J. Dairy Sci. 90:5334–5346
doi:10.3168/jds.2006-842

DairyWise, A Whole-Farm Dairy Model

R. L. M. Schils, M. H. A. de Haan,[1] J. G. A. Hemmer, A. van den Pol-van Dasselaar, J. A. de Boer, A. G. Evers, G. Holshof, J. C. van Middelkoop, and R. L. G. Zom
Animal Sciences Group, Wageningen UR, PO Box 65, 8200 AB Lelystad, the Netherlands

ABSTRACT

A whole-farm dairy model was developed and evaluated. The DairyWise model is an empirical model that simulated technical, environmental, and financial processes on a dairy farm. The central component is the FeedSupply model that balanced the herd requirements, as generated by the DairyHerd model, and the supply of homegrown feeds, as generated by the crop models for grassland and corn silage. The output of the FeedSupply model was used as input for several technical, environmental, and economic submodels. The submodels simulated a range of farm aspects such as nitrogen and phosphorus cycling, nitrate leaching, ammonia emissions, greenhouse gas emissions, energy use, and a financial farm budget. The final output was a farm plan describing all material and nutrient flows and the consequences on the environment and economy. Evaluation of DairyWise was performed with 2 data sets consisting of 29 dairy farms. The evaluation showed that DairyWise was able to simulate gross margin, concentrate intake, nitrogen surplus, nitrate concentration in ground water, and crop yields. The variance accounted for ranged from 37 to 84%, and the mean differences between modeled and observed values varied between –5 to +3% per set of farms. We conclude that DairyWise is a powerful tool for integrated scenario development and evaluation for scientists, policy makers, extension workers, teachers and farmers.

Key words: dairy farm, economy, environment, modeling

INTRODUCTION

In the European Union (**EU**), dairy production is a major contributor to the total value of agricultural production (EUROSTAT, 2005). At present, most milk is produced on specialized dairy farms. As in other industries, dairy farmers are constantly challenged to adjust their operational, tactical, and strategic management to maintain or improve the profitability of their enterprise under changing market conditions and increasing societal and environmental needs (Burrell, 2004). The 2003 CAP reform aimed to shift from price support for commodities to support targeted at environmental and other objectives (Cropper and Del Pozo-Ramos, 2006). Although milk quotas will remain until 2015, the dairy sector may be entering the pre-quota-abolition period (Burrell, 2004).

The dairy sector has to deal with a wide range of matters from a global scale, such as the Kyoto protocol on emission of greenhouse gases (**GHG**), to a regional scale, such as EU directives concerning standards on water quality, wildlife habitats, and animal welfare. Furthermore, national governments or county councils may impose additional environmental measures, such as on manure storage and application.

Although this is the common trend in the EU, there are considerable differences between individual countries in the way farms are affected by these socio-economic developments. In the Netherlands, where dairy farming is exceptionally intensive, farming systems are increasingly evaluated on their economical, social, and ecological sustainability (Van Calker, 2005). The high intensity of dairy farming, expressed in stocking rate or milk production per hectare, relies on significant imports of feed and fertilizer, resulting in environmentally undesirable losses of NO_3, NH_3, N_2O, P, and CH_4 (van Bruchem et al., 1999). The narrow scope on the basic functions of agriculture (i.e., food production and income for the rural population) has partly neglected the other functions of rural areas, and consequently increased the social pressure on farming (Vereijken, 2002). All these issues come together at the farm level.

A dairy farm is a complex system made up of several interacting subsystems such as livestock, manure management, soil, and crops. For a complete understanding of a farm system and its components, an interdisciplinary whole farm modeling approach is indispensable. Although several models exist that simulate a specific farm component, an integrated whole farm model applicable for the Netherlands has not been developed. The DairyWise model was developed to integrate the techni-

---

Received December 14, 2006.
Accepted July 13, 2007.
[1] Corresponding author: michel.dehaan@wur.nl

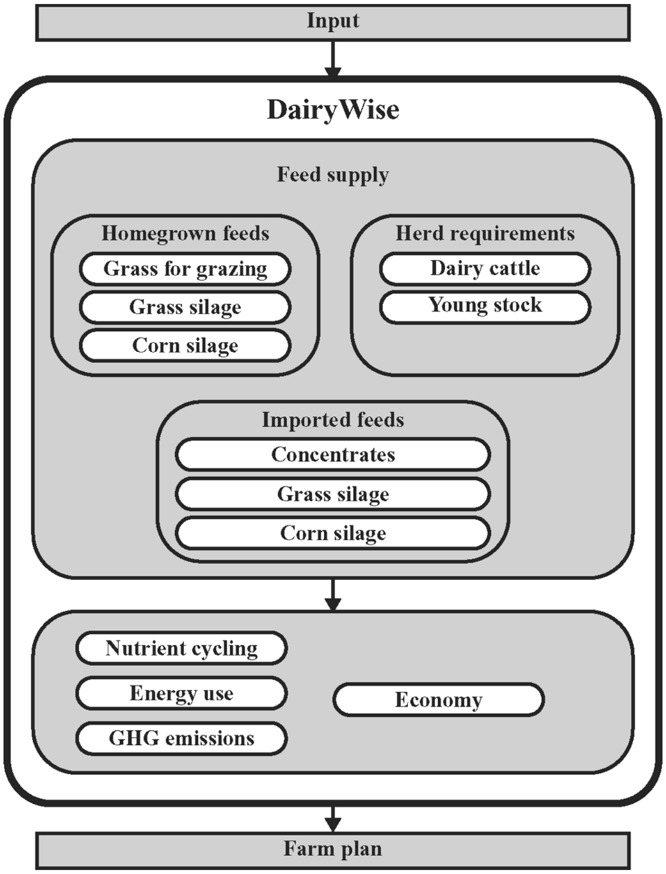

Figure 1. Modular structure of DairyWise. The model input consists of user-defined traits that describe a dairy farm. The Feed Supply model balanced the herd requirements with homegrown and imported feeds. The output of the Feed Supply model was the input of several submodels. The final model output consisted of a farm plan containing the technical, environmental, and economic data of the defined farm.

cal, environmental, and financial aspects of all major farm processes (i.e., feed and fertilizer import, crop management and feed production, animal feeding and production, manure production and utilization, and milk and meat exports). The DairyWise model combines already existing simulation models of specific subsystems into a whole farm model for use in interdisciplinary studies.

The objectives of this study were 1) to develop a whole farm dairy model, 2) to evaluate the model with data from experimental and commercial dairy farms, and 3) to identify prospective applications in research and knowledge transfer.

MATERIALS AND METHODS

Model Description

The DairyWise model integrates all major subsystems of a dairy farm into 1 whole-farm model (Figure 1). The central component of DairyWise is the FeedSupply model, which balances the herd requirements with the homegrown supply of grass and corn silage and imported feeds. The output generated by the FeedSupply model is fed into the different technical, environmental, and economic submodels.

Because the underlying experimental data and the detailed calculation procedures of the submodels have been published earlier, the description is restricted to the basic principles. All equations necessary to understand the model are available online (http://library.wur.nl/way/bestanden/clc/1847073.pdf; accessed Jul. 3, 2007).

Input Requirements

DairyWise has flexible input options depending on the required level of detail. The minimum data requirements contains 3 categories, including livestock and feed management, land and crop management, and miscellaneous. Livestock and feed management include the number of animals, the grazing system, and feeding strategy. The inputs in the category of land and crop management define the soil types, the area of forage crops, and the fertilizer application rates. If the user requires more details, it is possible to extend the list with additional inputs to overwrite the default values for many of the model parameters. Furthermore, the user is able to switch between closely linked parameters, like concentrate intake and milk production. In the default mode, the user determines the concentrate intake and the model calculates milk production. If the user chooses milk production as an input parameter, the model uses an iteration procedure to calculate the concentrate intake.

