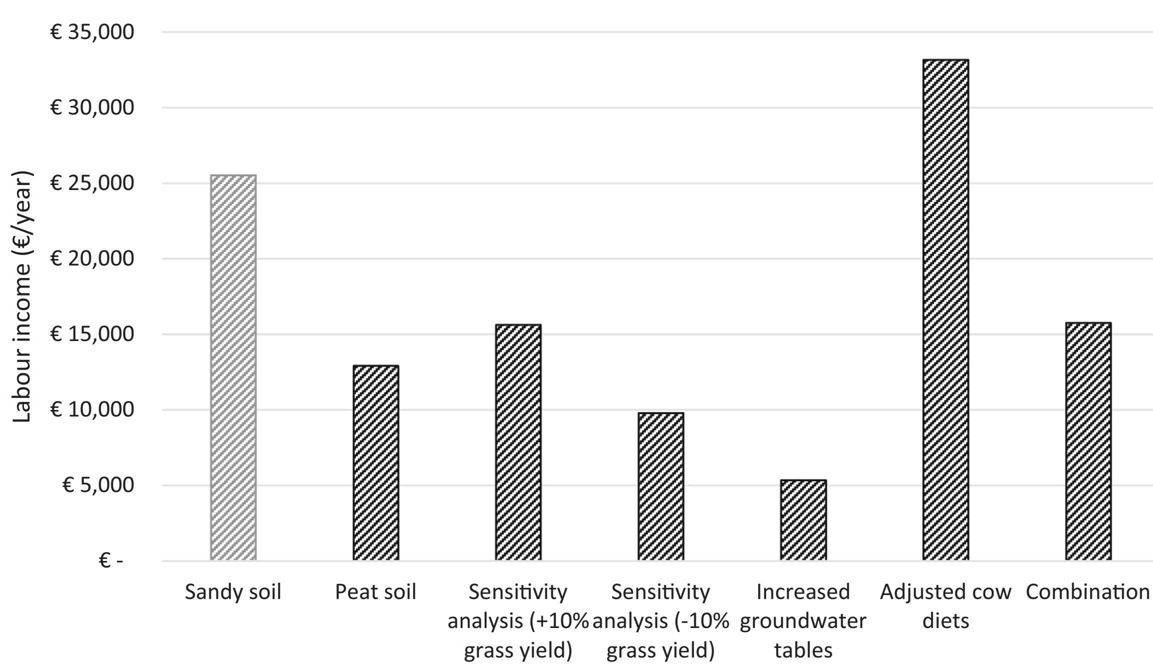

Fig. 2. Labour income of an average Dutch dairy farm on sandy soil and on peat soil, including a sensitivity analysis with 10% more and 10% less grass yield and different scenarios on peat soil: increased groundwater tables with subsurface drains, feeding an adjusted diet containing only grass and by-products, a combination with both increased groundwater tables with subsurface drains and feeding an adjusted diet containing only grass and by-products.

first three months of their lives, youngstock also received calf concentrates and milk replacer.

Less cows on the farm and feeding the adjusted diet resulted in lower revenues from milk and meat, but also lower fixed costs. There were no costs for roughage and concentrate purchase, except for €765 for calf concentrates. Variable costs on the dairy farm with adjusted diets were lower, mainly due to lower costs of buying by-products compared to roughage and concentrates. Some additional labour was required to ensilage some of the by-products before they could be fed, increasing the costs for hired labour. Costs for on-farm roughage production were also lower, since maize production is more expansive than grass production. In total, the labour income of the dairy farm on peat soil feeding the adjusted diet was €33,150, which was 157% higher compared to the dairy farm on peat soil feeding a regular diet (Fig. 2).

3.1.4. Combination: Increased groundwater table and feeding only grass and by-products

The dairy farm on peat soil with higher groundwater tables and feeding an adjusted diet of only grass and by-products, had 3 cows less compared to the dairy farm on peat soil with regular groundwater tables and diets (Appendix Table A3). This resulted in lower milk production and therefore lower farm intensity compared to a regular farm on peat soil. Dairy cow diets were comparable with the scenario with only the adjusted diet. However, due to lower grass yield in this scenario, less beet pulp and more brewers' grains were fed, supplemented with some breadcrumb meal in winter. In winter, youngstock were not fed with breadcrumb meal and wheat straw, but with more brewers' grains and additional potato pulp. Hired labour was higher compared to a regular dairy farm on peat soil, since harvesting and maintenance of grassland requires more time than maize land and some additional labour was required to ensilage some of the by-products before they can be fed. Total phosphate extraction was equal to the phosphate quota.

