ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Agricultural Systems 86 (2005) 333–348

AGRICULTURAL SYSTEMS

www.elsevier.com/locate/agsy

Simulating the influence of management decisions on the nutrient balance of dairy farms

J. Buysse [a], G. Van Huylenbroeck [a,*], I. Vanslembrouck [a], P. Vanrolleghem [b,1]

[a] *Department of Agricultural Economics, Ghent University, Coupure links 653, 9000 Gent, Belgium*
[b] *Biomath, Department Applied Mathematics, Biometrics and Process Control, Ghent University, Coupure links 653, 9000 Gent, Belgium*

Received 19 May 2003; received in revised form 17 September 2004; accepted 11 October 2004

Abstract

In order to evaluate the influence of management decisions on the nutrient balance of dairy farms a simulation model was developed. Three farm systems have been simulated: zero grazing, winter milk and summer milk. From the simulated farm systems the zero grazing farm has in all scenarios the lowest N-surplus. The winter milk farm system has a higher N-surplus than zero grazing but lower than the summer milk farm system. The results further indicate the positive effects of maize feeding in addition to grazing. More maize in the ration is especially good to lower the N-surplus during the grazing period in the summer. The benefits of more maize in the ration decrease when the fertilizer application rates decrease.

Keywords: Farm management model; Nutrient balance; Simulation; Dairy farming

---

[*] Corresponding author: Tel.: +32 9 264 59 25; fax: +32 9 264 62 46.
E-mail address: Guido.VanHuylenbroeck@UGent.be (G. Van Huylenbroeck).
[1] Tel.: +32 9 264 59 32; fax: +32 9 264 62 20.

0308-521X/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.agsy.2004.10.004

1. Introduction

There is a growing public concern about the increasing nitrate concentration in drinking water reserves and about the distortion of aquatic ecosystems through eutrophication (European Commission, 2002). Excessive nitrogen surpluses can indeed pose a threat on the environment, leading to pollution of water, air and soil (Pau Vall and Vidal, 1999). This has led to the nitrates directive (91/676/EC) of the European Union (EU). This directive aims to protect water from pollution by nitrogen from agricultural resources. In EU countries the major source of nitrogen is mineral fertilizer, while especially in regions of high livestock density, animal manure remains very important. In Belgium and the Netherlands livestock manure is responsible for more than 50% of the nitrogen inputs on the agricultural land (Pau Vall and Vidal, 1999).

Based on agricultural statistics, it can be calculated that the contribution of cattle in the total manure production in Flanders accounts for 47% of nitrogen and 38% of phosphorus. The pig and poultry sector contribute 39% and 11%, respectively, for nitrogen and 45% and 15%, respectively, for phosphorus (Deuninck et al., 2001). Dairy cattle produce approximately half of the cattle's manure. Also in the Netherlands the dairy sector is an important source of pollution. Dairy farming is responsible for 45% of the phosphate surplus and 60% of the nitrogen losses (Van Bruchem et al., 1999). Consequently in countries as Belgium and the Netherlands, where intensive animal production systems have been developed, a more efficient utilization of dietary nitrogen in dairy farming has a positive impact on the reduction of environmental pollution.

Michiels et al. (1998) compared nutrient balances of 41 Flemish farms. This research indicated that there are large differences in nutrient use efficiency and that possibilities exist to increase environmental efficiency by changing farm management. Two main approaches were suggested: (i) an optimization of the N-utilization at plant level and (ii) the reduction of N-pollution at animal level. The first approach aims at an optimal application of chemical fertilizer and manure on the land and consequently an adapted choice of crops. The second approach is to optimize the feed mix of the cow in order to increase the nutrient use efficiency at cow level. Both strategies are important but do mutually influence each other. One measure cannot simply be adjusted to another measure (Den Boer, 1999; Thornton and Herrero, 2001). Therefore, in this study a dynamic simulation model, simulating daily plant and animal production, is used to measure the overall impact of management decisions on the nutrient surplus at farm level.

The paper is organized as follows. In Section 2, the model is described. Section 3 gives some insight in the validation of the model and is followed by a discussion of the results in Section 4. Finally, Sections 5 and 6 deal with the discussion and the main conclusions.

2. The simulation model

The basic model and underlying mathematical relations have already been described in Van Huylenbroeck et al. (2000). The basic idea behind the model is to describe the N and P cycle at farm level based on relationships described in the literature. This combined information makes it possible to analyse the overall effect of management decisions on a dairy farm.

The model is based on: (i) nitrogen-grassland relations described by Thornley and Johnson (1990), (ii) feeding requirements from Jarrige (1988) and CVB (1996); and (iii) lactation functions from Wood (1967, 1977). These relations allow for calculation of animal and plant production on a daily basis.

2.1. General model

Fig. 1 gives a schematic representation of the model, showing how the model combines both plant and animal production.

The basic simulation model was originally implemented in Matlab code. For performance and interface reasons it has been rewritten in Delphi code with the additional benefit that it can also be used as a standalone simulation program.

In the following sections the model is described in more detail. First the animal production is explained, then the grazing strategy and finally some nutrient cycling aspects.