Crop Models

DairyWise has 2 separate models for the main forage crops grass and corn. The GrassGrowth model predicts the daily rate of DM accumulation of grass, including several feed quality parameters. It is an empirical model based on a series of field experiments on the main Dutch soils of sand, clay, and peat (Vellinga et al., 2004; Vellinga, 2006). All experiments were composed of a range of N applications, from 0 to 600 kg/ha per year. Additional core experiments included a range of growth times for each growing cycle necessary to derive growth curves. Regression analysis was used to derive growth curves for the potential DM yield without water limitation. The actual, water-limited DM yield was calculated with a drought factor, which was related to soil type and groundwater level. Soils with lower ground water levels can have DM yield reductions up

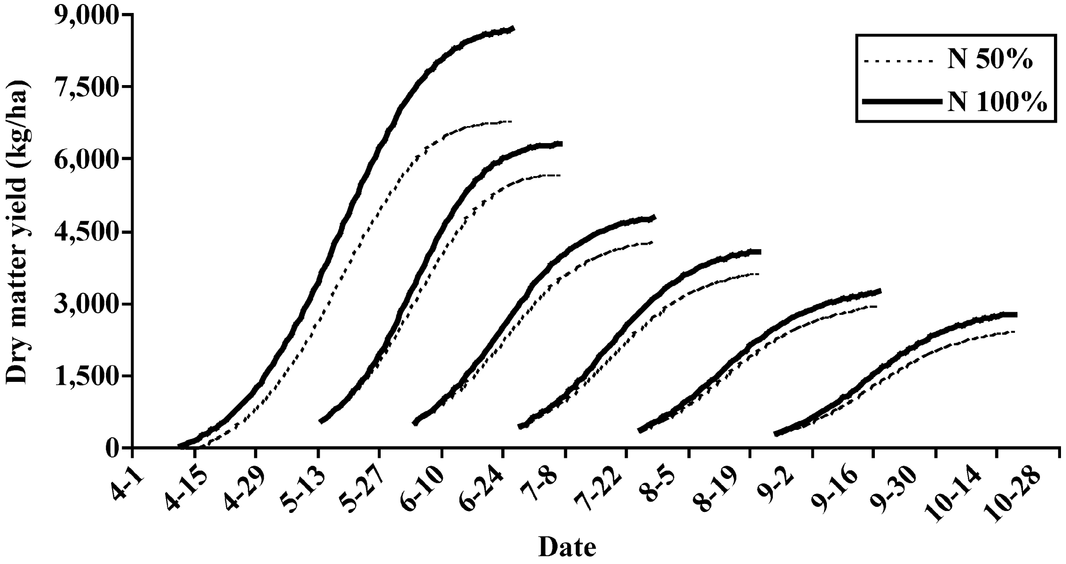

Figure 2. Growth curves for grassland without white clover on sandy soil in relation to N application and starting date. The N application level of 100% is equal to 120, 90, 60, 60, 30, and 30 kg/ha for the first to sixth growth cycle, respectively.

to 23% compared with soils with optimal moisture supply. All yields were based on perennial ryegrass (*Lolium perenne* L.) dominated swards.

The potential DM yield was a Gompertz function in which the maximum daily growth and the upper yield limit are the main traits. Both parameters are functions of a N supply factor composed of the effects of applied N, soil N, and residual N from previous fertilizer or manure applications. Different functions apply for the first and later growth cycles. An example of growth curves for individual growth cycles on sandy soil is shown in Figure 2.

The N yield of grassland is the product of DM yield and N concentration, but it was affected by a N dilution factor, representing the effect of growing period on N concentration. The N concentration in grass was related to a N supply factor, comparable with the N supply factor used for DM yield.

In the original experiments, harvested grass was analyzed for DM, crude fiber, CP, and crude ash, enabling the calculation of OM digestibility, NE_L (**VEM**; 1 VEM = 6.9 kJ of NE_L), digestible true protein, and degraded protein balance (Tamminga et al., 1994). These calculation procedures were included in the feeding value sections of the model.

The annual yield of grassland was the sum of the yields per cutting (Table 1). Because the yield in a certain cut was determined by its use, the annual yield of grassland was not a fixed value but depended on the cutting and grazing management. If grass was grazed, the DM yield generally ranged between 1,000 and 2,000 kg/ha, and if it was cut for silage, the yield generally varied between 2,500 and 4,500 kg/ha. Therefore, annual yields were generally higher if the proportion of grass cut for silage increased. Common grassland use in the Netherlands consists of grazing with the inclusion of 1 to 3 silage cuts per year. Yet, there is an increasing trend toward cutting only higher yields, but lower quality. With equal amounts of applied fertilizer, the DM yield increased among soil types in the order from sand, clay to peat. Nevertheless, peat soils usually received less fertilizer N as the soil N supply was higher than on mineral soils (Hassink, 1995).

Corn silage (*Zea mays* L.) is the most common forage crop. The N yield of corn is a function of N supply (Schröder et al. 1998), which were composed of applied fertilizer and manure, mineralization from plowed grassland and catch crops, and residual N from earlier applications. The actual DM yield of corn was calculated from a potential yield without N or water limitations. Reduction factors were defined for drought, weeding system, crop rotation, planting method, and reduced N application. The potential corn yield was updated annually to reflect the genetic improvements. At present the potential yield is 17,100 kg of DM ha/yr, while the actual yield for a sandy soil was modeled at 15,300 kg of DM ha/yr (Table 1). The energy content of conserved corn silage was set at a default value of 935 VEM/kg of DM, whereas the protein content depended on the N application.

Animal Models

DairyWise is composed of 2 separate models for dairy cows and young stock. The DairyCow model is an empir-

Table 1. Typical annual DM yields, nitrogen content and OM digestibility (OMD) of grass and corn silage predicted by the model for different soil types, N application rates, and grassland management

Item	Soil type	N applied (kg/ha)	Management	DM yield (1,000 kg/ha)	N content (g/kg of DM)	OMD (%)
Grassland	Sand	200	Grazing and cutting	12.3	28	80
	Sand	300	Grazing and cutting	13.4	32	80
	Sand	300	Cutting only	14.5	30	80
	Clay	300	Cutting only	14.9	30	79
	Peat	300	Cutting only	15.5	32	78
Corn silage	Sand	160		15.3	12	74

ical model that predicts feed intake and milk production of individual lactating and dry cows (Zom et al., 2002). The YoungStock model is an empirical model that simulates feed intake and growth of young stock (Mandersloot, 1989). The DairyHerd model combined the output of both models into a complete dairy herd. The feed intake of the DairyCow model was based on feeding trials with individual Holstein-Friesian animals fed ad libitum either roughage mixtures supplemented with fixed amounts of concentrates or TMR rations. The feed intake was calculated as the ratio between feed intake capacity (**FIC**) and satiety value (**SV**). The SV was a measure of the extent to which a feed limits the intake due to the triggering of a complex of chemostatic, hormonal, and physical processes that induce satiety. The FIC was the ability of the cow to process the intake-limiting SV units. For stall-fed rations, the feed intake of concentrate was defined by the user, whereas the roughage intake was calculated by the model. During grazing, concentrate intake, and supplemented roughages were user defined, and the model calculated fresh grass intake during grazing. The FIC was calculated as a function of animal traits, such as parity, DIM, and days pregnant. The SV of feed was calculated from the feed traits DM content, CP, crude fiber, and OM digestibility. There were separate functions for concentrate, fresh grass, grass silage, and corn silage.