Cost for buying by-products were lower compared to costs for concentrates and maize, however, costs for on-farm roughage production increased due to installation and maintenance of subsurface drains. More hired labour resulted in more labour costs, however, fixed costs were slightly lower in this scenario, since no barn expansion was required as it was on a regular dairy farm on peat soil. Total labour income of the dairy farm on peat soil with a combination of subsurface drains, increased groundwater tables and feeding the adjusted diet was €15,756, which was 22% higher compared to a regular dairy farm on peat soil (Fig. 2).

3.1.5. Sensitivity analysis

When grass yield on peat soil was 10% higher than assumed, the dairy farm would contain 5 cows less and therefore milk production and farm intensity were lower compared to the baseline dairy farm on peat soil (Appendix Table A3). Dairy cows were fed with more grass and less maize silage, while youngstock diets only contained more grass, but a similar amount of maize silage compared to the baseline dairy farm. Less labour was required due to lower numbers of dairy cows and youngstock. N_{min} application was 225 kg of N/ha and total phosphate excretion was equal to the phosphate quota. High grass yields resulted in lower revenues, due to lower number of animals, but also lower costs for roughage and fertilizer purchase. Furthermore, no manure had to be processed and less hired labour was required, lowering the costs even more. In total, labour income, when grass yield was 10% higher, was €15,612, which is 21% higher compared to the baseline dairy farm on peat soil.

When grass yields on peat soil was 10% lower than assumed, farm structure and management would be comparable with the baseline dairy farm (Appendix Table A3). However, to harvest enough feed for the animals, more labour and machinery use is required, resulting in higher costs for labour and on-farm roughage production. Therefore, variable costs were higher, while revenues were comparable, leading to a labour income of €3117, which was 76% lower compared to the baseline dairy farm on peat soil (Fig. 2).

3.2. Greenhouse gas emissions

3.2.1. Dairy farm on sandy and peat soil and sensitivity analysis

GHG emissions per kg FPCM on the farm on peat soil were considerably higher compared to the dairy farm on sandy soil (Fig. 3). This is primarily due to 1318 kg CO_2-equivalent per kg FPCM from CO_2 and N_2O emissions from peat oxidation. Furthermore, GHG emissions from some sources differed due to differences in farm structure of farms on peat soil compared to sandy soil; less cows resulted in lower CH_4 emissions from enteric fermentation, more maize land resulted in higher GHG emissions from machinery use and manure application, more purchased concentrates resulted in higher GHG emissions from concentrate production and less purchased roughage resulted in lower GHG emissions from off-farm roughage production. Increased grass yields resulted in higher GHG emissions and decreased grass yields in lower GHG emissions (Fig. 3). However, these differences were very small and can be neglected.

3.2.2. Increased groundwater tables

Subsurface drains and higher groundwater tables can prevent 454 kg CO_2-equivalent per ton FPCM to be emitted from peat oxidation. Since farm structure and management of the dairy farm on peat soil with subsurface drains and increased groundwater tables was comparable with a regular dairy farm on peat soil, GHG emissions from other sources were also comparable.

3.2.3. Feeding only grass and by-products

Feeding an additional cattle diet (only grass and by-products) resulted in comparable total GHG emissions to a regular diet, however the contribution of the different sources differed. Although there were fewer dairy cows, more CH_4 was emitted from enteric fermentation, since the emissions from by-products were higher than from grass and maize silage. Youngstock, however, emitted less CH_4 from enteric fermentation, since their diets consisted of less dry matter. Also, longer access to the pasture resulted in higher GHG emissions from manure, since faeces were not equally distributed. Moreover, GHG emissions from grassland increased, since all the farmland was used for grass production for grazing and silage making. Grassland requires more machinery use for harvesting and application of manure and artificial fertilizer, which results in higher GHG emissions. The increased GHG emissions from dairy cows, manure and grassland were compensated with zero GHG emissions from maize land, purchased roughages and especially concentrates. Also, no GHGs were emitted from by-products, since their emissions were assumed to be allocated to the main product.