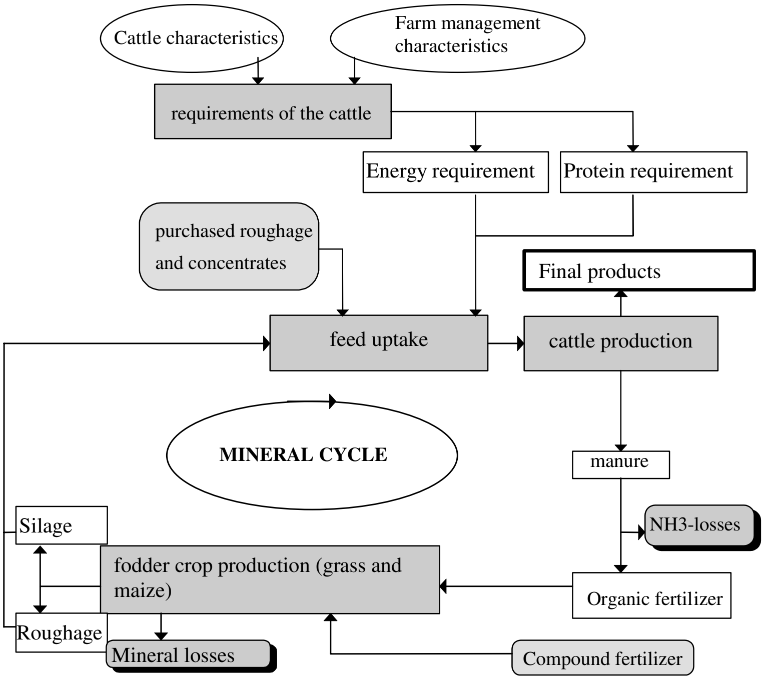

Fig. 1. Relationship between different modules in the model.

2.2. Animal production

At the start of a simulation, the user of the model has to choose a herd size and its characteristics such as production capacity and calving date. Based on lactation functions, the model calculates the production of milk for each cow on each day.

The daily feed requirements are calculated based on Jarrige (1988) and CVB (1996). The requirements and the supply of protein are expressed as Darm Verteerbaar Eiwit (DVE): the true protein digested in the small intestine. In addition, the Onbestendige Eiwit Balans (OEB) value (the ruminally degraded protein, RDP, balance) indicates the losses of N in the rumen. An OEB value above zero indicates a surplus of RDP relative to energy, which means that there is a potential loss of N. If the OEB value is below zero, there is a shortage of RDP relative to energy, which means that microbial protein synthesis is possibly impaired (Kuipers et al., 1999).

The daily requirements of energy are expressed as Voeder Eenheid Melk (VEM) or Feed Unity Milk. The Unité encombrement bovine (UEB) value indicates the maximum volume feed intake capacity of the cows.

The roughage ration in the model is based on the available grass and maize and the compound feed ration is simulated through an optimization of the feed balance.

At the start of the simulation, the user specifies the total area and the crops that will be cultivated. Depending on the selected grazing system, the grazing season is simulated in order to fulfil the requirements of the cattle. The excess grass production is mowed and ensiled for the winter period. At the beginning of the winter period the available feedstock determines the ration for the winter. This means that the winter roughage ration can be changed in the model in two ways. The first way is to simulate a different summer situation. Selecting a grazing system with more maize feeding during the summer period results in lower maize and more ensiled grass availability for the winter period. The second way to change the winter ration is changing the share of the crops cultivated. This modelling approach represents the actual decision making process of farmers. At the beginning of the season, a farmer decides the feed crop plan for the next year. Depending on the yields, he will then adjust the ration for the cows in order to minimize roughage surpluses at the end of the year.

To balance the feed requirements, the daily amount of compound feed is simulated through a linear programming optimization for each day. A least cost composition fulfilling the energy and protein requirements is determined for each cow based on the assumption that a farmer is able to compose a cow-dependent compound mixture. This is actually representing the situation when a feeding computer is used.

2.3. Grazing strategy

The grassland production is based on nitrogen-grassland relations described by Thornley and Johnson (1990) and a rotational grazing strategy with the number of rotation days as external variable.

The parcel size for the rotational management is simulated from the grass requirement of the cattle on the first grazing day. Based on herd size, the model calculates what parcel size is necessary to graze the herd during the number of days of the selected grass rotation strategy.

The grassland requirement depends on the feeding strategy. The user of the model can choose between feeding a fixed amount of maize, maximization of grass feeding or time-dependent maize feeding. In the latter the user can define a starting quantity and a final quantity of maize input. The model then calculates a linear daily increase of maize feeding.

Grassland production that is not used for grazing is mowed. Because the number of mowing cuts has an influence on the total yield of the grassland (Verbruggen, 2000), the model optimizes the mowing regime to achieve maximum yield. As the grass yield is a non-linear function of time and N-gift, the mowing regime is optimized with the Praxis-algorithm (Brent, 1973) that supports non-linear optimization.

2.4. Nutrient cycling aspects

The nutrient balance of a farm is the difference between the nutrient inputs and nutrient outputs at farm level. The most important inputs bought by the farmer are fertilizers, compound feed and, in case of shortage, extra forage. At the output side the nutrient content of milk, meat and potential surplus of forage are accounted for. N deposition is not considered because this is constant over all scenarios and has thus no influence on the conclusions.