The total energy intake of the animal was partitioned into 3 components. The first component combined the 3 sinks maintenance, growth, and pregnancy; the second component was milk production; and the third component was a 2-directional flow of mobilization or repletion of body tissue energy reserves. The energy requirements of the different components were related to production level, parity, and stage of lactation. The actual milk production was derived from a day-to-day comparison of the energy uptake with standardized milk production. The difference in energy uptake between the modeled cow and the standard cow led to a correction of the standard milk production.

The protein requirement was matched through variation in the protein content of the imported concentrate. DairyWise used 3 types of concentrate, differing in protein content. Figure 3 shows an example of daily milk production and feed intake of dairy cows in the first and third lactation.

The feed intake of the YoungStock model was based on default energy requirements according to a standard growth curve. The model aimed to maximize roughage intake. If the energy requirements cannot be met by roughage, concentrate was used to balance the ration. The total energy requirement was the sum of energy needed for maintenance, growth, gestation, and grazing activity.

The DairyCow and YoungStock models simulated individual animals, which were combined into a complete herd by the DairyHerd model. The dairy herd was made up according to different standard sets representing a spring-calving, an autumn-calving, or a staggered-calving herd (Mandersloot and van der Meulen, 1991). On a monthly basis, each set contained a proportional distribution of the animals among age groups and the number of cows calving according to a user defined annual replacement rate. Voluntary and involuntary culling rates were related to animal type and parity.

FeedSupply Model

The FeedSupply model balanced the herd requirements in terms of energy and protein with the supply of home grown and imported feeds. The homegrown feeds were grass, grazed or cut, and other forage crops, usually corn. The deficit between requirements and supply was imported as concentrates and roughage.

The gross yields of grass and forage crops were corrected for 1) grazing losses due to trampling, topping and rejection of grass near dung and urine spots, 2) field losses due to respiration, loss of leafs during tedding, windrowing, and harvest, and 3) conservation losses during storage due to fermentation, heating, and decay, and 4) feeding losses. The net uptake by the animals equaled the gross yield minus the total losses.

The DM grazing losses depended on the grassland management, and varied from 7% for zero-grazing systems to 22% for day-and-night grazing systems. The field losses depended on the number and type of harvest

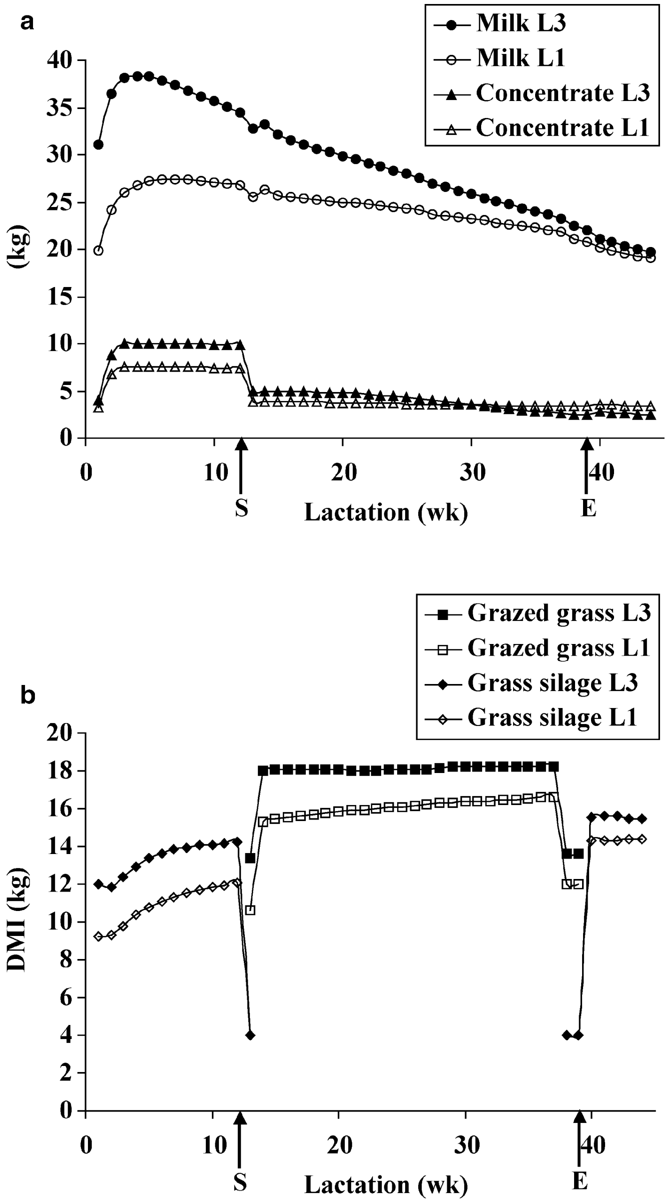

Figure 3. Daily milk production and intake of concentrate (a), and DMI of grazed grass and grass silage (b) for Holstein Friesian cows calving on February 1 in relation to parity (L1 and L3). Cows in the first lactation produce 7,000 kg of milk/yr, and cows in the third lactation produce 8,500 kg of milk/yr. The grazing season started at d 85 (S) and ended at d 273 (E).

activities. Each tedding operation led to 1.2% DM losses, whereas the final loading operation had a 2% DM loss. The conservation process changed the quality traits of stored silage so that the feeding value of silage was lower than that of fresh grass. Feeding losses were set at 2% for concentrates and 5% for roughages.

The model generated a grazing plan (Figure 4) based on the daily DM requirements of the herd and the supply of grass according to the growth curves of the grass growth model. The actual grazing plan depended on the preferred rotational grazing system, including the preferred grazing time per paddock, and choices in allowed feed supplementation in the grazing season. The first priority was the allocation of grass for grazing and surpluses were cut for silage, unless the model indicates that the system was running out of available grass for grazing. If a field was grazed 2 consecutive times, the second grazing was immediately followed by topping to remove the rejected areas. The total grassland area was subdivided in pens that were grazed during 2 to 4 d. For a period of 14 d in advance, the model calculated all possible permutations of pen choices and assigned marks to each pen for the number of available grasses, available grazing days, growth time, and previous use. The pen with the lowest mark was used for grazing.

In a similar manner a feeding plan was generated for the confinement period, again balancing the herd requirements with the quantity and quality of home-grown grass and forage silages, and imported feeds. The best quality silage (i.e., grass silage from the first and second cut and corn silage) was allocated to the highest yielding animals, whereas lower quality silage (e.g., silage from autumn harvests) was allocated to lower yielding animals.

The final output of the FeedSupply model contained all information on the yield and quality of home grown and imported feeds, and the level of feed intake and milk production. Together with additional inputs, the output of the FeedSupply model was used as an input for the other technical, environmental, and economic submodels.

Nutrient Cycling

The main components of a dairy farm with respect to nutrient cycling are herd, manure, soil/crop, and feed. The nutrient cycling submodel described the flow of N, P and potassium through these components, including NH_3 and NO_3 losses to the environment. Here are described those parts of the nutrient cycle that were not directly linked to the processes described earlier in the crop and animal production models (Schreuder et al., 1995). The nutrient flows in those processes (e.g., crop and animal nutrient uptake) were part of those models.