3.2.4. Combination: Increased groundwater table and feeding only grass and by-products

The combination of subsurface drains, higher groundwater tables and feeding an adjusted diet resulted in lower GHG emissions compared to a regular dairy farm on peat soil. GHG emissions from grassland were lower due to decreased peat oxidation and the increase in CH_4 emissions from enteric fermentation of dairy cows shown in the scenario with only the adjusted diet was also shown in this combination. Also, GHG emissions from youngstock were lower, since their diets consisted of less dry matter compared to the diet on the regular farm. More grazing resulted in higher emissions from manure and no GHGs were emitted from maize production and purchase of concentrates and roughages.

4. Discussion

This study used an existing economic-environmental LP model for Dutch dairy farms on sandy soil, which was converted into a model for dairy farms on peat soil. When converting the model to peat soil, it was assumed that the trend between kVEM/ha of grassland and N_{min}

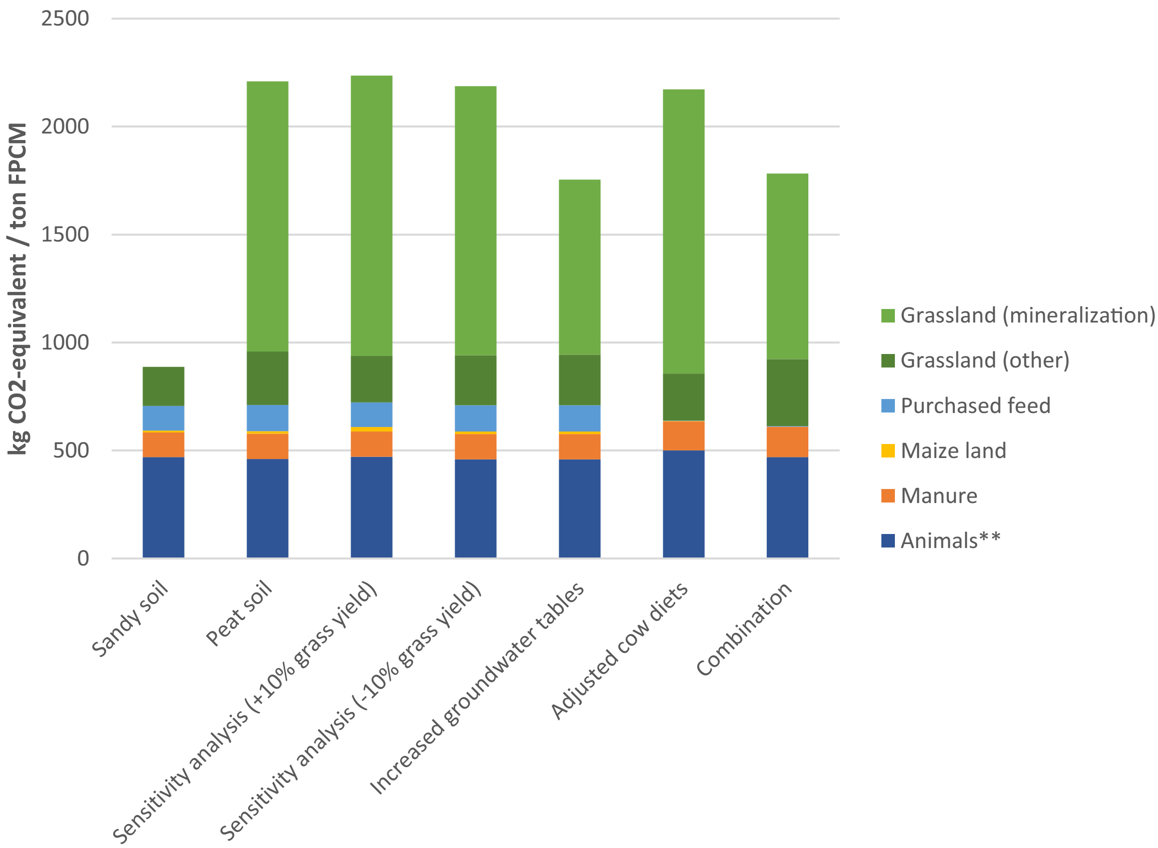

Fig. 3. Greenhouse gas (GHG) emissions in kg CO_2-equivalent/ton fat and protein corrected milk (FPCM) of dairy farms on sandy soil and peat soil, including a sensitivity analysis with 10% more and 10% less grass yield and different scenarios on peat soil: increased groundwater table with subsurface drains, feeding adjusted diets containing only grass and by-products or a combination with both increased groundwater tables with subsurface drains and feeding an adjusted diet containing only grass and by-products. GHG emissions were divided in different sources.* GHG emissions from mineralisation were divided in 92% CO_2 and 8% N_2O. ** GHG emissions from animals included CH_4 from enteric fermentation and emissions from litter, gas and electricity.

