Methods to determine the relative value of genetic traits in dairy cows to reduce greenhouse gas emissions along the chain

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ABSTRACT

Current decisions on breeding in dairy farming are mainly based on economic values of heritable traits, as earning an income is a primary objective of farmers. Recent literature, however, shows that breeding also has potential to reduce greenhouse gas (GHG) emissions. The objective of this paper was to compare 2 methods to determine GHG values of genetic traits. Method 1 calculates GHG values using the current strategy (i.e., maximizing labor income), whereas method 2 is based on minimizing GHG per kilogram of milk and shows what can be achieved if the breeding results are fully directed at minimizing GHG emissions. A whole-farm optimization model was used to determine results before and after 1 genetic standard deviation improvement (i.e., unit change) of milk yield and longevity. The objective function of the model differed between method 1 and 2. Method 1 maximizes labor income; method 2 minimizes GHG emissions per kilogram of milk while maintaining labor income and total milk production at least at the level before the change in trait. Results show that the full potential of the traits to reduce GHG emissions given the boundaries that were set for income and milk production (453 and 441 kg of CO₂ equivalents/unit change per cow per year for milk yield and longevity, respectively) is about twice as high as the reduction based on maximizing labor income (247 and 210 kg of CO₂ equivalents/unit change per cow per year for milk yield and longevity, respectively). The GHG value of milk yield is higher than that of longevity, especially when the focus is on maximizing labor income. Based on a sensitivity analysis, it was shown that including emissions from land use change and using different methods for handling the interaction between milk and meat production can change results, generally in favor of milk yield. Results can be used by breeding organizations that want to

include GHG values in their breeding goal. To verify GHG values, the effect of prices and emissions factors should be considered, as well as the potential effect of variation between farm types.

Key words: life cycle assessment, economic value, milk yield, longevity

INTRODUCTION

The need for strategies to reduce greenhouse gas (GHG) emissions from human activities, mainly consisting of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), has been highlighted (IPCC, 2007). Use of fossil fuel and land use change are identified as the primary sources for increased levels of atmospheric CO₂, whereas agriculture is identified as the primary source for increased levels of CH₄ and N₂O (IPCC, 2007). The majority of CH₄ emissions from agriculture relate to enteric fermentation of ruminants. About half of the total GHG emissions along the dairy production chain are enteric CH₄ (Hörtenhuber et al., 2010). To reduce CH₄ emissions, different strategies have been proposed; one of these strategies is increasing the productivity and efficiency of the dairy herd by selective breeding (Buddle et al., 2011; De Haas et al., 2011).

Productivity and efficiency can be increased by genetic improvement of traits such as milk yield, feed efficiency, longevity, and calving interval (Bell et al., 2011). Increasing milk yield per cow, for example, reduces CH₄ emissions per kilogram of milk by diluting CH₄ formed during fermentation of feed related to maintenance (Bannink et al., 2011; Bell et al., 2010, 2011). Bannink et al. (2011) showed that a 33% increase in production of fat- and protein-corrected milk (FPCM), from 17.2 kg/d in 1990 to 22.9 kg/d in 2008, reduced enteric CH₄ per kilogram of FPCM by 13%, from 17.6 to 15.4 g. Increasing longevity reduces CH₄ per kilogram of milk by reducing the number of female replacements producing CH₄ for maintenance and growth, without producing milk (Garnsworthy, 2004; Wall et al., 2010). Wall et al.

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(2010) showed that increasing longevity from an average of 3.0 to 3.5 lactations can reduce enteric CH₄ per kilogram of milk by 4.4%.

Changing a trait, such as milk yield or longevity, however, can affect the whole farm, including feeding strategy, management practices and purchases of inputs, such as concentrate and fertilizer (Bell et al., 2010; Wall et al., 2010). Evaluating the effect of a genetic improvement, therefore, requires modeling the whole farm. Moreover, optimization of farm management before and after a change in trait is required to prevent under- or overestimation of the effect of genetic improvement (Groen et al., 1997). Finally, if the effect concerns GHG emissions, the analysis should include emission along the chain (i.e., from production of farm inputs up to the farm gate) to avoid pollution swapping. By evaluating the effect of one unit change in individual traits on GHG emissions at the chain level, the relative value of each trait to reduce GHG emissions along the chain can be determined. A similar approach is used to calculate the relative economic value of traits (Groen, 1988; Koenen et al., 2000).

Two studies evaluated the effect of improving individual traits in dairy cows on GHG emissions at farm or chain level. Wall et al. (2010) evaluated the effect of increasing longevity on CH₄ and N₂O emissions at farm level, whereas Bell et al. (2011) evaluated the effect of increasing feed efficiency, milk yield, calving interval, and longevity on GHG emissions at the chain level. Both Wall et al. (2010) and Bell et al. (2011), however, did not optimize farm management with changing levels of genetic traits.

Farm management can be optimized based on different objectives, such as maximizing labor income (i.e., the main interest in deriving breeding objectives) or minimizing GHG emissions per unit product. It is not clear how a difference in objective affects the relative value of individual traits to reduce GHG emissions per kilogram of FPCM.

The objective of the current study was to compare 2 methods to determine the relative value of genetic traits in dairy cows to reduce GHG emissions along the milk production chain (i.e., up to the farm gate). Both methods are based on a whole-farm dairy model, use linear programming (LP) to optimize farm management, and include all GHG emissions along the chain, up to the farm gate. The first method is based on maximizing labor income of the farm family; the interrelated consequences for GHG emissions are evaluated as a side-effect. The second method is based on minimizing GHG emissions per kilogram of milk. We compared both methods by assessing the consequences of an increase in milk yield and longevity of cows on an average Dutch dairy farm on sandy soil.

MATERIALS AND METHODS

The first method is based on the exact same principle that is used to calculate economic values. A dairy farm LP model with the objective to maximize labor income was used to determine the economic benefit per unit change in milk yield and longevity. The effect on GHG emissions (i.e., the GHG value) was considered as a consequence. This method, therefore, shows the effect of economic optimization, which is currently the main interest in deriving breeding objectives, on GHG emissions. The second method uses the same model, but now minimizes GHG emissions per kilogram of milk along the chain (i.e., up to the farm gate), to determine the maximum GHG reduction per unit change in milk yield and longevity while maintaining initial labor income and milk production at the farm level (i.e., before trait improvement). This method, therefore, determines the full potential of a genetic trait to reduce GHG emissions along the chain, given the boundaries that were set for income and milk production. Results might change when reducing GHG emissions yields additional income. At this moment, however, no carbon-pricing scheme exists for agriculture.