In the default mode, DairyWise applied the fertilizing recommendations for agronomical optimal yields (Unwin and Vellinga, 1994), but the user is free to change the fertilizer application rates. The annual N application was partitioned over the individual growth cycles in relation to the expected yield level and application time. The level of N application on corn silage depended on the N supply from the soil, plowed grassland and catch crops, and past fertilizer and manure applica-

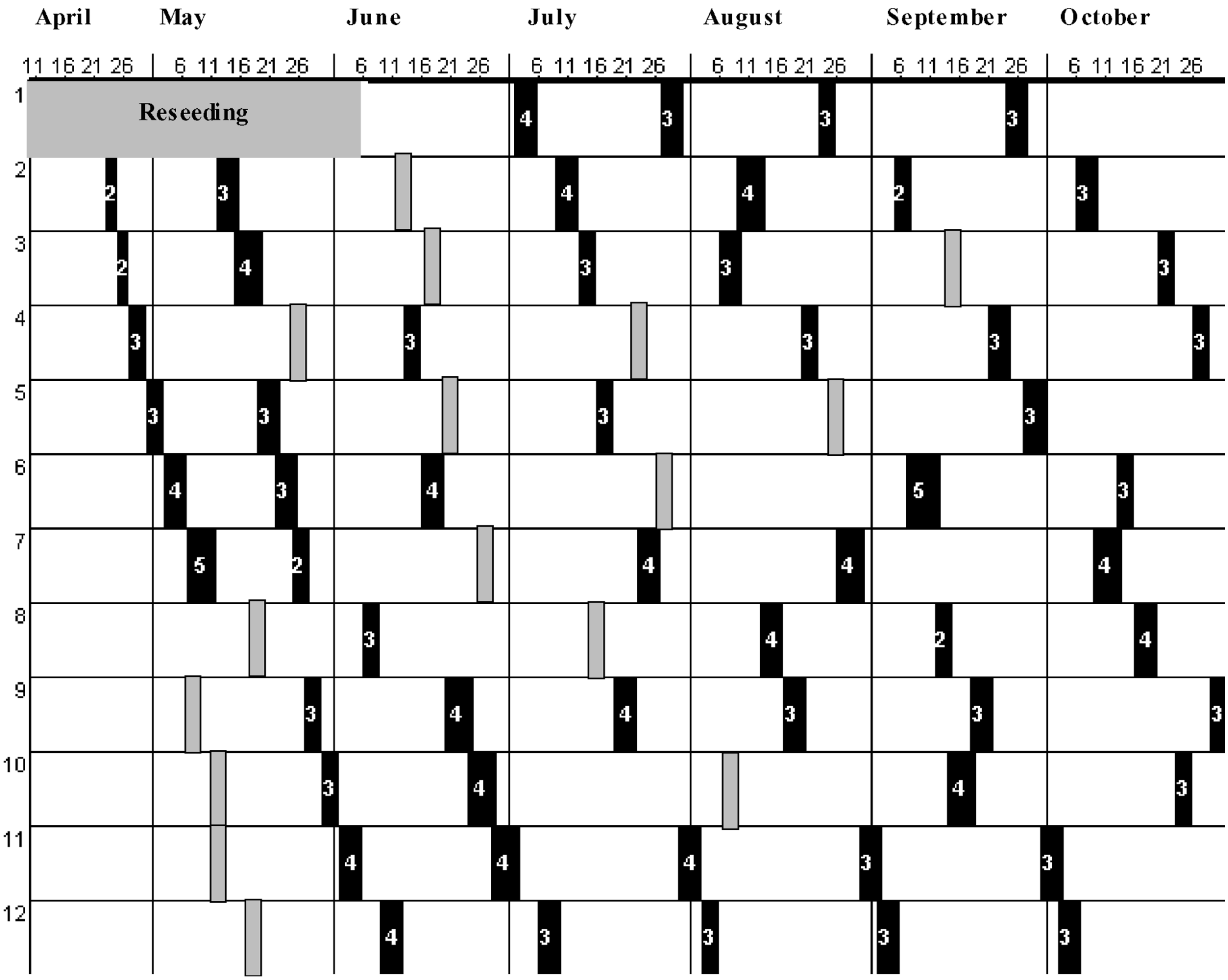

Figure 4. Grassland management plan of a dairy farm in the Netherlands with 12 grassland pens. Gray bars represent silage harvest. Black bars represent grazing periods, including the length of the grazing period in days.

tions. Phosphate and potassium applications depended on soil type and soil nutrient status, and for grassland, the type of management, and for corn silage the fertilizer application method. The application rates of fertilizer were reduced to compensate for the fertilizing value of nutrients in applied manure. The fertilizing value manure was accounted for through conversion into manure fertilizer equivalents. The N fertilizing value of manures depended on application method and time. For grassland 1 kg of manure N was equivalent to 0.28 to 0.50 kg of fertilizer N, whereas for corn silage this figure varied from 0.57 to 0.80 kg of fertilizer N. The phosphate and potassium fertilizing value was always 1 kg/kg.

The undigested fraction of N was excreted through feces. The digested N that was not utilized to meet animal requirements was excreted in the urine. For phosphate and potassium, the undigested fraction was excreted in the feces. For the available fraction, 3 and 80% of the P and potassium was excreted through urine. The protein digestibility of the complete ration was the weighed average of the digestibility of the ration components. The N content of milk was calculated directly from the protein content, while other nutrient requirements had default values for milk, meat, and the fetus.

The fraction of indoor excretion was related to the grazing system and roughage supplementation during the grazing period. The fraction of indoor excretion was then used to calculate the amounts of N, phosphate, and potassium in the manure storage. Additional nutrient flows to manure like bedding material and wasted feeds were accounted for as well.

Ammonia emissions were calculated from housing and manure storage, urine excretion during grazing, and manure and fertilizer application. DairyWise distinguished 3 sources of NH_3 emission from housing and storage. The emission from the floor and the internal manure storage, under a slatted floor, were a function of indoor temperature and protein in the animal diet (Van Duinkerken et al., 2003). The emission from external manure storages was a function of outdoor temperature and the storage construction traits height and roof type. The NH_3 emission from grazing was set at 8% of the excreted N (Bussink, 1994). The NH_3 emission from manure application depended on the application method, and varied from 2.5 to 25% of applied N (Huijsmans et al., 2001). Ammonia emission factors from fertilizers were set at 1% for calcium ammonium nitrate and 10% for ammonium sulfate.

Nitrate leaching to ground water was calculated for sandy soils according to the NO_3 leaching model of Vellinga et al. (2001). The amount of NO_3 leached was related to the amount of soil mineral nitrogen (**SMN**) to a depth of 1 m at the end of the growing season and soil type. The ground water table determined the partitioning of SMN in NO_3 leaching and denitrification. The lower the groundwater table, the higher the proportion of NO_3 leaching. For grassland a basic SMN was calculated from the difference between applied and harvested N. In the case of grazing, additional SMN was calculated from urine excretions.

The submodel NutrientCycling enabled the calculation of whole farm balances and farm gate surpluses. Internal balances for the animal, manure, soil/crop, and feed components could be established allowing calculation of resource use efficiencies for the different components as a tool to analyze strong and weak points of a dairy farm.

Energy Use

The energy use itself, as calculated in the submodel “energy use”, consisted of direct on farm and indirect energy use (Hageman, 1994). The direct energy use consisted of fuel and electricity use. The fuel use was calculated from the farm machinery activities and the associated energy use. Electricity was mainly used for milking, heating water, and cooling milk.

The indirect energy use was associated with the production of imported resources. In this respect, we distinguished i) purchased goods (i.e., fertilizer, concentrate, silage, and manure), ii) services (e.g., contractors), and iii) buildings and machinery. All purchased goods had energy coefficients per item, whereas services and buildings had energy coefficients related to their financial value.