application on the field was the same for grass on both soil types (Fig. 1). Only the starting point (in terms of kVEM/ha) was increased on peat soil. Furthermore, restrictions for nutritional requirements of dairy cows were limited to energy content, DVE, OEB, fill value and saturation value, however, vitamins and minerals were not accounted for. Since animal health and welfare were not included in this study, the diets calculated by the model might not be realistic. Especially for youngstock diets, which were only restricted by energy content, DVE, OEB and fill values, for example in the scenario with the adjusted diet in this study, where youngstock was only fed with by-products and no roughage at all.

In this study, phosphate quota was limiting milk production. This is in accordance with Klootwijk et al. (2016), who stated that increasing the number of dairy cows is profitable up to the level that requires manure processing or additional land to comply with the manure policy. They also showed that with increased barn capacity and higher milk price, phosphate quota would be purchased until yearly costs reach a level of €11/kg phosphate. In the current study, this price was €41/kg phosphate, which explains why no extra phosphate quota was purchased. Comparing the updated scenario on sandy soil with the results of Klootwijk et al. (2016), labour income increased over time. Increased milk price and number of dairy cows per farm resulted in more revenues in 2018 (this study) compared to 2015 (Klootwijk et al., 2016). On-farm maize production decreased and more maize silage and less concentrates were purchased. Fixed costs increased, due to changing prices and costs over time. Wageningen Economic Research (2017) supported this and showed an increase in family labour income from 2015 onwards.

To stop peat oxidation and stimulate peat formation, groundwater tables should be increased to the soil surface. However, the soil will become unsuitable for arable crop production and the area will become a peat swamp. Since peat meadows are a part of the typical Dutch landscape, this study chose to limit the increase in groundwater table to keep the agricultural landscape. This way, subsidence can be decreased with 2.8 mm/year (Jansen et al., 2009) and less GHGs will be emitted. However, subsidence and GHG emissions are not fully stopped and eventually, all peat will disappear and the captured carbon will be emitted. Still, it is important to look for methods that slow this process down and preserve as much peat as possible.

When feeding the adjusted diet, consisting of only grass and by-products, a lower fertilization level was chosen by the model compared to a regular dairy farm on peat soil. The model is very sensitive to the use of artificial fertilizer, because of its price. Increasing artificial fertilizer use does not always result in sufficient increase in grass production to be economically beneficial. Furthermore, the model chose to limit grazing to about 12 h per day, instead of the available 18 h per day, since the prices of by-products (mainly brewers' grains) were lower than the costs for grazed grass. Thus, in this study, the price of by-products largely determined the amount of grazing, together with some nutritional restrictions. Therefore, it would be interesting to look into more detail at this relationship between feeding by-products and hours of grazing to get more insight into the effect of different ratios on labour income and environmental impact.

The assumption was made that all GHG emissions from by-products were allocated to the main products, since intentionally food residues from the food industry were regarded as waste (Elferink et al., 2008). The volume of by-products depends on the demand for the main product. However, by-products are increasingly popular and their economic values increase, since they can be used for other sources than dairy cattle feed too, for example biofuels or feed for other animals. Zhu and van

Ierland (2004) stated that food residues should be ascribed an environmental impact, which can be done based on economic value or energy content. This implies that differences in allocation result in different GHG emissions (Opio et al., 2013). Since, in this study, no GHG emissions were allocated to the by-products, using a different way of allocation will result in higher GHG emissions, however, the magnitude of this increase depends on the method of allocation. Together with increased GHG emissions from manure and enteric fermentation, the dairy farm feeding the adjusted diet will emit more GHG emissions than the dairy farm feeding a regular diet. However, Van Zanten et al. (2014) showed that shifting the application of by-products can reduce the environmental impact of the livestock sector, but it is important to carefully assess the environmental consequences of using by-products as animal feed and also include potential changes in impacts outside the livestock sector, for example the impact on the bio-energy sector.