Dairy Farm LP Model

The dairy farm LP model used is based on Berentsen and Giesen (1995). This static year model includes all relevant activities and constraints that are common to Dutch dairy farms, such as on-farm feed production, purchase of feed products, and animal production, including rearing of young stock. The model distinguishes a summer and a winter period regarding feeding. Dietary options include grass from grazing, grass silage, maize silage, and 3 types of concentrates that differ in protein levels (i.e., standard, medium, and high). Nutritional values of the feed ingredients are in Table A1. Available land can be used as grassland or as maize land. Constraints of the model include fixed resources of the farm (e.g., land area, family labor), links between activities (e.g., fertilizer requirements of grass and arable land with available nutrients from manure and purchased fertilizers), and environmental policies [e.g., limits to the application of total mineral nitrogen and phosphate (P₂O₅) fertilization]. For a more detailed description of the model, see Van Middelaar et al. (2013a).

The central element of the LP model is an average dairy cow from the Holstein Friesian breed with a given milk production and longevity, calving in February, and conditions representing the dairy cattle of the farm. Feed requirements (energy and protein) and intake capacity of this average cow were determined using the bio-economic model of Groen (1988). The same model

was used to determine herd composition and yearly replacement rate, based on the average longevity of the cow. The replacement rate determines the number of young stock that needs to be kept on the farm for yearly replacement of the dairy cows.

The dairy farm model was adapted to future production circumstances to allow exploration of economic and environmental consequences of selective breeding. The generation interval of dairy cattle was assumed to be 7 yr (CRV, 2012); therefore, production circumstances were defined for 2020. In 2015, the milk quota system will be abolished in the European Union, and therefore no milk quota was assumed. Furthermore, prices of milk components and purchased feed products were adapted based on price prediction for 2020 (Wageningen UR, 2013). Milk price was assumed to be €32.3 per 100 kg of milk. Price of purchased maize silage was assumed to be €42 per t, and for concentrates was €180 (standard protein), €208 (medium protein), and €260 (high protein) per tonne. Grass yield per hectare was increased by 1.5% per year, based on historical data analysis (Berentsen et al., 1996). In the case of 200 kg of N fertilization per ha per year, this implies a grass yield of 72.2 GJ of NE_L/ha per year in 2020. The yield of maize silage per hectare was increased by 100 kg of DM/yr (Rijk et al., 2013), resulting in 108.2 GJ of NE_L/ha per year in 2020. For the environmental policies, no changes in limits to the application of N are expected (C. M. Groenestein, Wageningen UR, Wageningen, the Netherlands, personal communication, 2012). Therefore, the annual maximum amount of total mineral N per hectare is 250 kg for grassland and 140 kg for maize land, and the annual maximum amount for N per hectare from animal manure is 250 kg for farms with at least 70% grassland and 170 kg for farms with less than 70% grassland. Limits to the application of P₂O₅ are reduced to an annual maximum of 90 kg of P/ha for grassland and 60 kg of P/ha for arable land (based on soils with an average phosphate content), according to the new standards for 2020 (Vierde Nederlands Actieprogramma Nitratrichtlijn, 2009).

Calculating GHG Emissions

We used the life cycle assessment (LCA) to calculate emissions of CO₂, CH₄, and N₂O from the different stages along the production chain, up to the moment that milk leaves the farm gate. The LCA is an internationally accepted and standardized method to evaluate the use of resources and emission of pollutants along the chain (Bauman and Tillman, 2004; Rebitzer et al., 2004). Processes included are the extraction of raw materials to produce farm inputs, the manufacturing and distribution of these inputs, and all processes on the

dairy farm. Stages related to the transport and processing of milk were assumed to be unaffected by the breeding strategies, and therefore were not included in the analysis. Methods to calculate annual (i.e., recurrent) emissions are described in this section. Methods to calculate nonrecurrent emissions from land use change are described in the sensitivity analysis.

Emissions from the production of synthetic fertilizer, pesticides, tap water, and energy sources (gas, diesel, and electricity) were based on Ecoinvent (2007), from the production of saw dust on Thomassen et al. (2008), and from the production of concentrates and milk replacer on Vellinga et al. (2013). Emissions from production of concentrates include emissions from the production of inputs (e.g., fertilizers, pesticides, machinery, and energy), direct and indirect N₂O emissions from cultivation, CO₂ emissions from liming and urea fertilization, emissions from drying and processing, and emissions from transport in between stages, up to the farm gate. Emission calculations for the production of purchased maize silage were similar to the calculations that were used for on-farm production of maize silage, because purchased maize silage was assumed to be produced in the Netherlands. Similar to on-farm feed production, yield per hectare of purchased feed products (i.e., concentrates and maize silage) were increased by 100 kg of DM/yr (Rijk et al., 2013), resulting in a decrease in emissions from cultivation per kilogram of ingredient. Emission factors per tonne of purchased concentrate and maize silage are included in Table A2.

Emissions of CH₄ from on-farm processes relate to enteric fermentation and to manure management. Enteric CH₄ from dairy cows was calculated based on empirical relations between DMI of feed ingredients and CH₄ emission factors per ingredient. The CH₄ emission factors per feed ingredient were based on Vellinga et al. (2013) and are included in Table A2. For young stock, enteric CH₄ emission was based on Intergovernmental Panel on Climate Change (IPCC) Tier 2 methods and default values (i.e., the average gross energy content of feed is assumed to be 18.45 MJ/kg of DM, and 6.5% of the gross energy intake is converted to CH₄; IPCC, 2006). Emissions of CH₄ from manure management were based on national inventory reports (i.e., 0.746 kg of CH₄/t of manure produced in stables, and 0.110 kg of CH₄/t of manure produced during grazing; De Mol and Hilhorst, 2003).

Emissions of CO₂ from on-farm processes related to the combustion of diesel and gas were based on Ecoinvent (2007). Emissions of N₂O from on-farm processes include both direct and indirect N₂O from manure management and from N application to the field, including N from manure, synthetic fertilizers, and crop residues. Indirect N₂O emissions result from N that is removed

Table 1. Production traits and feed requirements per cow, and yearly replacement rate of the dairy herd for the reference scenario and after increasing milk yield and longevity with 1 genetic SD¹

Item	Production traits				Feed requirements ²			
	Milk yield (kg/yr)	Fat (%)	Protein (%)	Longevity ³ (d)	Energy (GJ of NE _L /yr)	Protein ⁴ (kg of DVE/yr)	Intake capacity (kg/yr)	Replacement rate (%)
Reference ⁵	8,758	4.32	3.51	2,150	44,553	545	6,009	27.0
Increased milk yield	9,445	4.32	3.51	2,150	46,961	583	6,137	27.0
Increased longevity	8,795 ⁶	4.31	3.51	2,420	44,712	547	6,037	22.5

¹Genetic SD for milk yield is 687 kg/yr, and for longevity 270 d (CRV, 2012).

