PERGAMON

Intl. Trans. in Op. Res. 7 (2000) 171–183

INTERNATIONAL TRANSACTIONS IN OPERATIONAL RESEARCH

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A simulation model to evaluate the impact of environmental programmes on dairy farms

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Received 7 June 1999; received in revised form 15 January 2000; accepted 26 January 2000

Abstract

A simulation model has been developed to determine the impact of the implementation of environmental programmes putting restrictions on fertiliser use and mowing date on dairy farms. In the paper, the simulation model is described and results showing the trade-offs between the economic, environmental and nature protection criteria are given. Finally, the optimal compromise is found using multi-criteria analysis. © 2000 IFORS. Published by Elsevier Science Ltd. All rights reserved.

Keywords: Farm management model; Environmental constraints; Simulation; Trade-off analysis; Multi-criteria analysis

1. Introduction

In recent years, policy tools have been developed to prevent environmental pollution from agriculture and to stimulate countryside stewardship by farmers (Van Huylenbroeck and Whitby, 1999). In Belgium, a country with a high livestock density, these programmes mainly concentrate on grassland management because meadows have the highest environmental potential and are rather vulnerable for N-leaching due to surplus application of manure and other fertilisers. As most programmes are voluntary schemes, it is important to determine the

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PII: S0969-6016(00)00017-4

trade-off between the expected economic losses (and thus necessary incentives for farmers) and environmental benefits.

Consequently, a decision support model has been developed to calculate the economic and environmental effects of the implementation of environmental programmes on dairy farms. The aim of the model is to simulate the effects of these programmes on the production, management and economic results of the farms. Although in literature a number of applications with mathematical programming can be found (Berentsen and Giessen, 1995; Paccini et al., 1998), for this application a dynamic simulation model is preferred as this allows to better describe and model the rather complex internal relationships on dairy farms. Simulation also allows a better presentation of real decision situations than optimisation models as such.

In Section 2, the general model structure and the most important modules are described, followed by a validation of the model in Section 3. Section 4 illustrates the use of the model with applications for a standard Flemish dairy farm, while in Section 5 the model is extended with a multicriteria tool that allows the comparison of scenarios.

Based on a number of input data describing the simulated farm and the environmental programme, the model first determines the feed requirements of cattle as well as the feed production on the farm. This results in three indicators: the farm income as an indicator of the economic performance of the farm, the nitrogen surplus as an indicator of the environmental pollution by the farm and the land necessary to maintain the production level as an indicator of the land available for nature protection. As will be shown, the model can not only be used to determine the trade-off between the economic losses and environmental pollution, but also to evaluate the possible impact of nature protection programmes requiring late mowing and low nitrogen input on (part) of the farm land. This allows to study the trade-off between the nature protection and environmental objectives because farmers accepting nature protection constraints on part of their land will normally try to intensify the rest of their area.

2. The dynamic simulation model

As indicated in Section 1, a dynamic simulation model is preferred to a mathematical programming model to analyse the influence of restrictions on the dairy farm because of the complex relationships between on the one hand the feed production and on the other hand the feed requirements of the cattle. This relationship contains a dynamic component as both grass growth and feed requirements are function of time. The grass growth is not only function of inputs such as nitrogen, but also of the moment of application of the fertilisers, the moment of harvest and the season of the year (grass growth is e.g. higher in spring than in summer or autumn). The feed requirements of cattle are depending on their weight and for dairy cows of the milk yield, factors which are fluctuating in function of age and calving date. Hence, a dynamic model has been developed allowing to follow the situation on the farm day by day. The model simulates the grass growth and feed requirements for a whole calendar year and makes for each day the balance between supply and demand of feed. In the case of a grass surplus, this surplus is mowed while in the case of a shortage maize or compound feed is supplemented. An extra difficulty, that requires a feedback loop in the model, is that weight gain and milk yield of the cattle are also function of the feed availability (in quantity and quality), factor which is on its turn influenced by the fertiliser input.

The model structure is given in Fig. 1 and consists of five modules which are shortly described hereafter. In the input module (which is developed within a graphical user interface) the user has to submit the data about the farm (available area, number of parcels, herd structure, production level of different groups of cattle) as well as about the farm management system (fertilisation, feeding and grazing strategy) and optionally, the management constraints on certain parcels. The user can choose between a very detailed input per animal and parcel, allowing to simulate individual farms, or a more general input per group of animals and parcels with similar characteristics.