The amount of compound fertilizer needed is calculated as the difference between the need of soil N and P of the crops and the amount applied through available manure. The amount of N and P in the manure is calculated as the difference between the cow's intake of N and P and its output, both at cow level. The calculated amount of N is multiplied by a working coefficient and a summer and winter manure coefficient of 20% and 80%, respectively. The working coefficient (z) indicates that $1/z$ kg N in manure is necessary to replace 1 kg N in compound fertilizer for the same yield. Schils and Snijders (1988) report a working coefficient of 56%. The summer and winter manure coefficients take into account that only a part of the N excreted by the animals is finally available for spreading on the land. In the winter there are mainly storage losses. During the summer only a part of the faeces and urine is captured as manure in the stable. The largest part is disposed directly on the land by the cows. Standard the programme applies a summer and winter manure coefficient of 20% and 80%, respectively.

Because other studies indicate that in practice there is a very large variation of these coefficients, the results section contains a sensitivity analysis of these values. Schreuder et al. (1995), for instance, do not take the N surplus during summer into account. Nevens and Reheul (1998) found that the short-term fertilization effect of N in manure is only 15% while the long-term effect is 60%. Lewis et al. (2002) have shown that the effect strongly depends on the application date and form of the manure.

3. Validation

The model was validated with recent data of farms participating in a nutrient balance-monitoring project (Table 1) (Mulier et al., 2003). These farms do not reflect average results of Flemish dairy farms, because they are encouraged to decrease nutrient surpluses.

Because the simulation model feeds the cows exactly what they need, it was expected that the simulated nutrient surpluses are lower than the observed farm data. Table 2 shows that this is not the case, probably because some of the observed farms do better for certain parameters than the assumptions for these parameters in the model. They can use storing and spreading techniques resulting in a higher working coefficient of manure than the average level of 56% assumed.

Also the collected data can contain a lot of variations. Mulier et al. (2003) indicates four major restrictions to the accurate calculation of farm level nutrient balances: (1) the wide variability that is allowed between actual and reported nutrient composition of concentrated feed; (2) the estimates of the amount and composition of manure; (3) the assessment of changes in standing stock on the farm between the beginning and end of the reporting period; and (4) the accuracy of the data supplied by the farmers.

From the large variation between computed and observed values two possible conclusions can be derived. A first possible conclusion is that the model is not capable of reproducing baseline conditions and should not be used. A second possible

Table 1
Farm characteristics included in the model

Farm characteristics	Farm 1	Farm 2	Farm 3	Farm 4
Number of cows	52	71	115	85
Milk production (l per cow/year)	7850	8218	6891	8703
Maize (ha)	19	16	36	33
Grassland (ha)	18	14	36	21

Table 2
Comparison of observed and simulated farm data

Validation results	Farm 1		Farm 2		Farm 3		Farm 4	
	Computed	Observed	Computed	Observed	Computed	Observed	Computed	Observed
N in sold products (10^3 kg)	3.9	4.1	2.2	3.4	5.2	4.9	6.0	6.1
N in compound feed (10^3 kg)	3.0	2.5	6.0	4.9	8.3	9.6	6.8	9.3
N in fertilizer (10^3 kg)	7.0	8.3	3.1	2.9	10.8	22.1	7.7	9.6
N in forage (10^3 kg)	0.0	0.0	1.1	1.1	0.0	0.0	0.0	0.0
N surplus (10^3 kg/ha)	1.6	1.2	2.3	1.6	1.9	2.6	1.6	1.6

conclusion is that the observed data are very much influenced by external factors such as weather conditions and measurement errors. A simulation model capable of doing analysis without the influence of these external factors is then the only possible approach to make conclusions about the influence of management decisions on the nutrient surplus at farm level. Because the model is based on different extensively tested and validated functions described in the literature, this second conclusion is retained.

4. Simulation results

As indicated, the model is used to simulate the influence of management decisions on the nitrogen surplus. Simulations are done for a farm with the following characteristics:

- 40 cows.
- A production of 7000 kg of milk per cow in the first lactation and 8000 kg per cow from the second lactation on.
- A protein content of the milk of 3.4%, a fat content of 4.4%, a lactation period of 44 weeks and an interlactation of eight weeks.
- The grazing season starts April 27th and runs until October 2nd (this is an average season under Flemish conditions).

Because calving dates influence the age, weight and feed ration of the calves in a one-year simulation period, young stock is not simulated for this application. This facilitates the comparisons between different simulation scenarios.

The period between two calving dates is assumed to be one year. Three farm systems have been simulated. In the winter milk farm system, cows are calving in October while in the summer milk farm system the calving date is the first of April. In addition a zero grazing farm system has been simulated, with a calving date the first of April.

The acreage of the farm systems is 19 ha for the summer and winter milk farm systems. The zero grazing farm system needs less land to be self-sufficient in fodder crops and has therefore only 17 ha of land.

For these three farm systems results are simulated for different summer rations and varying grass–maize ratios. They are described in the next two sections. Afterwards a comparison is made between the three farm systems and results are tested for sensitivity on fertilizer application rates and the summer and winter manure coefficients.