²The diet has to meet a minimum requirement for energy (NE_L), a minimum requirement for true protein digested in the small intestine (DVE), and a minimum requirement for rumen-degradable protein balance (OEB, not included in the table, for all scenarios set to 0 g/d). In addition, a maximum for intake capacity is included (kg of DM of the reference feed according to Jarrige, 1988).

³Longevity is defined as the actual age in days.

⁴DVE = true protein digested in the small intestine according to Dutch standards (Tamminga et al., 1994).

⁵The reference scenario is based on an average Holstein Friesian dairy cow in 2013 (CRV, 2012).

⁶First lactation yield was the same as in the reference scenario.

from the farm via leaching of NO₃⁻ and volatilization of NH₃ and NO_x (IPCC, 2006). Emissions of N₂O from crop residues were based on IPCC (2006). Other N₂O emissions were based on national inventory reports and are described in more detail by Van Middelaar et al. (2013a).

Different GHG emissions were summed based on their equivalence factor in terms of CO₂ equivalents (CO₂e) (100-yr time horizon): 1 for CO₂, 25 for CH₄, and 298 for N₂O (Forster et al., 2007). Emissions were calculated per tonne of FPCM (i.e., milk corrected to a fat percentage of 4.0% and a protein content of 3.3%; Product Board Animal Feed, 2008). After summing emissions, they were allocated to the different outputs of the farm (i.e., milk and meat from culled calves and cows) based on the relative economic value of these outputs (i.e., economic allocation; Wageningen UR, 2008). Economic allocation is used most commonly in LCA studies of livestock products (De Vries and De Boer, 2010).

Setup of the Analysis

The LP model was used to determine the farm plan for a farm in the technical and institutional setting of 2020 and with a cow that has the same characteristics as an average Holstein Friesian cow in 2013. The farm area is 85 ha, which is the estimated size of an average Dutch dairy farm in 2020 (Rabobank, 2009). All manure produced on the farm needs to be applied on the farm (i.e., on grassland and maize land). Traits of the average cow, including milk yield, fat and protein content of the milk, and longevity, were based on the database of an international cattle improvement cooperative (CRV, 2012) and are included in Table 1. Table 1 also includes information on feed requirements. Based

on the assumption that farmers become more efficient in the future, safety margins for true protein digested in the small intestine, as well as for rumen-degradable protein balance, were set to zero. In previous studies, safety margins for true protein digested in the small intestine were set at 100 g/cow per day and 200 g/cow per day for rumen-degradable protein balance (Van Middelaar et al., 2013a). The maximum amount of fresh grass intake in summer was set to 12 kg of DM/cow per day, based on ad libitum grass intake of cows grazing during day times (Taweel et al., 2004; Abrahamse et al., 2009). Optimization of management variables based on maximizing labor income resulted in the reference scenario.

To determine the effect of a 1-unit change in milk yield and longevity, each trait was increased with 1 genetic SD while keeping the other traits constant. The genetic SD for milk yield of the Holstein Friesian breed in the Netherlands is 687 kg/cow per year (SD applies to milk yield of a mature cow), and for longevity it is 270 d (CRV, 2012). Longevity was defined as the actual age in days. Using the model of Groen (1988), the effect of this change on average production, feed requirements, herd composition, and replacement rate was determined. Increasing milk yield increased feed requirements (Table 1). Increasing longevity changed herd composition (i.e., more cows in later lactations) and decreased replacement rate and number of young stock. Due to an increase in the number of cows in later lactations, milk yield of the average cow increased and fat content of the milk decreased. Increasing longevity, therefore, indirectly resulted in an increase in feed requirement of dairy cows due to an increased average weight and milk production (Table 1).

The new data on milk yield, feed requirements, and replacement rate for the 2 scenarios (i.e., increasing

milk yield and increasing longevity) were incorporated in the model; subsequently, the effect on GHG emissions was determined by 1 of 2 methods. The first method maximized labor income and estimated the interrelated consequences for GHG emissions at chain level. The second method minimized GHG emissions per kilogram of milk and explored the potential of the traits (i.e., milk yield and longevity) to reduce these emissions. For the second method, 2 additional constraints were required. Labor income and total milk production at the farm level were required to be equal or higher than in the reference scenario. Labor income was restricted to estimate the potential of the traits to reduce GHG emissions without sacrificing income. Milk production was restricted to avoid milk that has to be produced somewhere else, which would indirectly mean an increase in GHG emissions from deforestation (i.e., more land required to produce the same amount of milk).

Deriving Economic and GHG Values

The economic value represents the change in labor income expressed per cow per year as a result of 1 genetic SD improvement on milk yield and longevity while keeping the other traits constant. Labor income was defined as gross returns minus variable and fixed costs (including depreciation and interest on fixed assets). Gross returns include revenues of selling of milk and meat (animals). Variable and fixed costs include feed costs, fertilizer costs, costs of building, and other variable and fixed costs. Change in labor income was calculated as labor income after change in genetic merit minus labor income before change in genetic merit. To calculate the economic value per trait, this change was divided by the number of dairy cows present before the change in genetic merit (Groen, 1989).

The GHG value represents the change in GHG emissions expressed per cow per year as a result of 1 genetic SD improvement on milk yield and longevity while keeping the other traits constant. Whereas deriving economic values is based on maximizing labor income at farm level, deriving GHG values is based on minimizing GHG per unit of product. Changes in GHG emissions were calculated as kilograms of CO₂e per tonne of FPCM before a change in genetic merit minus kilograms of CO₂e per tonne of FPCM after a change in genetic merit. To calculate the GHG values per trait, this change was multiplied with the FPCM production per cow per year before the change in genetic merit.

Sensitivity Analysis

Two main sources of uncertainty in assessments of GHG emissions of livestock products result from ac-

counting for emissions from land use change (LUC) and handling the link between milk and meat production (i.e., co-product handling; Flysjö et al., 2012; Zehetmeier et al., 2012). In a sensitivity analysis, we explored the effect of including LUC emissions and using different methods for co-product handling using the results of the previous optimization.

Emissions from LUC. Land use change can have an important effect on GHG emissions and carbon sequestration. In the current study, 2 types of LUC are distinguished: on-farm LUC (i.e., conversion of grassland into maize land and vice versa) and off-farm LUC (i.e., deforestation caused by agricultural expansion).