2.1. Feed requirement module

Based on the input of production characteristics, this module calculates for each individual animal (or group of similar animals) the uptake capacity as well as energy and protein

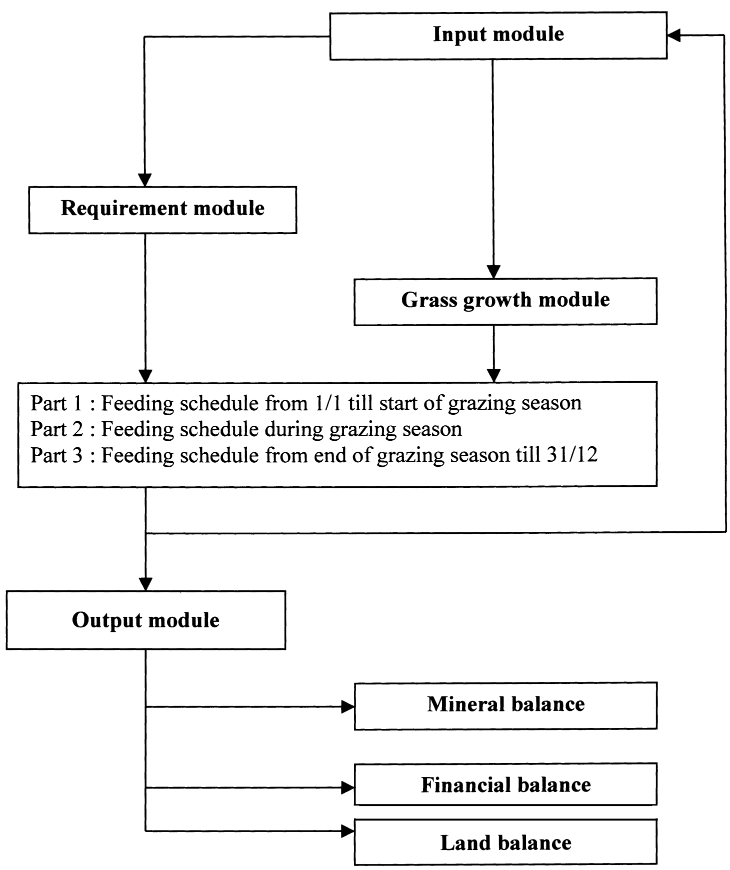

Fig. 1. Schematic representation of the simulation model.

requirements. For the dairy cows this calculation is based on the equation given by Wood (1967) that takes into account the requirements for dairy production, growth, maintenance and reproduction (Mandersloot and van der Meulen, 1991). The model of Van Arendonk (1985) is used to reproduce the daily protein and fat content on the basis of average lactation characteristics, while the weight variation due to lactation and pregnancy is described with the model of Korver et al. (1985). For the calculations of protein requirements the Dutch DVE-system (see CVB, 1996 or Berentsen, 1999) is applied. The energy requirement as well as the uptake capacity of the cattle are calculated applying algorithms described in Jarrige (1988). This French system has the advantage of simulating more correctly the influence of quality differences due to late mowing or lower N-use than the Dutch system.

2.2. Grass growth module

The grass growth module is crucial for the simulation of the influence of environmental constraints on dairy farms as it is at this level that most restrictions such as reduced fertilisation or late mowing have a direct impact. To simulate the influences at parcel level an empirical model fitted on the basis of observed data at field level is preferred to a mechanistic model simulating the influences of solar energy and rainfall at crop level. Basis for modelling the grass growth is the dynamic logistic model of Thornley and Johnson (1990, p. 78).

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \mathrm{RGR}_{\max} W - \frac{\mathrm{RGR}_{\max} W^2}{W_{\max}}$$

In the above equation, W is the grass yield (in kg ha^{-1}), $\mathrm{RGR}_{\max}$ is the maximum relative growth per day (kg day^{-1}), $W_{\max}$ is the maximum attainable grass yield, and t is the time.