Model inputs were based on averages of Dutch dairy farms on peat and sandy soil. However, true values can differ among regions in the Netherlands, depending on weather, environment, farm management and local government. The sensitivity analyses showed that fluctuations in grass yield influenced labour income, but only had a slight impact on the GWP of the dairy farm on peat soil. Also, methods were evaluated for a typical-Dutch dairy farm, so results are specific for the Dutch situation. However, since productivity in terms of milk yield per cow largely influences GHG emissions per kg of milk (Gerber et al., 2011), overall conclusions from this study can be used as an indicator for regions with comparable milk yield per cow, e.g. other countries in Western Europe, but also in Eastern Europe, Scandinavia, North America and Oceania. Further research might reveal whether there are differences in environmental and economic impact in different countries, climates or dairy farm systems.

This publication is among the first to report greenhouse gas emission intensities from dairy farming on peat soils. Our results on emission intensities are comparable of those of previous studies. For instance, Schils et al. (2006) reports 2.0 kg CO_2 eq kg $FPCM^{-1}$ for farms on peat soils in the Netherlands, while Vellinga et al. (2011) reports an average of 1.075 ± 0.146 kg CO_2 eq kg $FPCM^{-1}$ for 24 Dutch dairy farms, including farms on sand (16), peat (6) and clay (2) soils.

To fit in the circular food system in terms of land use, peat soils should only be used for grass production for cattle (Van Zanten et al., 2018). However, as confirmed in this study, dairy farms on peat soil have a high GWP, mainly due to oxidation of peat, since groundwater tables are currently kept low. Increasing these groundwater tables not only result in lower GWP, also biodiversity and water infiltration increase (Deru et al., 2018). Besides GWP, there are also other impacts on the environment which were not included in this study, such as: nitrogen and phosphate surpluses, depletion of fossil energy and phosphorous sources, biodiversity conservation, land degradations and pollution (Gerber et al., 2013). Furthermore, in this study, farmers were able to use some farmland on clay soil to produce maize silage, but in the circular food system, this land should be used for direct food production for humans. Moreover, global production of animal sourced food is limited by the quantity and quality of the biomass streams in the circular food system.

5. Conclusions

Dairy farms on Dutch peat soils have a lower labour income and considerably higher GWP compared to dairy farms on sandy soils. Installing subsurface drains and increasing the groundwater tables can reduce the GWP, but also lead to lower labour income. Feeding only grass and by-products increased labour income, but did not result in the expected decrease in GWP. The combination of subsurface drains, higher groundwater tables and feeding only grass and by-products resulted in lower GHG emissions, with even a small increase in labour income.

Declaration of Competing Interest

The authors have no conflict of interest.

Table A1
Feed characteristics of dietary options on sandy soil (CVB, 2018) and peat soil (CVB, 2018; Eurofins Agro, 2017; Hoekstra et al., 2017) and market price for purchased feed products (KWIN-V, 2018).

Feedstuff	VEM (/kg of DM)		DVE (g/kg of DM)		OEB (g/kg of DM)		Fill value (/kg of DM)		Saturation value (/kg of DM)		Nitrogen (g/kg of DM)		Phosphorous (g/kg of DM)		Market price (€/ton DM)
Soil	Sand	Peat	Sand	Peat	Sand	Peat	Sand	Peat	Sand	Peat	Sand	Peat	Sand	Peat	
Concentrates[1]							0.4	0.4	0.28	0.28					
Standard	940	940	90	90	5	5					21.7	21.7	4.1	4.1	225
Medium	940	940	120	120	25	25					29.0	29.0	4.5	4.5	260
High	940	940	180	180	74	74					43.5	43.5	7.2	7.2	325
Grazed grass							3.0	3.0	1.02	1.02			4.1	4.1	–
100 kg of N	955.7	955.6	92.91	92.90	6.07	6.07					27.26	27.27			
125 kg of N	960.0	960.0	93.92	93.91	9.31	9.31					28.96	28.98			
150 kg of N	964.2	964.1	94.90	94.89	12.67	12.67					28.68	28.69			
175 kg of N	968.1	968.0	95.85	95.84	16.14	16.15					29.40	29.41			
200 kg of N	971.8	971.7	96.78	96.77	19.74	19.75					30.13	30.15			
225 kg of N	975.3	975.2	97.68	97.67	23.45	23.46					30.87	30.88			
250 kg of N	978.5	978.5	98.55	98.54	27.28	27.29					31.62	31.63			
275 kg of N	981.6	981.5	99.39	99.38	31.23	31.24					32.37	32.39			
Grass silage							1.9	1.9	0.89	0.89			4.1	4.1	–
100 kg of N	850.6	850.6	69.00	68.99	18.00	18.01					24.74	24.75			
125 kg of N	853.7	853.6	69.86	69.85	22.22	22.23					25.64	25.65			
150 kg of N	856.7	856.6	70.68	70.67	26.43	26.43					26.52	26.53			
175 kg of N	859.5	859.4	71.46	71.45	30.62	30.63					27.39	27.39			
200 kg of N	862.2	862.2	72.20	72.19	34.80	34.81					28.22	28.23			
225 kg of N	864.8	864.7	72.91	72.90	38.97	38.98					29.04	29.05			
250 kg of N	867.3	867.2	73.58	73.57	43.13	43.13					29.84	29.85			
275 kg of N	869.6	869.5	74.21	74.20	47.27	47.28					30.61	30.62			
Maize silage	918.0	976.0	49.00	49.00	−36.00	−38.00	1.6	1.6	0.86	0.86	10.24	10.24	1.8	1.8	138