Conversion of grassland into maize land results in nonrecurrent emissions due to a change in soil organic carbon stocks (Vellinga and Hoving, 2011; Van Middelaar et al., 2013a). Conversion of maize land into grassland, conversely, can contribute to carbon sequestration. Carbon sequestration was estimated to be 81 t of C/ha for permanent grassland, and 41 t of C/ha for maize land (see Van Middelaar et al., 2013a). Conversion of grassland into maize land results in an emissions of 163 t of CO₂e/ha [see Van Middelaar et al. (2013a) for a detailed description of the calculation], whereas conversion of maize land into grassland reduces CO₂ emissions by 147 t/ha (40 t of extra C sequestration equals 147 t of CO₂).

Deforestation is another type of LUC that results in high amounts of GHG. Currently, forest is cleared on a large scale to provide land for crop cultivation and pasture. Because of the globalization of food and feed markets, it could be stated that every hectare of land that is used for commercial production is indirectly responsible for deforestation worldwide (Audsley et al., 2009). To determine the effect of LUC emissions on deforestation in our results, we used the method proposed by Audsley et al. (2009). They divided total GHG emissions from deforestation at the world scale for the year 2004 (based on Barker et al., 2007) by the total amount of land used for agricultural production, resulting in 1 emission factor of 1.43 t of CO₂e/ha of land. We applied this emission factor in our study and included on-farm land and land used to produce purchased feed products, including concentrates and maize silage (Table A2).

Methods for Handling of Co-Products. We allocated GHG emissions to milk and meat based on economic allocation. Another option to handle co-products is system expansion, implying that we account for changes in GHG emissions resulting from the production of additional co-products (i.e., meat from culled calves and cows). In that case, all emissions from processing calves and cows are attributed to milk, whereas emissions related to the production of meat that is

replaced by these products, such as pork and chicken, are subtracted. By increasing milk yield and longevity, the ratio of milk over meat production changes, and methodological choices on how to handle co-products might affect results.

In the case of system expansion, emissions from processing of calves and cows and from the production of alternative products, such as pork and chicken, need to be calculated. For all meat products, we calculated emissions per kilogram of edible product and included processes up to the gate of the slaughterhouse. For culled dairy cows and young stock older than 12 mo, we assumed no further processing and included emissions related to transport and slaughtering only. Surplus calves were assumed to be sold to the white veal industry, which is most common in the Netherlands. Emissions related to processing of these calves were based on H. Mollenhorst (Wageningen UR, Wageningen, The Netherlands, personal communication) and include emissions from feeding, housing, transport, and slaughter. Assumptions on live weight, amount of edible products per animal, and emissions per kilogram of edible product from culled calves and cows are included in Table A3.

Meat from culled calves and cows was assumed to substitute either pork, chicken, or beef from suckler cows, in a ratio of 1:1, based on kilograms of edible product. Emissions from the production of pork, chicken, and beef were based on De Vries and De Boer (2010). De Vries and De Boer (2010) only included emissions up to the farm gate. Emissions related to transport and slaughtering, therefore, were based on the same method that was used for dairy cows. Total GHG emissions along the chain assumed was 7.3 kg of CO₂e/kg of edible pork, 5.6 kg of CO₂e/kg of edible chicken, and 23.4 kg of CO₂e/kg of edible beef. Calculations were made for all 3 alternatives. In the case of pork, for example, we multiplied the amount of edible products from culled calves and cows (i.e., based on the number of animal removed from the farm) with the emission factors presented in Table A3. Subsequently, we subtracted the same amount of edible products multiplied by the emission factor per kilogram of edible pork. The final result was added to the emissions related to dairy farming and divided by the total amount of FPCM to determine GHG emission per tonne of FPCM.

RESULTS AND DISCUSSION

Maximizing Labor Income

Diets and Farm Plan. Table 2 shows diets, farm plan, and farm outputs of the reference scenario and the scenarios in which milk yield and longevity were

increased with 1 genetic SD. Results are based on maximizing labor income.

For the reference scenario the following results apply. In summer, the maximum amount of fresh grass is fed because grazing is the cheapest way of feeding. Subsequently, maize silage in combination with a small amount of medium protein concentrates is added to meet requirements for energy and rumen-degradable protein balance. In winter, the diet contains 2.7 kg of DM grass silage per cow per day, based on the amount of grass remained after grazing. Again, maize silage in combination with medium protein concentrates is added to meet requirements for energy and rumen-degradable protein balance. The reference scenario has 168 dairy cows, 59.5 ha of grassland, and 25.5 ha of maize land. The number of cows is based on the amount of manure that can be applied on the farm according to environmental legislation. In the reference scenario, application standards on the amount of P₂O₅ were restricting (Table 2). The area of grassland is exactly 70%, which is the minimum requirement for farms to comply with the derogation regulation that allows the application of 250 kg of N/ha per year from animal manure, instead of 170 kg of N/ha per year; total milk production is 1,543 t of FPCM/yr (i.e., 18.2 t of FPCM/ha). Current Dutch dairy farms on sandy soils produce on average about 13.4 t of FPCM/ha (FADN, 2012). This means that our reference scenario is more intensive compared with current practice. This results from higher grass and maize yields per hectare (i.e., based on predicted increase in yield for 2020) and from application of precision feeding (i.e., ignoring safety margins for rumen-degradable protein balance and true protein digested in the small intestine commonly applied in practice). Labor income in the reference scenario is €115,050/yr.

Increasing milk yield by 1 genetic SD changed the diets and farm plan of the reference scenario (Table 2). The number of cows increased and part of the maize land was changed into grassland. Diets were changed to meet the increasing requirements for energy and protein and because the area of grassland increased. This resulted from an increase in the number of cows and P₂O₅ application standards being restricting (more P₂O₅ from animal manure can be applied on grassland than on maize land). In the reference scenario, the costs of an increase in grassland at the expense of maize land were higher than the revenues of keeping more cows. After increasing milk yield, the revenues per cow increased and outweighed the costs of an increase in the area of grassland at the expense of maize land. After increasing milk yield, the number of cows and grassland increased until application standards for N from animal manure became restricting (Table 2). Total milk production at the farm level increased to 1,691 t of FPCM/

Table 2. Diets, farm plan, and farm outputs for the reference scenario and after increasing milk yield and longevity with 1 genetic SD, based on maximizing labor income