4.1. Influence of the summer ration

To analyse the effects on the N-surplus of maize input during the grazing period, different levels of maize feeding during the summer period are simulated. Fig. 2 gives the results for the summer milk and winter milk farm systems for three

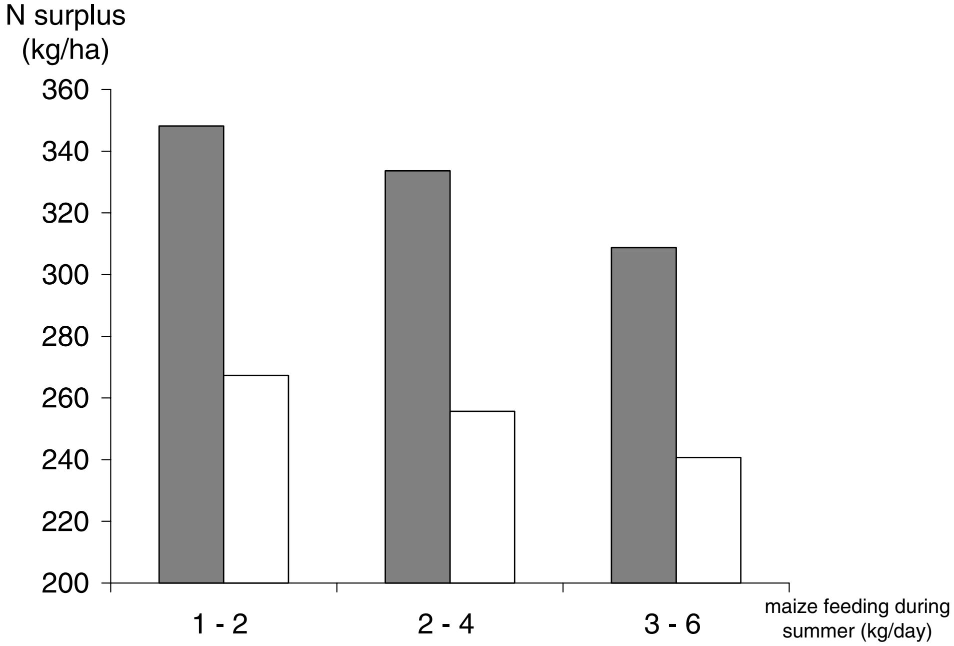

Fig. 2. Influence of the summer ration on the N-surplus of the summer milk farm system (■) and the winter milk farm system (□).

different levels of maize feeding. The results indicate that the winter milk farm system and a higher maize input during the summer lower the N-surplus. The fertilizer application rates for this simulation are 300 kg N/ha for grassland and 200 kg N/ha for maize.

Different reasons explain these results. A first reason is that more maize during summer and more milk production during winter result in less grazing. As grazing is less efficient than mowing with equal amount of N-fertilization, this results in a lower N-surplus for the wintermilk farm system. Secondly, mowing gives a more N-rich winter feed resulting in better N-recycling, as can be derived from the difference between the winter (80%) and summer (20%) manure coefficient. Thus, the N-surplus at cow level is 60% better recycled during winter than during summer. Another reason is the OEB-balance. Grazing without maize feeding results in a surplus of RDP relative to energy and a positive OEB-balance. A positive OEB-balance indicates that more N-losses occur. Because maize contains more energy relative to RDP, higher maize feeding can lower the OEB-balance, resulting in lower N-losses.

The higher efficiency of mowing compared to grazing has also several reasons. Grazing is done at 1700–2200 kg DM (dry matter)/ha while for mowing this is 2500–4500 kg DM/ha. Under grazing conditions the grass growth is therefore not reaching its maximum potential, resulting in a lower yield for grazing as illustrated in Fig. 3.

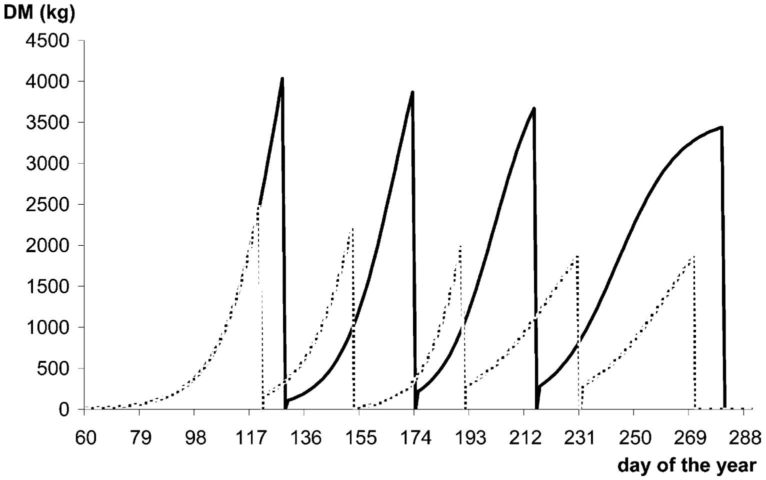

Fig. 3. Growth curve of grass under the mowing ▬ and grazing ▬ regime.

Another less important reason for the lower efficiency of grazing is the need for permanent supply, in the model achieved by rotational grazing. A consequence of rotational grazing is that at the beginning of the grazing season the cows graze the first parcel before the optimal yield and the last parcel is grazed beyond the optimal yield. In the last grazing cycle the first parcel is grazed three weeks before the end of the grazing season. The grass growth of these three weeks is not used for feeding, resulting in a yield loss. Thus, grazing instead of mowing results in sub-optimal use of overall grass supply at the beginning and at the end of the grazing season. Disadvantages of mowing are the silage losses and the extra labour requirement for mowing and ensiling the grass. This, however, has less impact on the N-balance.

4.2. Influence of the grassland–maize ratio

At N-fertilizer application rates of 300 kg/ha grassland and 200 kg/ha maize, maize feeding has a better influence than feeding grass on the N-balance of a dairy farm. This is illustrated in Fig. 4. There are two important reasons for this. Forage maize lowers the OEB-balance and maize needs less N-fertilizer for higher energy content. Further, the same arguments as those used for the extra maize content in the summer ration hold here as well (see Section 4.1).