Greenhouse Gases

Methane, N_2O, and carbon dioxide emissions were calculated in the submodel GHG emissions, with emission factors according to those used in Dutch emission inventories (Schils et al., 2006). Methane emissions were calculated from manure storage and from enteric fermentation, the latter with different emission factors for concentrate, grass products, and maize (*Zea mays* L.) silage.

Direct N_2O emissions were coupled to manure management, excreted N during grazing, manure application, fertilizer use, crop residues, mineralization from peat soils, grassland renewal, and biological N fixation. The emission factors were related to soil type and ground water level, with generally higher emissions on organic soils and wetter soils.

Indirect N_2O emissions were those emissions that occurred after N was lost from the system. It applies to NO_3 leaching, NH_3 volatilization, and N_2O emission. To complete the greenhouse gas emissions, carbon dioxide emissions were related to the fossil fuel based energy use. Different emission factors were used for the categories fuel consumption, electricity use, indirect energy use, and fertilizer use.

Economy

The economic submodel “farm budget” calculated the financial results of the dairy activity. The measures to describe the overall financial performance were gross margin, farm income, and cost of milk production. Gross margin was defined as the difference between revenues and variable costs, with or without costs for contractors. Farm income was the difference between gross margin and fixed costs, minus a compensation for the farmer’s labor. The cost of milk production was expressed per 100 kg of milk and was calculated as the difference between costs and revenues, other than milk revenues.

The financial revenues from the dairy activity consisted of milk and animal sales, and in the case of surplus home grown silage, feed sales. Additional income could be generated through subsidies as EU milk or meat support.

The variable costs comprised feed, energy, crop protection, fertilizers, seeds, and several minor costs. The main fixed costs were the farmers and hired labor, buildings and machinery depreciation and maintenance, and interest. The current prices of resources and commodities were stored in a database. The prices were updated annually, but individual prices could be adjusted as required.

Table 2. Main characteristics of representative Dutch dairy farms on sand, clay, or peat soil, and key outputs of DairyWise

	Soil type		
Item	Sand	Clay	Peat
Model input			
Dairy cows (n)	63	71	64
Young stock (n)	44	48	39
Area (ha)	35	41	39
Grass	27	37	37
Corn	8	4	2
Grazing system	Daytime only	Day and night	Day and night
Milk production (kg/yr)	7,620	7,750	7,440
Milk quota (1,000 kg)	481	551	474
Model output			
Fertilizer N application (kg of N/ha)	175	220	158
Self-sufficiency roughage (%)	72	107	77
Feed intake (kg of DM/yr)	6,444	6,450	6,488
Nitrogen surplus (kg/ha)	212	235	225
Ammonia emission (kg/ha)	43	58	74
Nitrate in groundwater (mg/L)	55	—	—
Nitrous oxide emission (kg/ha)	11	13	32
Methane emission (kg/ha)	336	342	306
Energy use (GJ/ha)	58	57	52
Financial margin (k€)	140	169	140
Production cost (€/kg of milk)	0.40	0.38	0.42

DairyWise Output

The output was a farm plan consisting of summarized and detailed results. The reporting tool had the ability to directly compare the summary of 4 farm plans. In general, the summary reports contained the consolidated data for the total herd and farm. Detailed reports contained more data: i) per season, month, week or day, ii) per animal group or individual animal, and iii) per crop or per field. Reports could be generated in text (.txt), portable document (.pdf) or MS excel (.xls) formats. To illustrate the range of aspects handled by DairyWise, Table 2 summarizes some output variables for representative dairy farms in the Netherlands. The input data for the model were generated from national farm accountancy data (LEI, 2004).

Farm Data

Evaluation of DairyWise was performed with data from commercial and experimental dairy farms in the Netherlands. The first data set consisted of 20 commercial dairy farms in northern regions. All farms were clients of 1 accountancy firm that was responsible for the data collection. The farms varied in size from 19 to 438 ha, with 68 to 100% of the cultivated area in grass, 29 to 272 dairy cows, and 290,000 to 2,074,000 kg of milk quota. The large variation in farming intensity resulted in a wide range of fertilizer N use and consequently a wide range in crop yields. The annual milk production per cow varied from 6,126 to 10,752 kg of fat and protein corrected milk production, 4% fat and 3.3% protein). The input variables, collected in the year 2004, were the areas of grassland and corn silage, fertilizer N application, number of dairy cows and young stock, and milk production per cow, including fat and protein production. The evaluated parameters were

1) gross margin (€/100 kg of milk), defined as total sales minus costs for feed, animals, crops, and contractors;
2) nitrogen surplus (kg of N/ha per year), defined as the difference between inputs through feed, fertilizer, manure, and deposition, and outputs in milk, meat, feed, and manure;
3) total crop yield (kVEM/ha per year), calculated as the difference between total herd requirement minus energy uptake through concentrate and imported silage. The recording methods on the commercial farms were not detailed enough to calculate separate yields for grassland and forage yields.
4) concentrate intake (kg/cow per year), including concentrate fed to young stock.

The second data set consisted of a combination of 3 experimental farms and 6 commercial pilot farms in the Netherlands. Compared with the first group, the farms in this group had very specific environmental or financial goals. The farmers were coached more intensively and they were involved in an extensive data collection program. The 6 commercial pilot farms were part of the "cows & opportunities" network (Oenema et al., 2001). The farmers that participated in this network had committed themselves to accomplish environmental targets several years ahead of the rest of the country. Data for the year 2003 were used. The first experimental farm De Marke was part of the cows & opportunities network with even more stringent environmental objectives (De Haan, 2001). For De Marke, the average data were used from 1993 to 1997. The 2 other experimental farms were both involved in a research program aimed at a reduction of the cost of milk production by means of different strategies. The strategy of the low-cost farm was to reduce the costs of milk production by minimizing investments in building and labor, a low concentrate input, and extended grazing. The strategy of the high-tech farm was cost reduction by means of improved efficiency through automatic milking and other technological innovations like the use of robots for roughage feeding and manure scraping. For the latter 2 experimental farms, data were used from the year 2004. Compared with the first data set of the commercial farms, the model input was extended with soil type, ground water level, fertilizer, and manure application on grassland and forage crops and grazing management. The evaluated variables were as follows:

1) Nitrogen surplus (kg of N/ha per year), defined as the difference between inputs through feed, fertilizer, manure and deposition, and outputs through milk, meat, feed, and manure.
2) Gross margin (€/100 kg of milk), defined as total sales minus costs for feed, animals, and crops, but excluding contractor costs. Contractor costs were excluded because they were affected too much by additional work related to the nature of experimental farms.
3) Net grassland yield (kg of DM/ha per year), defined as the sum of harvested grass silage, excluding field and conservation losses, and net grass intake during grazing.
4) Nitrate in ground water (mg/L), for the farms on sandy soils only. Nitrate concentrations in the first meter of ground water were measured extensively as part of a national water quality monitoring system (Boumans et al., 2001).

Evaluation Procedure

Regression analysis was used to evaluate the model output. The regression line Y = β_0 + β_1 X, with Y = observed and X = modeled, should have $\beta_0 = 0$ and $\beta_1 = 1$, which denotes a 45° line through the origin. As we were interested in evaluating the difference between Y and X, the model had a good fit if β_0 and β_1 were not significantly different from 0 and 1, respectively.