Item	Reference	Milk yield	Longevity
Diet (kg of DM/cow per day)			
Summer period			
Grass silage, 225 kg of N/ha	12.0	12.0	12.0
Maize silage	8.4	8.9	8.4
Concentrate, medium protein	0.7	1.3	0.7
Diet restriction ¹	E,R	E,R	E,R
Winter period			
Grass silage, 225 kg of N/ha	2.7	5.0	4.2
Maize silage	8.0	8.9	8.4
Concentrate, medium protein	6.5	4.6	5.0
Diet restriction ¹	E,R	E,R	E,R
Farm plan			
Dairy cows (n)	168	171	182
Young stock ² (U)	51	52	46
Grassland, 225 kg of N/ha (ha)	59.5	67.9	67.4
Maize land (ha)	25.5	17.1	17.6
Synthetic fertilizer			
kg of N/ha	107	113	112
kg of P ₂ O ₅ /ha	—	—	—
Purchased maize silage (t of DM)	207	396	381
Purchased concentrate (t of DM)	247	207	213
Manure application restriction ³	P	aN, P	aN, P
Farm output			
Milk (t of FPCM ⁴)	1,543	1,691	1,677
Dairy cows (n)	45.3	46.0	40.9
Young stock, >12 mo (n)	3.9	4.0	3.6
Young stock, <12 mo (n)	2.1	2.1	1.9
Calves (n)	116.8	118.6	135.7
Farm income (€)	115,050	135,477	128,765

¹The diet can be restricted by: E = energy requirements; R = rumen-degradable protein balance; T = true protein digested in the small intestine; I = intake capacity.

²One unit includes 1 animal <12 mo and 0.96 animal >12 mo.

³The intensity of the farm is restricted by the possibility to apply manure. Manure application can be restricted by tN = total mineral N; aN = N from animal manure; P = P₂O₅.

⁴FPCM = fat- and protein-corrected milk.

yr, and labor income increased to €135,477. This is an increase of €122/cow per year.

Increasing longevity by 1 genetic SD reduced the replacement rate of the dairy herd (from 27.0% in the reference scenario to 22.5% after increasing longevity). Similar to milk yield, this resulted in a situation where maize land was changed into grassland to increase to amount of P₂O₅ that can be applied on the field, and hence the number of dairy cows. Because of the reduced replacement rate, less young stock was kept (Table 2), reducing manure production of the herd. As a result, the number of dairy cows increased to 182. Again, the application standard for N from animal manure limited a further increase of dairy cows. Total milk production at the farm level increased to 1,677 t of FPCM/yr, and labor income increased to €128,765; this is an increase of €82/cow per year.

GHG Emissions. Table 3 shows GHG emissions for the reference scenario and changes in emissions after increasing milk yield and longevity with 1 genetic SD. Results are based on maximizing labor income.

In the reference scenario, total GHG emissions per tonne of FPCM added up to 882 kg of CO₂e without allocation, and 796 kg of CO₂e based on economic allocation. The most important contributor was CH₄ from enteric fermentation (50%). Other important contributors were emissions from manure and from production of concentrates (both 13%). Studies on current milk production systems find values around 1,000 kg of CO₂e/t of FPCM based on economic allocation (Flysjö et al., 2011; Zehetmeier et al., 2012; Van Middelaar et al., 2013a). Differences are explained by the higher productivity and efficiency representing the technical and institutional setting of 2020 in combination with precision feeding, compared with other studies that represent current production circumstances. These results imply that future dairy farms can reduce their environmental effect in terms of GHG emission per tonne of FPCM when aiming for an increase in efficiency.

Increasing milk yield by 1 genetic SD changed GHG emissions from various aspects (Table 3). Changes are expressed in kilograms of CO₂e per tonne of FPCM

Table 3. Greenhouse gas emissions for the reference scenario and the effect of increasing milk yield and longevity with 1 genetic SD (in kg of CO₂ equivalent/t of fat- and protein-corrected milk) based on maximizing labor income

Item	Reference	Milk yield	Longevity
Animal emission			
Enteric CH ₄ emission dairy cows	372	-5	3
Enteric CH ₄ emission young stock	73	-5	-12
Manure	118	-5	-6
On-farm feed production			
Grassland	67	6	6
Maize land	37	-14	-13
Production of farm inputs			
Maize silage	24	18	17
Concentrate, dairy cows	110	-27	-23
Concentrate, young stock	8	-1	-1
Synthetic fertilizer	51	-2	-2
Other inputs	23	-1	0
Total emissions	882	-36	-32
Economic allocation	796	-27	-23

without allocation. Increasing milk yield per cow reduced emissions per tonne of FPCM by diluting emissions related to maintenance and young stock. In addition, emissions changed because of changes in diets and farm plan. Emissions from the production of purchased maize silage increased (18 kg of CO₂e/t of FPCM), because the amount of maize silage in the diets increased whereas the production of on-farm maize silage decreased. Given the decline in amount of concentrate required per tonne of FPCM, emissions from concentrate production decreased (27 kg of CO₂e/t of FPCM). Increasing milk yield by 1 genetic SD decreased total GHG emissions per tonne of FPCM by 36 kg of CO₂e using no allocation, and by 27 kg of CO₂e using economic allocation. Based on economic allocation, the GHG value of milk yield is 247 kg of CO₂e/cow per year.

Increasing longevity by 1 genetic SD mainly affected emissions related to young stock and production of feed for dairy cows. Due to a lower replacement rate, emissions related to young stock (enteric CH₄ and emissions from concentrate production) decreased by 13 kg of CO₂e/t of FPCM. Due to a change in the diets of dairy cows toward more roughage and less concentrates, emissions from production of grass and maize silage increased by 10 kg of CO₂e/t of FPCM (including on- and off-farm production), whereas emissions from production of concentrates decreased by 23 kg of CO₂e/t of FPCM (Table 3). Increasing longevity by 1 genetic SD decreased total GHG emissions per tonne of FPCM by 32 kg of CO₂e using no allocation, and by 23 kg of CO₂e using economic allocation. Based on economic allocation, the GHG value of longevity is 210 kg of CO₂e/cow per year, which is 15% lower than the GHG value of milk yield.

Minimizing GHG Emissions

Diets and Farm Plan. Table 4 shows diets, farm plan, and farm outputs of the reference scenario and the scenarios in which milk yield and longevity were increased by 1 genetic SD. Results for the scenarios with increased milk yield and longevity are based on minimizing GHG emissions per kilogram of milk. In all scenarios, labor income and total milk production had to equal or exceed the amounts of the reference scenario. The reference scenario and its results, therefore, are exactly the same as for the method based on maximizing labor income (Table 2).