Fig. 5 shows the results in case of zero grazing. As indicated before, the N-surplus decreases with higher maize areas. The P-surplus, on the other hand increases with more maize production. The first reason is that maize and grassland are equally P-fertilized, but because grassland has a higher protein yield, the P-export is higher. This higher P-use efficiency at field level for grassland than maize is not influenced by the efficiency at cow level because the surplus of P at cow level is in the model assumed to be fully recycled on land (Tamminga, 1992) in contrast with N where important losses occur.

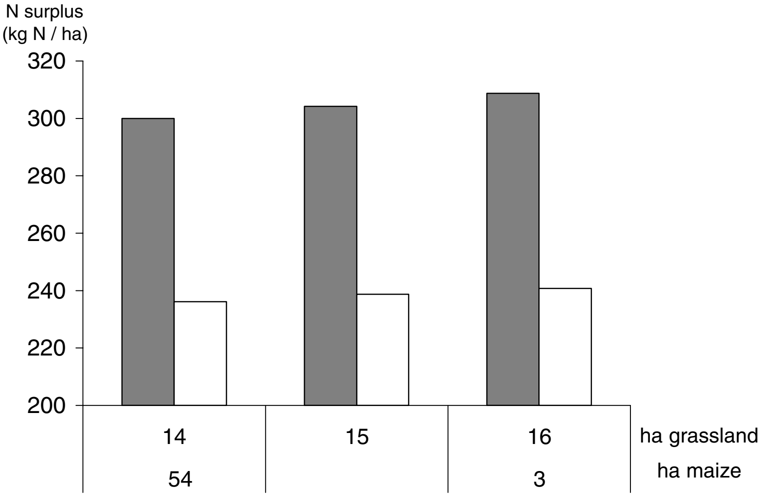

Fig. 4. Influence of the grassland–maize ratio on the N-surplus (kg/ha) for the summer milk farm system (■) and the winter milk farm system (□).

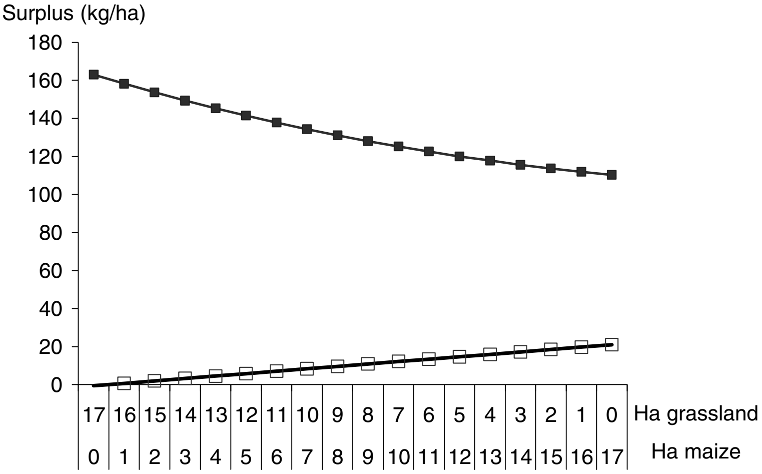

Fig. 5. Influence of the grassland–maize ratio on the N-surplus (■) and P-surplus (□) in case of zero grazing.

4.3. Summer milk, winter milk and zero grazing

As can be derived from Fig. 6 the annual variation of N-input at cow level is influenced by two major factors. The first and most important is the lactation curve. Two months after calving the milk production and daily N-input reach a maximum.

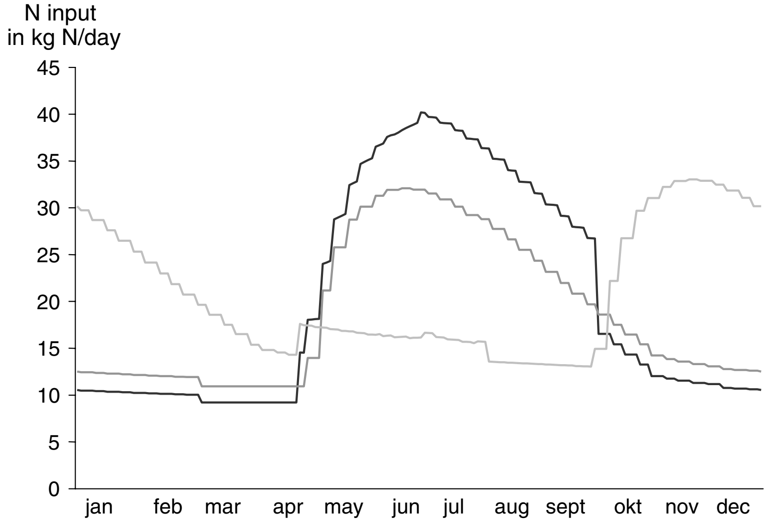

Fig. 6. Annual variation of N-input for the whole herd on the summer milk (▬), zero grazing (▬) and the winter milk (▬) farm systems.