RESULTS

On the commercial farms (Figure 5), the modeled N surplus was 3% higher than the observed surplus, with a variation between −14 and +11%. As imports through fertilizer and exports in milk were input variables for the model calculations, the variation in N surplus was mainly determined by differences in feed imports and manure exports. On the pilot and experimental farms (Figure 6), the N surplus was underestimated by 1%, with a range from −16 to +12%. It is surprising that the 2 largest deviations were observed on 2 experimental farms where the N surplus was underestimated by 15 and 16%. On the high-tech experimental farm the model underestimated the protein content of the concentrates on the farm, whereas on the experimental farm De Marke, the model overestimated the grassland yields and the roughage sales. For both data sets the variance accounted for was high, and the lack of significance for $\beta_0 \neq 0$ and $\beta_1 \neq 1$ confirmed the good model fit (Table 3).

For both data sets, gross margin was underestimated by 1%, with a range from −12 to +15%. On the majority of the commercial farms, the gross margin was modeled between €23 and €27 per 100 kg of milk, compared with the actual range of €21 to €29 per 100 kg of milk.

On the commercial farms, net crop yields were overestimated by 3% with a variation from −14 to +20%. In the lower yield range, up to 9,000 kVEM/ha, the modeled crop yields generally overestimated the observed crop yields. Above a crop yield of 9,000 kVEM/ha, the modeled yields were generally lower than the observed yields. Furthermore, the difference between modeled and actual yields increased at higher yield levels. The average net grass yield on the experimental and pilot farms was underestimated by 1%, with a variation of −11 to +13%. Within the 4 evaluated variables, the crop yield was most directly linked to local soil and weather circumstances. Therefore, it was no surprise that this variable had the largest differences between modeled and observed values, with a low variance accounted for and high standard error (Table 3). Nevertheless, the lack of significance of the regression parameters confirmed a good model fit.

On the commercial farms, concentrate intake by dairy cows was underestimated by 1%, with a variation from −13 to +12%. The largest variation was at the intermediate feeding levels.

On the pilot and experimental farms on sandy soil, the NO_3 concentration in ground water was underestimated by 5%. There was no relation between the deviations in N surplus and NO_3 leaching.

DISCUSSION

Evaluation

In general, the evaluation showed that DairyWise produced acceptable results with differences between

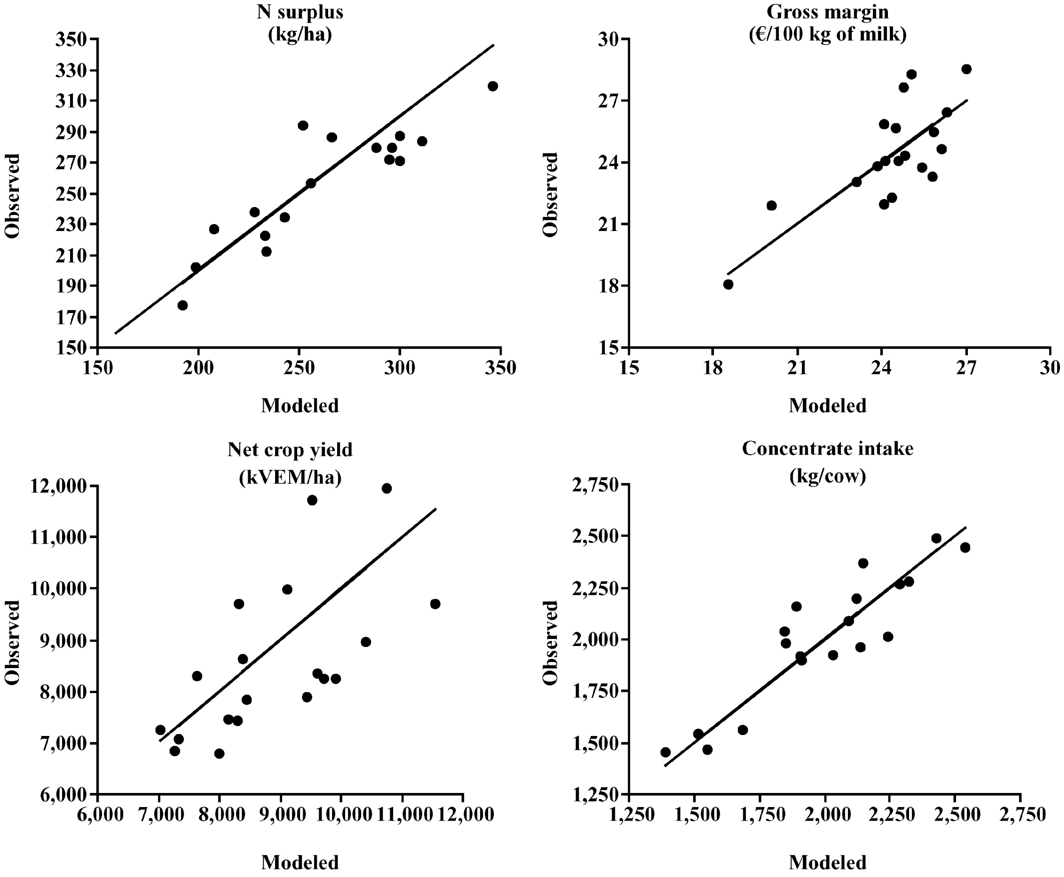

Figure 5. Observed and modeled nitrogen surplus, gross margin, net crop yield, and concentrate intake for 20 commercial dairy farms.

modeled and observed values of −5 to +3% over a set of farms. For individual farms the deviation varied from −19 to +20%. The results were slightly better for the experimental and pilot farms than for the commercial farms. This was not surprising because there were more observed data available for the experimental and pilot farms than for the commercial farms.

It has to be realized that the underlying experimental farm field data were averages of several years, and thus the modeled output applies for a year under average weather circumstances. The actual weather in individual years affected the difference in observed and modeled values. Moreover, individual management styles of farmers were not always similar to the general code of good agricultural practice as implemented in DairyWise. Although the quality of the individual predictions was acceptable, it was more important that changes in management were reflected in the modeled farm plans. The evaluation showed that the model gave acceptable results for current commercial farms and for pilot future farms with new management strategies.

Integrated Whole-Farm Approach

A dairy farm is a complex system with several interacting subsystems. The utilization of homegrown feeds by animals and the return of excreta to the soil-crop system is an essential feature of many ruminant livestock systems. This distinguishes dairy systems from intensive pig or poultry production systems where compound feeds are imported and animals and manure are exported, and from arable systems where fertilizers and manure are imported and crops are exported. Whole-farm models of dairy systems must provide an accurate representation of the internal cycling of materials and their constituents as well as the exchange of materials and nutrients between the farming system and its environment. Moreover, such models should reliably predict the effects of changes in management. For dairy farming systems in the Netherlands, DairyWise was able to simulate internal and external flows of materials and nutrients, and calculate the related economic traits. The whole farm approach, adopted in DairyWise, en-