Increasing milk yield by 1 genetic SD and, subsequently, minimizing GHG emissions per tonne of FPCM affected the diet and farm plan. Labor income and total milk production were not restricting, which means that the optimal solution within the feasible region was determined by other constraints. The level of N fertilization on grassland reduced from 225 to 200 kg of N/ha per year. A reduction in N fertilization on grassland reduced emissions from cultivation per kilogram of DM grass and grass silage, whereas enteric CH₄ emissions increased (Table A3). Within the limits of environmental legislations on the application of manure, a fertilization level of 200 kg of N/ha per year resulted in the lowest GHG emissions per tonne of FPCM. The amount of concentrates in the diets was minimized. In summer, a decrease in kilograms of DM grass per cow per day allowed for an increase in kilograms of DM maize silage per cow per day, and a maximum roughage uptake within the limiting intake capacity. Also, in winter, the maximum amount of roughage was fed. In both diets, high-protein concentrates were added to fulfill requirements

Table 4. Diets, farm plan, and farm outputs for the reference scenario and after increasing milk yield and longevity with 1 genetic SD, based on minimizing greenhouse gas emissions

Item	Reference	Milk yield	Longevity
Diet (kg of DM/cow per day)			
Summer period			
Grass, 200 kg of N/ha	—	11.7	12.0
Grass, 225 kg of N/ha	12.0	—	—
Maize silage	8.4	9.3	8.4
Concentrate, medium protein	0.7	—	—
Concentrate, high protein	—	1.3	0.8
Diet restriction ¹	E,R	E,R,I	E,R
Winter period			
Grass silage, 200 kg of N/ha	—	4.5	5.3
Grass silage, 225 kg of N/ha	2.7	—	—
Maize silage	8.0	11.2	10.4
Concentrate, medium protein	6.5	—	—
Concentrate, high protein	—	2.9	2.3
Diet restriction ¹	E,R	E,R,I	E,R,I
Farm plan			
Dairy cows (n)	168	157	178
Young stock ² (U)	51	48	45
Grassland, 200 kg of N/ha (ha)	—	62.4	72.5
Grassland, 225 kg of N/ha (ha)	59.5	—	—
Maize land (ha)	25.5	22.6	12.5
Synthetic fertilizer			
kg of N/ha	107	92	95
kg P ₂ O ₅ /ha	—	—	—
Purchased maize silage (t of DM)	207	338	512
Purchased concentrate (t of DM)	247	141	117
Manure application restriction ³	P	P	P
Farm output			
Milk (t of fat- and protein-corrected milk)	1,543	1,558	1,640
Dairy cows (n)	45.3	42.4	40.0
Young stock, >12 mo (n)	3.9	3.7	3.5
Young stock, <12 mo (n)	2.1	1.9	1.8
Calves (n)	116.8	109.3	132.7
Farm income (€)	115,050	127,301	120,428

¹The diet can be restricted by: E = energy requirements; R = rumen-degradable protein balance; T = true protein digested in the small intestine; I = intake capacity.

²One unit includes 1 animal <12 mo and 0.96 animal >12 mo.

³The intensity of the farm is restricted by the possibility to apply manure. Manure application can be restricted by: P = P₂O₅.

for rumen-degradable protein balance. Although concentrates result in a lower enteric CH₄ emission than grass and grass silage, emissions during production are much higher (Table A2). The number of cows was restricted by P application standards and the area of grassland (because application standards are higher for grassland than for maize land). The area of grassland was determined by the amount of grass and grass silage in the diet, and hence by the maximum intake capacity of the cow. With total milk production as a minimum constraint, the number of cows increased as long as the increase in grass and grass silage was fully consumed and P application standards were not restricting. After increasing milk yield, this balance was reached at 157 cows, which is lower than the number of cows in the reference scenario. Total milk production increased from 1,543 to 1,558 t of FPCM/yr, and

labor income from €115,050 to €127,301/yr; this is an increase of €73/cow per year.

Increasing longevity resulted in a similar strategy as increasing milk yield. Nitrogen fertilization on grassland reduced to 200 kg of N/ha per year and the amount of concentrates was minimized. The number of cows increased to 178; a further increase was restricted by P application standards in combination with limits to the amount of grass and grass silage in the diets. Total milk production increased to 1,640 t of FPCM/yr, and labor income to €120,428/yr; this is an increase of €32/cow per year.

GHG Emissions. Table 5 shows GHG emissions of the reference scenario and changes in emissions after increasing milk yield and longevity with 1 genetic SD. Results are based on minimizing GHG emissions per kilogram of milk. For the reference scenario, results are

Table 5. Greenhouse gas emissions for the reference scenario and the effect of increasing milk yield and longevity with 1 genetic SD (in kg of CO₂ equivalent/t of fat- and protein-corrected milk) based on minimizing greenhouse gas emissions

Item	Reference	Milk yield	Longevity
Animal emission			
Enteric CH ₄ emission, dairy cows	372	−2	11
Enteric CH ₄ emission, young stock	73	−5	−12
Manure	118	−5	−5
On-farm feed production			
Grassland	67	−1	8
Maize land	37	−5	−20
Production of farm inputs			
Maize silage	24	15	32
Concentrate, dairy cows	110	−48	−62
Concentrate, young stock	8	−1	−1
Synthetic fertilizer	51	−8	−8
Other inputs	23	0	0
Total emissions	882	−60	−59
Economic allocation	796	−49	−48

exactly the same as for the method based on maximizing labor income (Table 3).

After increasing milk yield per cow, N fertilization on grassland was decreased and the diets of the dairy cows were changed. Per tonne of FPCM, emissions related to on-farm feed production, enteric fermentation, and production of various farm inputs decreased. Most important was the reduction in emissions from concentrates production (48 kg of CO₂e/t of FPCM without allocation). Emissions from the production of purchased maize silage were the only emissions that increased (15 kg of CO₂e/t of FPCM). Overall, emissions per tonne of FPCM decreased by 60 kg of CO₂e using no allocation, and by 49 kg of CO₂e using economic allocation. Based on economic allocation, the GHG value of milk yield is 453 kg of CO₂e/cow per year.

After increasing longevity, the number of young stock decreased, N fertilization on grassland decreased, and the diets of dairy cows changed. Per tonne of FPCM, emissions related to young stock, on-farm feed production, and production of synthetic fertilizer decreased; most significant was the reduction in emissions from concentrate production. Emissions from production of purchased maize silage and enteric fermentation of dairy cows increased. Overall, emissions per tonne of FPCM decreased by 59 kg of CO₂e using no allocation, and by 48 kg of CO₂e using economic allocation. Based on economic allocation, the GHG value of longevity is 441 kg of CO₂e/cow per year, which is 3% lower than the GHG value of milk yield.