The second factor is the grazing period. Both in the winter milk farm system and summer milk farm system a sharp increase in N-input can be observed during the grazing period. The OEB-balance with young grass is too high, resulting in high excretion of N. The manure produced by cows during the stable period is also better recycled than manure produced during a grazing period. This explains the big difference in total surplus between Figs. 4 and 5. It may therefore be concluded that zero grazing has a positive effect on the nutrient balance of a dairy farm. Further, farms with grazing have higher nutrient use efficiency the more winter milk they produce.

4.4. Sensitivity analysis

A sensitivity analysis was performed to analyse the influence of fertilizer application rates and the summer and winter manure coefficients on the above results and conclusions.

The simulation results in Fig. 7 illustrate the positive effect of reduced N-fertilization on the N-surplus of a dairy farm. Fig. 7 shows a similar effect for the three farm systems modelled. This means that the level of N-fertilization does not change the conclusions of the previous sections for the different farm systems. Zero grazing appears to be the best option for optimal nutrient management, independent whether 200 or 400 kg N/ha fertilization is used.

For maize feeding the conclusion is different. The benefit on the N surplus of feeding maize decreases with decreasing fertilizer levels. This can be seen by comparing the N-surplus in Fig. 5 (300 kg N/ha) and the N-surplus in Fig. 8 (200 kg N/ha). For

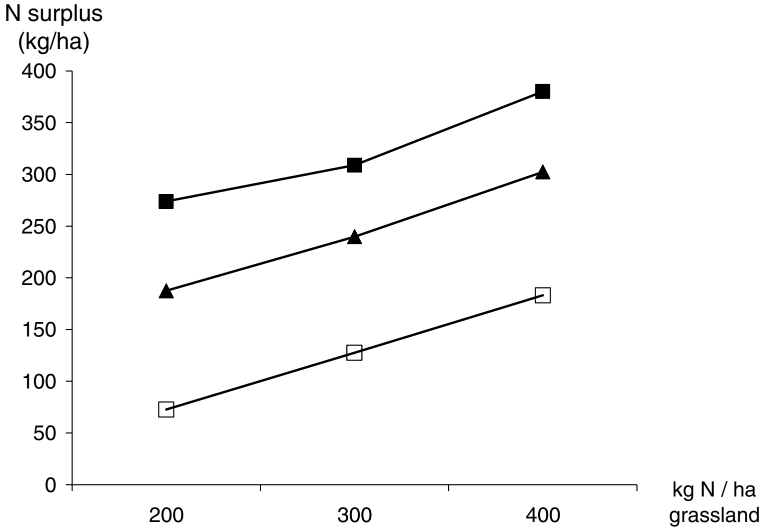

Fig. 7. N-surplus with three N-fertilization levels for the summer milk (■), winter milk (▲) and zero grazing (□) farm systems.

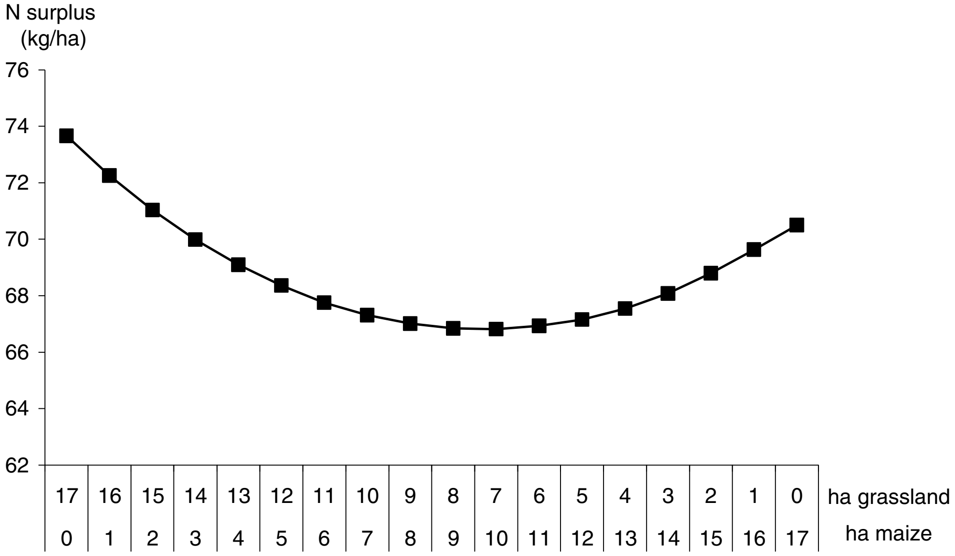

Fig. 8. N-surplus for the zero grazing farm system with fertilization of 200 kg N/ha on grassland and 140 kg N/ha on maize.

a high fertilization level, 100% maize gives the lowest N-surplus (Fig. 5). For a lower fertilization level (Fig. 8) the N-surplus is lower with a grass–maize mixture than with 100% maize.