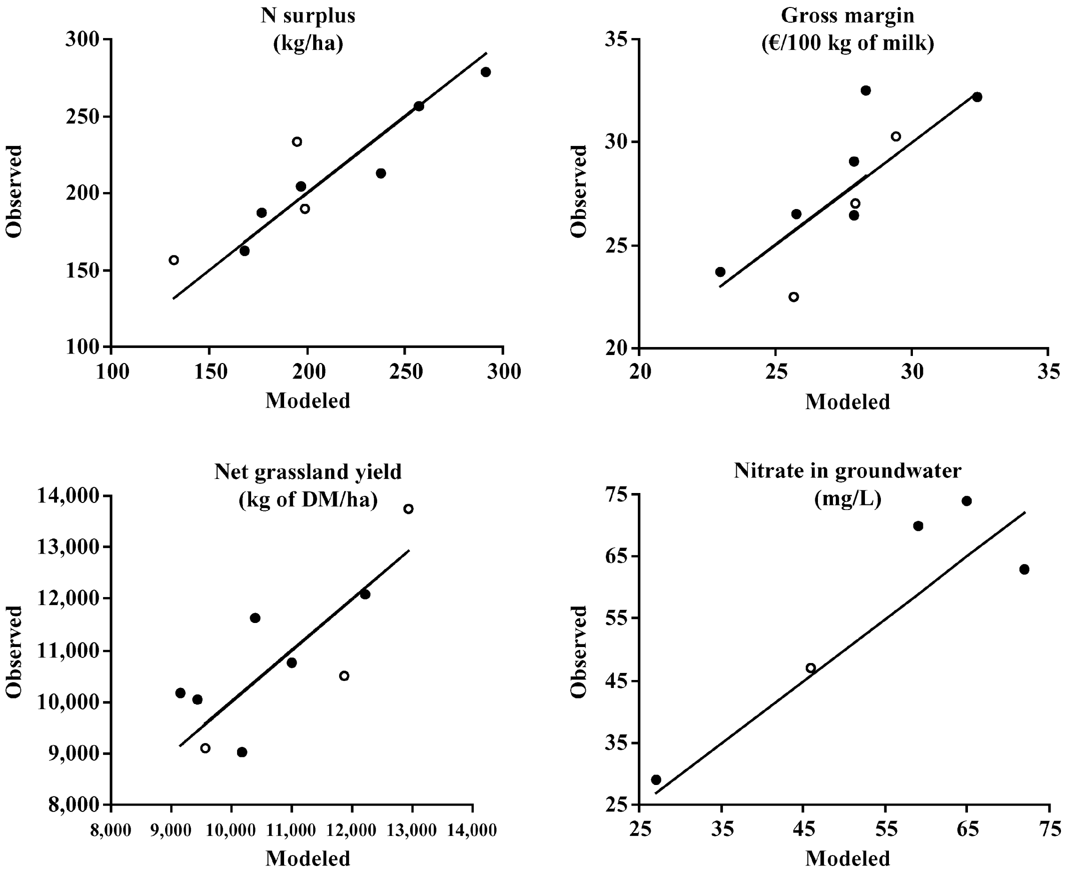

Figure 6. Observed and modeled nitrogen surplus, nitrate in ground water, gross margin, and net grassland yield for 6 pilot farms (●) and 3 experimental farms (○).

sured that the interactions between the relevant themes were taken into account. Effects of changes in 1 farm component were not confined to that particular subsystem, but were transferred throughout the whole farm system. Consequently, such an approach prevented those issues that are viewed in isolation and management options were proposed without reflecting the effect on other relevant issues. For example, it was obvious that farm strategies with reduced grazing would lead to a shift from outdoor excretion to indoor excretion. Ammonia emissions during grazing would be reduced, but this would be offset by increased NH_3 emission from the housing system. Manure could be used more efficiently, which in turn lead to a lower fertilizer requirement, lower NO_3 leaching losses and lower N_2O emissions. On the other hand the quality of

Table 3. Model evaluation for commercial farms (set 1) and pilot and commercial farms (set 2), showing mean actual and mean predicted values, variance accounted for (R^2) and SE and estimates (Est), SE, and t probability (t_pr)[1]

		Mean				β_0			β_1		
Set	Parameter	Actual	Model	R^2	SE	Est	SE	t_pr	Est	SE	t_pr′
1	N surplus (kg/ha per yr)	259	266	85.9	19.8	28.3	21.8	0.212	0.869	0.080	0.119
	Gross margin (€/100 kg of milk)	24.4	24.3	52.6	1.68	2.33	4.71	0.627	0.908	0.193	0.640
	Net crop yield (kVEM/ha per yr)	8,600	8,892	37.4	1,165	1,762	1,962	0.381	0.769	0.219	0.305
	Concentrate intake (kg/cow per yr)	2,032	2,022	84.3	133	111	192	0.570	0.950	0.094	0.604
2	N surplus (kg/ha per yr)	209	206	82.5	17.2	48	26.5	0.113	0.781	0.125	0.125
	Gross margin (€/100 kg of milk)	27.8	27.6	62.4	2.15	−2.19	7.97	0.792	1.087	0.288	0.771
	Net grassland yield (kg of DM/ha per yr)	10,784	10,748	56.1	999	1,294	2,852	0.664	0.883	0.264	0.670
	Nitrate in groundwater (mg/L)	57	54	76.3	9.04	5.7	14.3	0.718	0.947	0.254	0.848

[1] For β_1, the t probability (t_pr′) is given for $\beta_1 = 1$.

the ingested grass was reduced, increasing the concentrate requirement.

Whole-farm models of dairy systems were developed earlier with a variety of methodological approaches, system boundaries and different emphasizes on the studied aspects. In the United States, the DAFOSYM model (Rotz et al., 1999) has a similar overall structure to DairyWise, with separate submodels such as a herd model (Rotz et al., 1999). In Europe several dairy farm models have been published, mostly developed and evaluated for specific regional circumstances. The Moorepark Dairy Systems model for instance is a stochastic budgetary simulation model for Irish dairy farms (Shalloo et al., 2004). Some models are able to simulate dairy farms in a wider European context such as FarmGHG (Olesen et al., 2006) and FarmSim (Saletes et al., 2004), but these models lack the ability to evaluate farm economics.

A key feature present in DairyWise is its ability to simulate grazing systems, including the management effects such as N application and grazing system on growth and quality of grass, the consequent effects on animal intake and excretion, and finally the effect of manure production and composition on grassland. Most models have simplified grazing systems or are only used for stall-fed animals. The model of Cros et al. (2003) contains a well-developed simulation of a rotational grazing system, but is confined to the grazing period only.

The DairyWise model is an empirical model based on crop and animal experiments in the Netherlands. Therefore, its applicability is restricted to these regions. Currently, a model is being built for the Flemish regions in Belgium, bordering to the south of the Netherlands. The main adaptations are the prices of inputs and a correction for crop yields.

Model Application

Generally, whole farm models are suitable to assess the technical, environmental, and financial implications of alternative farm management strategies, often under changing external conditions. As stated earlier, the whole-farm approach ensures that potential negative trade-offs are taken into account and that positive synergies are identified. Alternatively, when analyzing effects on a farm scale, higher integration levels should not be ignored. It is possible that certain strategies, developed within a whole farm approach, have a positive effect, whereas the effect on a regional, national, or even higher scale might be neutral or even negative. The import of roughage or the export of manure has a positive effect on the farm gate N balance as the losses associated with forage production and manure application are not associated to the farm in question, but are transferred to other farms. In the case of energy use, DairyWise and FarmGHG (Olesen et al., 2006) take into account the prefarm energy consumption for the production and transport of materials used on the farm. For other variables and especially for downstream postfarm processes, most models do not take into account possible transfer of effects.

The DairyWise model is currently used in research, extension and teaching. Research related applications are, for instance i) the development and exploration of cost-effective mitigation strategies for N losses, P losses and greenhouse gas emissions, ii) the exploration of long term strategies for dairy farms under changing market conditions, and iii) the exploration of proposed changes in government policies. In extension, DairyWise is used to explore future farm strategies for individual farms and for study groups of farmers working under similar environmental conditions. As the model operates on a farm level, it is relatively easy for farmers to learn and understand the underlying processes on their own farm. In teaching, DairyWise is used to explain and demonstrate the principles of material and nutrient flows within dairy systems.