Sensitivity Analysis

Emissions from LUC. It is important to realize that changing genetic traits does not only affect annual emissions, but can also affect nonrecurrent emissions

related to on-farm LUC. After increasing milk yield and longevity, maize land was changed into grassland contributing to CO₂ sequestration. Using method 1, this change in land use resulted in sequestration of 667 kg of CO₂e/t of FPCM per unit change of milk yield, and 636 kg of CO₂e/t of FPCM per unit change of longevity. Using method 2, sequestration was 252 kg of CO₂e/t of FPCM for milk yield and 1,062 kg of CO₂e/t of FPCM for longevity. Results show that both traits result in CO₂ sequestration due to on-farm LUC. Using method 1, the importance of milk yield relative to longevity increases, whereas for method 2 the importance of longevity increases. Opposite the annual emissions used to calculate GHG values, emissions from on-farm LUC are nonrecurrent and therefore cannot be included in the GHG value of traits.

Emissions from deforestation were calculated for 2004 (Barker et al., 2007; Audsley et al., 2009). Under the assumption that the rate of deforestation in 2004 can be used as an indicator for other years, emissions from deforestation were treated as recurrent emissions and included in the GHG values. Using method 1, including emissions from deforestation increased the GHG value of milk yield from 247 to 260 kg of CO₂e/cow per year and of longevity from 210 to 219 kg of CO₂e/cow per year. This increase in GHG values resulted from a decrease in land use per tonne of FPCM. Using method 2, the GHG value of milk yield decreased from 453 to 435 kg of CO₂e/cow per year and of longevity from 441 to 406 kg of CO₂e/cow per year. Including emissions from deforestation did not affect the relative importance of the traits and the absolute change in GHG values was limited. When the pressure on land use and the importance of deforestation increases, it can become relevant to include emissions from deforestation in GHG values and in the optimization procedure. Because of high

Table 6. Greenhouse gas (GHG) values of milk yield and longevity (kg of CO₂ equivalent/cow per year) using different methods for handling co-products, based on maximizing labor income and minimizing GHG emissions

Item	Maximizing labor income		Minimizing GHG emissions	
	Milk yield	Longevity	Milk yield	Longevity
No allocation or system expansion	326	291	552	544
Economic allocation	247	210	453	441
System expansion				
Pork	303	186	529	439
Chicken	321	201	547	453
Beef	133	50	359	302

uncertainty and variation in calculating emissions from deforestation, and because they differ in nature from annual emissions at farm-level, GHG values should be presented with and without emissions from deforestation (Van Middelaar et al., 2013b; Flysjö et al., 2012).

Methods for Handling of Co-Products. Table 6 shows the GHG values of milk yield and longevity using different methods for handling of co-products. Results show that methodological choices affect GHG values.

The GHG values of milk yield and longevity change when using system expansion instead of economic allocation and vary for different alternative products (Table 6). The absolute change in GHG values was the same for method 1 and 2. With system expansion, the difference in GHG values between milk yield and longevity are larger than with economic allocation. When longevity increases, fewer cows but more calves are culled. Because calves have a higher emission factor per kilogram of edible product than cows, increasing longevity increased emissions related to processing of culled animals, and hence resulted in a lower GHG value than an increase in milk yield.

Of the 3 alternative products, beef resulted in the lowest GHG values. Producing beef results in high emissions. Under the assumption that meat from culled calves and cows replaces beef from suckler cows, these emissions are subtracted from the GHG emissions of milk. An increase in milk yield or longevity means that, per kilogram of FPCM, less meat is produced that can substitute beef, and hence fewer emissions are subtracted per kilogram of FPCM. When fewer emissions are subtracted, total reduction per kilogram of FPCM is lower, and therefore so is the GHG value. Overall, these results indicate that increasing milk yield results in a higher GHG value than longevity when co-products are included in the analyses.

General Discussion

Using method 1, increasing milk yield with 687 kg/cow per year reduced GHG emissions by 4.1% to 6.8% (no allocation or system expansion). Bell et al. (2011)

found a reduction of 9.5 to 13.2% per genetic SD improvement of 1,241 kg of ECM/cow per year; those authors, however, increased milk yield while maintaining the same feed intake, which makes direct comparison difficult. For longevity, we found a reduction in GHG emissions of 3.6 to 6.7% when increasing the average number of lactations from 3.25 to 3.90 (no allocation or system expansion). Wall et al. (2010) found a reduction of 4.3% when increasing longevity from 3.0 to 3.5 lactations, but only included CH₄ and N₂O emissions at farm level. Both Wall et al. (2010) and Bell et al. (2011) did not optimize farm management with changing levels of genetic traits, which can lead to over- or underestimation; they also used different methods to calculate emissions. To calculate enteric CH₄ emissions, for example, we used feed-specific emission factors derived from mechanistic modeling techniques. This method is found to be more precise than the IPCC Tier 1 and 2 methods that were used by Wall et al. (2010) and Bell et al. (2011) (Kebreab et al., 2008; Alemu et al., 2011). Harmonization of methods to calculate GHG values is important when breeding organizations want to include environmental performance into their breeding goal.

Based on the results presented in the current study, milk yield is more important than longevity when both economics and reducing GHG emission are relevant (method 1: the economic value of milk yield is 49% higher than the value of longevity and the GHG value is 18% higher). If only reducing GHG emissions is relevant, milk yield and longevity are approximately equally important (method 2: the GHG value of milk yield is only 3% higher than the value of longevity). In that case, however, milk yield still has a higher economic value than longevity (€73/cow per year compared with €32/cow per year). This indicates that, in a situation where labor income becomes restricting, milk yield could result in a higher GHG value than longevity because more money is available to implement improvement options.

Results were based on a situation without output limitations, which allows for a change in the number of

cows. In addition, management factors, such as on-farm roughage production and purchases of feed, changed with a change in trait. As a result, GHG values not only represent the direct effect of a change in traits, but also the indirect effect due to changes in the number of cows and management factors. Because these factors are variable and can be influenced by the traits of the cow, including both direct and indirect effects, a change in traits was assumed to be most accurate for estimating GHG values.

Differences in diets and farm plan between method 1 and 2 show that dairy farmers are likely to change their management when standards to reduce GHG emissions are introduced. Compared with method 1, method 2 resulted in a reduction in N fertilization on grassland, and a reduction in the amount of concentrates. Results of both methods are influenced by the reference scenario, including farm size and environmental policies. In addition, production characteristics of the average cow in the reference scenario might have influenced results. This means that changing the constraints of the model or aspects of the reference scenario might change the results (Berentsen and Tiessink, 2003). Before using GHG values to define the breeding goal, the effect of such changes should be considered. Furthermore, a wider sensitivity analysis regarding prices and emission factors is required to verify the relative value of traits.