Table A2
Feed characteristics of by-products (CVB, 2018) and market price (Feedvallid, 2019; Schothorst Feed Research, 2018; Wageningen Economic Research, 2017).

Feedstuff	VEM (/kg DM)	DVE (g/kg DM)	OEB (g/kg DM)	Fill value (/kg DM)	Saturation value (/kg DM)	Nitrogen (g/kg DM)	Phosphorous (g/kg DM)	Market price (€/ton DM)
Potato pulp	1031	91	−69	0.8	0.55	13.0	0.9	5.44
Breadcrumb meal	1137	108	−51	−0.22	0.26	19.4	1.9	158.05
Wheat straw	425	−5	−41	4.30	1.66	6.6	0.9	115.24
Brewers' grains	821	139	58	0.37	0.29	39.7	4.6	46.55
Beet pulp	1060	93	−64	1.05	0.70	13.4	0.9	9.79
Sunflower meal	699	106	144	0.44	0.33	49.3	10.2	138.97

Table A3
Farm structure, management and labour income of an average Dutch dairy farm on sandy soil and on peat soil, including a sensitivity analysis with 10% more and 10% less grass yield and different scenarios on peat soil: increased groundwater tables with subsurface drains, feeding an adjusted diet containing only grass and by-products, a combination with both increased groundwater tables with subsurface drains and feeding an adjusted diet containing only grass and by-products.

Item	Unit	Sandy soil	Peat soil	Sensitivity analysis (+10% grass yield)	Sensitivity analysis (−10% grass yield)	Increased groundwater tables	Adjusted cow diets	Combination
Farm structure								
Dairy cows	No.	90	87	83	87	87	84	84
Youngstock	No. (YSU)	59 (30)	57 (29)	55 (28)	57 (29)	57 (29)	56 (29)	56 (29)
Total milk production	ton/year	761	731	705	731	731	710	710
Total farm land	ha	50	56	56	56	56	56	56
Grassland	ha (%)	47 (94)	52 (93)	52 (93)	52 (93)	52 (93)	56 (100)	56 (100)
N_{min} application	kg N/ha/year	225	250	225	250	250	125	250
Maize land	ha (%)	3 (6)	4 (7)	4 (7)	4 (7)	4 (7)	0 (0)	0 (0)
Farm intensity	kg milk/ha	15,216	13,058	12,581	13,058	13,047	12,677	12,677
Summer diet cow								
Grass	kg DM/cow/day	10	10	10	10	10	12.2	12.1
Grass silage	kg DM/cow/day	3.5	1.4	2.1	1.4	1.0	0	0
Maize silage	kg DM/cow/day	6.5	6.7	6.0	6.7	6.9	0	0
Concentrates	kg DM/cow/day	0.7	1.9	1.9	1.9	2.0	0	0
Beetpulp	kg DM/cow/day	0	0	0	0	0	2.7	2.7
Potatopulp	kg DM/cow/day	0	0	0	0	0	0	0
Sunflower meal	kg DM/cow/day	0	0	0	0	0	0	0
Breadcrumb meal	kg DM/cow/day	0	0	0	0	0	0	0
Brewers' grains	kg DM/cow/day	0	0	0	0	0	6.0	5.8
Winter diet cow								
Grass silage	kg DM/cow/day	7.1	9.3	10.3	9.3	9.3	14.7	14.8
Maize silage	kg DM/cow/day	7.4	5.0	4.3	5.0	5.0	0	0
Concentrates	kg DM/cow/day	2.3	2.3	2.2	2.3	2.3	0	0
Beetpulp	kg DM/cow/day	0	0	0	0	0	1.8	1.3
Potatopulp	kg DM/cow/day	0	0	0	0	0	0	0
Sunflower meal	kg DM/cow/day	0	0	0	0	0	0	0
Breadcrumb meal	kg DM/cow/day	0	0	0	0	0	0	0.2