During the last 10 yr several Web-based products have been derived from the DairyWise model with key themes as NO_3 leaching, grassland reseeding, nature schemes, grazing strategies, fertilizer recommendations, and N policy. Users were required to fill in a limited number of questions. After submitting the questionnaire, DairyWise as a whole or some submodels were executed and the output was returned to the user, either directly on the Web or as an e-mail. A standalone version of the model can be obtained from the Animal Sciences Group.

CONCLUSIONS

DairyWise is an empirical model that simulates technical, environmental, and financial processes on a dairy farm. The model was evaluated with data from current commercial dairy farms as well as with pilot commercial and experimental dairy farms. DairyWise is useful for integrated scenario development and evaluation for scientists, policy makers, extension workers, teachers, and farmers.

REFERENCES

Boumans, L. J. M., B. Fraters, and G. Van Drecht. 2001. Nitrate in the upper groundwater of 'De Marke' and other farms. NJAS-Wagen. J. Life Sci. 49:163–177.

Burrell, A. 2004. The 2003 CAP reform—Implications for the EU dairy sector. Outlook Agric. 33:15–25.

Bussink, D. W. 1994. Relationships between ammonia volatilization and nitrogen-fertilizer application rate, intake and excretion of herbage nitrogen by cattle on grazed swards. Nutr. Cycl. Agroecosyst. 38:111–121.

Cropper, M. R., and L. Del Pozo-Ramos. 2006. Impacts of CAP reforms on animal production systems. Pages 615–623 in Proc. EGF 21st General Meet., Badajoz, Spain.

Cros, M. J., M. Duru, F. Garcia, and R. Martin-Clouaire. 2003. A biophysical dairy farm model to evaluate rotational grazing management strategies. Agronomie 23:105–122.

De Haan, M. H. A. 2001. Economics of environmental measures on experimental farm 'De Marke'. NJAS-Wagen. J. Life Sci. 49:179–194.

EUROSTAT. 2005. Europe in figures, Eurostat yearbook 2005. European Union, Luxembourg.

Hageman, I. W. 1994. Invloed bedrijfsfactoren op energieverbruik melkveebedrijven. Rapport nr. 150. Page 126 in Proefstation voor de Rundveehouderij, Schapenhouderij en Paardenhoudrij, Lelystad, the Netherlands.

Hassink, J. 1995. Prediction of the non-fertilizer N-supply of mineral grassland soils. Plant Soil 176:71–79.

Huijsmans, J. F. M., J. M. G. Hol, and M. M. W. B. Hendriks. 2001. Effect of application technique, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to grassland. NJAS-Wagen. J. Life Sci. 49:323–342.

LEI. 2004. Farm Accountancy Data Network, Landbouw Economisch Instituut, Den Haag, the Netherlands.

Mandersloot, F. 1989. Simulatie van voeding en groei van jongvee. Rapport nr. 116. Page 61 in Proefstation voor de Rundveehouderij, Paardenhouderij en Schapenhouderij, Lelystad, the Netherlands.

Mandersloot, F., and M. A. van der Meulen. 1991. Het melkveemodel. Publikatie nr. 71. Page 23 in Proefstation voor de Rundveehouderij, Paardenhouderij en Schapenhouderij, Lelystad, the Netherlands.

Oenema, J., G. J. Koskamp, and P. J. Galama. 2001. Guiding commercial pilot farms to bridge the gap between experimental and commercial dairy farms; the project 'Cows & Opportunities'. NJAS-Wagen. J. Life Sci. 49:277–296.

Olesen, J. E., K. Schelde, A. Weiske, M. R. Weisbjerg, W. A. H. Asman, and J. Djurhuus. 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agric. Ecosyst. Environ. 112:207–220.

Rotz, C. A., L. D. Satter, D. R. Mertens, and R. E. Muck. 1999. Feeding strategy, nitrogen cycling, and profitability of dairy farms. J. Dairy Sci. 82:2841–2855.

Saletes, S., J. Fiorelli, N. Vuichard, J. Cambou, J. E. Olesen, S. Hacala, M. Sutton, J. Fuhrer, and J. F. Soussana. 2004. Greenhouse Gas Emissions from Agriculture. Mitigation Options and Strategies. Pages 203–208 in Proc. Greenhouse Gas Emissions from Agriculture. Mitigation Options and Strategies. Leipzig, Germany.

Schils, R. L. M., A. Verhagen, H. F. M. Aarts, P. J. Kuikman, and L. B. J. Šebek. 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Glob. Change Biol. 12:382–391.

Schreuder, R., J. C. van Middelkoop, J. Aalenhuis, and F. Mandersloot. 1995. Mineralenstroom milieumodule in BBPR. Publikatie nr. 99. Page 33 in Proefstation voor de Rundveehouderij, Schapenhouderij en Paardenhouderij, Lelystad, the Netherlands.

Schröder, J. J., J. J. Neeteson, J. C. M. Withagen, and I. Noij. 1998. Effects of N application on agronomic and environmental parameters in silage maize production on sandy soils. Field Crops Res. 58:55–67.

Shalloo, L., P. Dillon, M. Rath, and M. Wallace. 2004. Description and validation of the Moorepark Dairy System Model. J. Dairy Sci. 87:1945–1959.

Tamminga, S., W. M. Vanstraalen, A. P. J. Subnel, R. G. M. Meijer, A. Steg, C. J. G. Wever, and M. C. Blok. 1994. The Dutch Protein Evaluation System—The DVE/OEB-System. Livest. Prod. Sci. 40:139–155.

Unwin, R. J., and T. V. Vellinga. 1994. Fertiliser recommendations for intensively managed grassland. Pages 590–602 in Grassland and Society. Pages 590–602 in Proc. 15th General Meet. Eur. Grassl. Fed. Wageningen Press, Wageningen, the Netherlands.

van Bruchem, J., H. Schiere, and H. Van Keulen. 1999. Dairy farming in the Netherlands in transition towards more efficient nutrient use. Livest. Prod. Sci. 61:145–153.

Van Calker, K. J. 2005. Sustainability of Dutch dairy farming. A modelling approach. PhD thesis. Wageningen University, Wageningen, the Netherlands.

Van Duinkerken, G., G. Andre, M. C. J. Smits, G. J. Monteny, K. Blanken, M. J. M. Wagemans, and L. Sebek. 2003. Relatie tussen voeding en ammoniakemissie vanuit de melkveestal. Page 66 in Praktijkrapport Rundvee 25, Praktijkonderzoek Veehouderij, Lelystad, the Netherlands.

Vellinga, T. V. 2006. Management and nitrogen utilisation of grassland on intensive dairy farms, PhD Thesis. Wageningen University, Wageningen, the Netherlands.

Vellinga, T. V., G. Andre, R. L. M. Schils, and O. Oenema. 2004. Operational nitrogen fertilizer management in dairy farming systems: Identification of criteria and derivation of fertilizer application rates. Grass Forage Sci. 59:364–377.

Vellinga, T. V., A. H. J. Van der Putten, and M. Mooij. 2001. Grassland management and nitrate leaching, a model approach. NJAS-Wagen. J. Life Sci. 49:229–253.

Vereijken, P. H. 2002. Transition to multifunctional land use and agriculture. NJAS-Wagen. J. Life Sci. 50:171–179.

Zom, R. L. G., J. W. Van Riel, G. Andre, and G. Van Duinkerken. 2002. Voorspelling voeropname met koemodel. Praktijkrapport Rundvee 11. Praktijkonderzoek Veehouderij, Lelystad, the Netherlands.