Methods used to calculate relative GHG values of genetic traits included not only emissions at farm level, but also emissions from the production of farm inputs (e.g., purchased feed). Although the dairy sector is not responsible for reducing emissions from industrial processes related to the production of farm-inputs, it is important to consider these off-farm emissions in the analysis. Excluding these emissions might yield strategies that reduce emissions at farm level, but increase emissions during production of farm-inputs (i.e., pollution swapping). By purchasing feed ingredients with a low environmental effect, dairy farmers can contribute to reduced emissions. In addition, this approach is consistent with accounting for costs of farm inputs in the calculation of economic values.

To illustrate the 2 methods presented in the current study, we only considered the effect of an increase in milk yield and longevity. Correlations between traits were not considered because we assumed that these traits will be included in the breeding goal. When calculating GHG values of longevity, we did not account for the potential loss in genetic gain through replacement heifers being genetically superior to older cows. Including this potential loss would decrease GHG values of longevity.

The need to include GHG values into breeding goals is currently limited, but might increase because of the

increasing concerns about GHG emissions. Relative GHG values can be used in a similar way as economic values (i.e., to determine which traits are most important when aiming for a certain goal, in this case minimizing GHG emissions).

Results show that N₂O emissions related to N fertilization of grassland are negatively correlated with CH₄ emissions related to enteric fermentation of grass and grass silage from grassland. Thus, reducing N fertilization on grassland reduces N₂O emissions, but increases enteric CH₄ emissions. Hence, the net effect on GHG emissions per tonne of milk is minimal, and reducing N fertilization on grassland below 200 kg of N/ha in a situation similar to our study does not pay off.

CONCLUSIONS

Both methods presented in the current study provide insight into the GHG value of genetic traits, but give different information. Which method to use depends on the objective of the dairy industry and the standards they have to meet. Method 1 shows the GHG value of traits in situations where maximizing labor income is the main objective, which relates to current practice. Method 2 shows the full potential of traits to reduce GHG emissions given the boundaries that were set for income and milk production, and relates to a situation where lowering emissions becomes more important than increasing income. Calculating GHG values of milk yield and longevity shows that the full potential of both traits to reduce GHG is about twice as high as the reduction based on maximizing labor income. In addition, milk yield has a higher GHG value than longevity, especially when the focus is on maximizing labor income. Including emissions from LUC and using different methods for handling co-products generally changed results further in favor of milk yield. Results can be used by breeding organizations that want to include GHG values in their breeding goal. To verify GHG values, the effect of prices and emissions factors should be considered, as well as the potential effect of variation between farm types.

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APPENDIX

Table A1. Nutritional values of feed ingredients¹

Dietary option	NE _L (MJ/kg of DM)	DVE ² (g/kg of DM)	OEB ³ (g/kg of DM)	N (g/kg of DM)	P (g/kg of DM)	Fill value ⁴ (kg/kg)
Concentrate						
Standard protein	7.2	100	5.6	24.1	4.5	0.29–0.72
Medium protein	7.2	133	27.8	32.2	5.0	0.29–0.72
High protein	7.2	200	83.3	48.3	8.0	0.29–0.72
Fresh grass						
125 kg of N	6.6	94	9.3	28.0	4.1	0.93
175 kg of N	6.7	96	16.1	29.4	4.1	0.93
225 kg of N	6.7	98	23.5	30.9	4.1	0.93
275 kg of N	6.8	99	31.2	32.4	4.1	0.93
Grass silage						
125 kg of N	5.9	70	22.2	25.6	4.1	1.08
175 kg of N	5.9	71	30.6	27.4	4.1	1.08
225 kg of N	6.0	73	39.0	29.0	4.1	1.08
275 kg of N	6.0	74	47.3	30.6	4.1	1.08
Maize silage	6.6	58	–36.0	13.4	1.9	1.02

¹All feed ingredients are available in summer and winter, except for fresh grass (only in summer).

²DVE = true protein digested in the small intestine according to Dutch standards (Tamminga et al., 1994).

³OEB = rumen-degradable protein balance according to Dutch standards (Tamminga et al., 1994).

⁴Fill value per kilogram of feed expressed in kilograms of a standard reference feed (see Jarrige, 1988). The fill value of concentrates increases with an increase in concentrate intake.

Table A2. Emissions factors for enteric fermentation and production per feed product

Feed product	Enteric fermentation ¹ (g of CH ₄ /kg of DM)	Production ² (g of CO ₂ equivalent/kg of DM)	
		Excluding LUC ³	Including LUC
Grazed grass			
125 kg of N/ha	23.74	128–284	313–469
175 kg of N/ha	22.74	142–337	309–504
225 kg of N/ha	21.74	156–386	311–541
275 kg of N/ha	20.74	171–435	316–580
Grass silage			
125 kg of N/ha	22.74	153–301	329–477
175 kg of N/ha	21.74	164–349	322–507
225 kg of N/ha	20.74	175–393	322–540
275 kg of N/ha	19.74	187–438	325–575
Maize silage, home grown	17.74	157–229	251–323
Maize silage, purchased	17.74	176	267
Concentrate			
Standard protein	20.09	724	836
Medium protein	19.55	741	862
High protein	19.93	774	934

¹Emission factors 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).

²Emissions from production of home grown grass and maize silage depend on type of fertilizer (organic or synthetic), which is an outcome of the LP model. Emissions per kilogram of DM can vary between the lowest (100% organic fertilizer) and the highest (100% synthetic fertilizer) figure. Emissions factors are presented excluding and including emissions from land use change. Including land use change involves an additional emission of 1.43 t of CO₂ equivalent/ha due to deforestation worldwide (Audsley et al., 2009). Land use per tonne of DM maize silage is 0.061 ha, and per tonne of DM concentrates is 0.087 (standard protein), 0.094 (medium protein), and 0.125 ha (high protein).

³LUC = land use change.

Table A3. Live weight and amount of edible product per animal, and emission factors per kilogram of edible product related to cows and calves culled from the dairy farm

Item	Live weight ¹ (kg/animal)	Edible product ² (kg/animal)	Emission factor ³ (kg of CO ₂ equivalent/kg of edible product)
Dairy cows	650	264	0.4
Heifers	545	221	0.4
Young stock, >12 mo	320	130	0.4
Calves (white veal)	225	101	10.5

¹Based on Remmelink et al. (2012).

²The ratio between edible product and live weight was estimated based on the ratio for beef (0.43; De Vries and De Boer, 2010) and the ratio between live weight and carcass weight for dairy cattle according to Šebek and Temme (2009) and Wageningen UR (2013).

³Emissions from transport and slaughtering of dairy cows, heifers, and young stock >12 mo were based on Finnish Environmental Institute (2002). Emissions from production of white veal (emissions from feeding, housing, transport, and slaughter) are based on H. Mollenhorst (Wageningen UR, Wageningen, the Netherlands, personal communication, 2013).