(continued on next page)

Table A3 (*continued*)

Item	Unit	Sandy soil	Peat soil	Sensitivity analysis (+10% grass yield)	Sensitivity analysis (−10% grass yield)	Increased groundwater tables	Adjusted cow diets	Combination
Brewers' grains	kg DM/cow/day	0	0	0	0	0	1.0	1.4
Summer diet youngstock								
Grass	kg DM/YSU/day	10.6	10.5	10.6	10.5	10.5	8.5	8.6
Concentrates	kg DM/YSU/day	1.0	1.0	1.0	1.0	1.0	0	0
Potatopulp	kg DM/YSU/day	0	0	0	0	0	0	2.5
Breadcrumb meal	kg DM/YSU/day	0	0	0	0	0	2.5	0
Brewers' grains	kg DM/YSU/day	0	0	0	0	0	0	0
Winter diet youngstock								
Grass silage	kg DM/YSU/day	3.5	4.6	4.9	4.6	4.6	0	0
Maize silage	kg DM/YSU/day	6	5	5.0	5.0	5.0	0	0
Calf concentrates	kg DM/YSU/day	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Concentrates	kg DM/YSU/day	1.0	1.0	1.0	1.0	1.0	0	0
Potatopulp	kg DM/YSU/day	0	0	0	0	0	0	5.2
Breadcrumb meal	kg DM/YSU/day	0	0	0	0	0	5.2	0
Wheat straw	kg DM/YSU/day	0	0	0	0	0	5.2	0
Brewers' grains	kg DM/YSU/day	0	0	0	0	0	3.4	4.5
External inputs								
Purchased maize silage	ton DM/year	226	160	127	160	162	0	0
Purchased concentrates	ton DM/year	62	78	73	75	79	2	2
Hired labour	hour	435	478	372	520	488	718	837
Manure management								
Total excretion	kg of P_2O_5/year	4109	4415	4192	4415	4464	4192	4192
Extra phosphate quota	kg of P_2O_5/year	0	0	0	0	0	0	0
Revenues (total)	€/year	338,772	328,948	317,746	328,947	328,677	319,986	319,986
Milk	€/year	282,404	271,441	261,532	271,440	271,201	263,514	263,514
Livestock sale	€/year	36,657	35,430	34,137	35,430	35,399	34,395	34,395
Governmental payment	€/year	19,711	22,077	22,077	22,077	22,077	22,077	22,077
Variable costs (total)	€/year	154,301	158,395	146,233	161,513	165,752	130,926	148,320
Concentrate purchase	€/year	21,658	27,441	26,013	27,441	28,242	765	765
Roughage purchase	€/year	30,339	21,403	17,020	21,403	21,668	0	0
On-farm roughage prod.	€/year	55,913	61,668	60,665	63,963	67,355	58,844	69,785
By-products	€/year	0	0	0	0	0	21,728	25,841
Manure processing	€/year	0	1947	0	1947	2386	0	0
Hired labour	€/year	8557	9416	7348	10,239	9613	14,135	16,475
Other	€/year	37,834	36,520	35,187	36,520	36,488	35,454	35,454
Fixed costs	€/year	158,951	157,648	155,892	157,648	157,595	155,910	155,910
Labour income	€/year	25,520	12,903	15,621	9786	5330	33,150	15,756

YSU = youngstock unit (1 YSU = 1.95 calf; 1 calf <1 year old +0.96 calf >1 year old). N_{min} = mineral nitrogen.

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