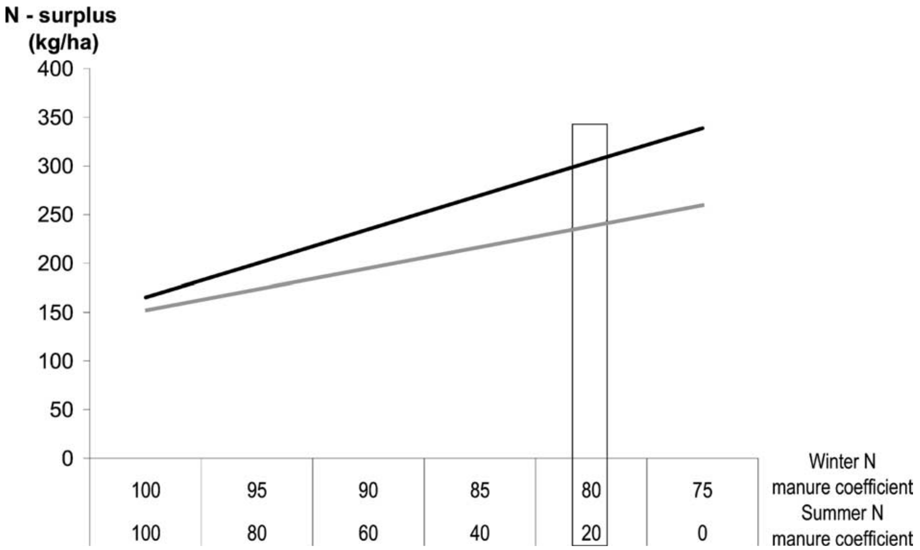

Fig. 9. N-surplus for the summer milk (▬) and the winter milk (▬) farm system with varying summer and winter N coefficients.

The results of the sensitivity analysis of the summer and winter manure coefficients are illustrated in Fig. 9. It can be seen that the main conclusion remains valid even with very different summer and winter manure coefficients. The N-surplus of a winter milk farm system is lower than the surplus of a summer milk farm system even if the same manure coefficient for summer and winter is assumed. The higher the difference between both coefficients, the higher the difference in N-surplus in both farm systems becomes.

5. Discussion

The model confirms the results of other studies (Jarvis et al., 1996; Michiels et al., 1998; Vermeltfoort et al., 2001) by indicating the positive effects of supplementing grazing with maize feeding on the N-surplus. These results have important implications for policy measures in Flanders and The Netherlands. The Flemish and Dutch governments asked a derogation from the Nitrate Directive of the European Union for grassland, allowing higher organic fertilizer applications on grassland than on other crops. This can be justified from an agronomic viewpoint as grass is able to utilize the higher fertilization levels more efficiently than other crops. However, at cow level grassland is not always the best option for a low N-surplus. A derogation for grassland could stimulate Dutch and Flemish farmers to cultivate more grass instead of maize or other fodder crops. This would lead to an overall lower nutrient use efficiency on the dairy farms with high fertilizer application rates. Van Bruchem et al. (1999) report that more maize in the feed ration also results in a higher quality of the manure produced by the cattle. As this is not simulated in the model, the positive effects of maize could be even larger than assumed by our model.

From a nutrient use efficiency perspective our model shows that zero grazing is the best option. Vermeltfoort et al. (2001) came to a similar conclusion with a statistical comparison of nutrient balances of different farms in the Netherlands. In practice, an increasing number of dairy farmers (in particular in the Netherlands) already applies zero grazing.

However, besides nutrient use efficiency, also labour income is an important consequence of management decisions. It could be expected that zero grazing results in a higher cost. With the present model this could not be assessed (although the model contains an economic calculation) because these costs depend too much on characteristics of the farm structure, such as the system of milking installation and acreage of pasture near the farm, which are not included in the model so far. Other research indicates different effects of zero grazing on labour income. Overvest and Laevenkloosterman (1984) and Coléno and Duru (1999) suggest a negative impact of zero grazing on the labour income of the farmer. On the contrary a statistical analysis of 54 specialized dairy farms in the Netherlands showed that less grazing has no negative impact on farm income. Bondt et al. (2001) state that farm income and grazing are not directly linked. Larger scale farms with automated milking and limited available land could benefit from zero grazing while smaller farms with more land could be better off with grazing.

Van der Schans (2000) evaluated other side effects of zero grazing. He suggested a negative impact on nature, wildlife, public perception of the dairy sector, countryside and animal welfare. As a reaction a Dutch cheese factory already reacted with a price premium of 1 eurocent for farmers that apply grazing.

6. Conclusion

In general, the analysis in this paper has illustrated the potential of the developed model for quantitatively evaluating the impact of management decisions on the nutrient balance of a dairy farm. The advantage of using models is the possibility of combining separately known functions in one simulation in order to draw conclusions not only at field or at cow level, but also at overall farm level. Further, external parameters influencing observed nutrient balances such as weather conditions and measurements errors can be eliminated, so that the exact influence of practices and systems can be evaluated. As illustrated, the model can be used to evaluate either management options at farm level, but also the effect of possible policy options. Introducing a number of economic and environmental indicators such as ammonia emission, labour income, financial performance indicators and so on could extend the application range of the model as e.g. in the models described by Herrero et al. (1999), Ramsden et al. (1999) and van Calker et al. (2004). This will, however, require additional input parameters as well.

Acknowledgements

This research was enabled by the financial support of the Ghent University Research Fund. The authors also acknowledge the help of the editor and reviewers in improving the final version of this paper.

References

Bondt, N., Jansen, L.F., Hoste, R., 2001. Economie en welzijn op melkveebedrijven: een verkennend onderzoek. LEI, Den Haag.

Brent, R.P., 1973. Algorithmes for Minimization Without Derivatives. Prentice-Hall, Engelwood Cliffs, NJ.

Coléno, F.C., Duru, M., 1999. A model to find and test decision rules for turnout date and grazing area allocation for a dairy cow system in spring. Agricultural Systems 61, 151–164.

CVB, 1996. Voedernormen landbouwhuisdieren en voederwaarde veevoeders. Centraal veevoederbureau, Lelystad.

Den Boer, D.J., 1999. Management als kans om de N-benutting in de melkveehouderij te verbeteren. In: Samenvatting symposium Nutriënten Management 1999. Nutriënten Management Instituut, Wageningen.

Deuninck, J., Dhont, S., Viaene, J., 2001. Structurele Aanpassingen voor de Vlaamse Varkenshouderij. Universiteit Gent, Gent.

European Commission, 2002. Implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Commission of the European Communities, Brussels.

Herrero, M., Fawcett, R.H., Dent, J.B., 1999. Bio-economic evaluation of dairy farm management scenarios using integrated simulation and multiple-criteria models. Agricultural Systems 62, 169–188.

Jarrige, R., 1988. Alimentation des bovins, ovins et caprins. INRA, Parijs.

Jarvis, S.C., Wilkins, R.J., Pain, B.F., 1996. Opportunities for reducing the environmental impact of dairy farming managements: a systems approach. Grass and Forage Science 51, 21–31.

Kuipers, A., Mandersloot, F., Zom, R.L.G., 1999. An approach to nutrient management on dairy farms. Journal of Dairy Science 82 (suppl 2), 84–89.

Lewis, D.R., McGechan, M.B., McTaggart, I.P., 2002. Simulating field-scale nitrogen management scenarios involving fertiliser and slurry applications. Agricultural Systems 73, 1–22.

Michiels, J., Carlier, L., Verbruggen, I., 1998. Mineralenbalansen en hun gebruik op melkveebedrijven. In: Van Huylenbroeck, G., Jacobs, G. (Eds.), Naar een duurzame grasland en groenvoederuitbating. Ministerie van landbouw, Brussel, pp. 27–49.

Mulier, A., Hofman, G., Baecke, E., Carlier, L., De Brabander, D., De Groote, G., De Wilde, R., Fiems, G., Janssens, G., Van Cleemput, O., Van Herck, A., Van Huylenbroeck, G., Verbruggen, I., 2003. A methodology for the calculation of farm level nitrogen and phosphorous balances in Flemish agriculture. European Journal of Agronomy 20, 45–51.

Nevens, F., Reheul, D., 1998. Gebruik van toegediende stikstof door grasland en groenvoedergewassen. In: Van Huylenbroeck, G., Jacobs, G. (Eds.), Naar een duurzame grasland en groenvoederuitbating. Ministerie van landbouw, Brussel, pp. 85–108.

Overvest, J., Laeven-kloosterman, A.F., 1984. Grasland-gebruikssystemen op het gezinsbedrijf. Praktijkonderzoek veehouderij, Wageningen.

Pau Vall, M., Vidal, C., 1999. Nitrogen in agriculture. In: European Commission, Agriculture, Environment, Rural Development, Facts and Figures. A Challenge for Agriculture. European Communities, Luxembourg, pp. 167–180.

Ramsden, S., Gibbons, J., Wilson, P., 1999. Impacts of changing relative prices on farm level dairy production in the UK. Agricultural Systems 65, 201–215.

Schils, R.L.M. Snijders, P.J.M., 1988. Stikstofwerking van runderdrijfmest op grasland. Publicatie nr.60, PR Lelystad.

Schreuder, R., van Middelkoop, J.C., Aalenhuis, J., Mandersloot, F., 1995. Mineralenstroom milieumodule in BBPR. Praktijkonderzoek veehouderij, Wageningen.

Tamminga, S., 1992. Nutrition management of dairy cows as a contribution to pollution control. Journal of Dairy Science 75, 345–357.

Thornton, P.K., Herrero, M., 2001. Integrated crop-livestock simulation models for scenario analysis and impact assessment. Agricultural Systems 70, 581–602.

Thornley, J.H.M., Johnson, I.R., 1990. Plant and Crop Modelling. Oxford Science Publications, Oxford.

Van Bruchem, J., Verhoeven, F., Brussaard, L., Tamminga, S., 1999. Diet and manure characteristics in relation to nitrogen flows in a dairy farming system. In: van der Heide, D. et al. (Eds.), Regulation of Feed Intake. CAB International, Wallingford, UK.

van Calker, K.J., Berentsen, P.B.M., de Boer, I.M.J., Giesen, G.W.J., Huirne, R.B.M., 2004. An LP-model to analyse economic and ecological sustainability on Dutch dairy farms: model presentation and application for experimental farm de Marke. Agricultural Systems 82, 139–160.

Van der Schans, F.C., 2000. Koeien binnen of buiten? Afwegingen bij het weiden van melkvee. Centrum voor Landbouw en Milieu, Utrecht.

Van Huylenbroeck, G., Jacobs, G., Vanrolleghem, P., 2000. A simulation model to evaluate the impact of environmental programmes on dairy farms. International Transactions in Operational Research 7, 171–183.

Verbruggen, I., 2000. Graslandopbrengsten. 5b land- en tuinbouw Meetjesland 5 (2), 8–9.

Vermeltfoort, J., Breembroek, J., Muller, B., Van Dijk, H., Beldman, A., Ondersteijn, C., 2001. Analyse melkveebedrijven. Project praktijkcijfers 2, Houten.

Wood, P.D.P., 1967. Algebraic model of the lactation curve in dairy cattle. Nature 216, 164–165.

Wood, P.D.P., 1977. The biometry of lactation. Journal of Agricultural Science 88, 333–339.