After transformation of $\mathrm{RGR}_{\max}$ and substituting t_{maxGR}, the day that the maximum growth rate is reached, by a quadratic function of t_{start} and the N-input, to capture the influence of the starting date of the growing season and the N-fertilisation, the following non-linear algebraic equation is obtained from the original differential equation:

$$W = \frac{4\left(C_1 + C_2 N + C_3 N^2\right)}{\left(C_4 + C_5 t_{\mathrm{START}} + C_6 t_{\mathrm{START}}^2\right)} 1 + e^{\left(C_4 + C_5 t_{\mathrm{START}} + C_6 t_{\mathrm{START}}^2\right)\left(\left(C_7 + C_8 t_{\mathrm{START}} + C_9 t_{\mathrm{START}}^2\right) - t\right)}$$

in which C_1–C_9 are coefficients to be estimated from the data, t_{start} the day the growing season starts, N the units of applied nitrogen in kg and t the observed calendar day.

Using the maximum likelihood method, method that has been preferred to other methods such as the Ordinar Least Square method because of the high number of parameters, the model has been fitted on the basis of experimental data obtained from Behaeghe (1979) and Asijee (1993) for normal growth conditions and from Nevens and Reheul (1998) for the grass growth under management constraints.

The resulting model permits to simulate the daily grass growth under Flemish weather conditions in function of the N-fertilisation, the N-application date, the mowing date and a possible delay in the growth due to seasonal and other factors. An example is given in Fig. 2. The module not only calculates the quantitative impact (expressed in dry matter production per hectare) of different management decisions, but also their impact on the quality of the grass (expressed by protein and energy content) as well as the influence on uptake. Differences in uptake can, for instance, be due to differences in the taste of grass of different quality or age.

2.3. Central module

In the central module of the model the requirements of the cattle are compared with the supply of feed, taking into account the feed, strategy applied by the farmer and the quality of available nutrients. For the winter period, when the cows remain in the cowsheds, the optimal mix between roughage, maize and compound feed is calculated. With the help of a linear programming module the least cost composition fulfilling the energy and protein requirements is determined.

For the grazing period, the central module is optimising the grassland management by determining the area required to satisfy the feed requirements of all animals present (taking into account both herd size and composition). In Fig. 3, such a simulated grassland management calendar is illustrated. The grassland management can change in function of the applied fertilisation, feeding strategy (amount of maize or compound feed given), the rotation period, etc. To be sure that a certain management is possible an intelligent feedback module is incorporated that adapts the results in function of the feasibility of certain internal simulated decisions (such as required N-application or mowing date). This means that when a certain management is calculated to be infeasible, the values of the initial parameters are stepwise adapted until a feasible solution is reached.

2.4. Output module

In the output module, results of the different modules as well as overall results at farm level can be generated. The three main outputs are the financial balance, the mineral balance

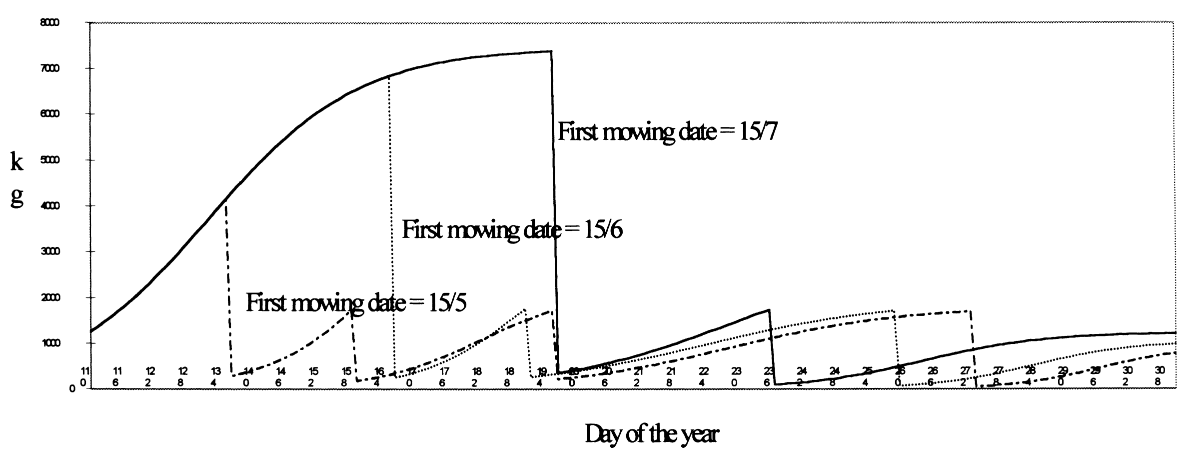

Fig. 2. Simulation of growth curves with different mowing dates.

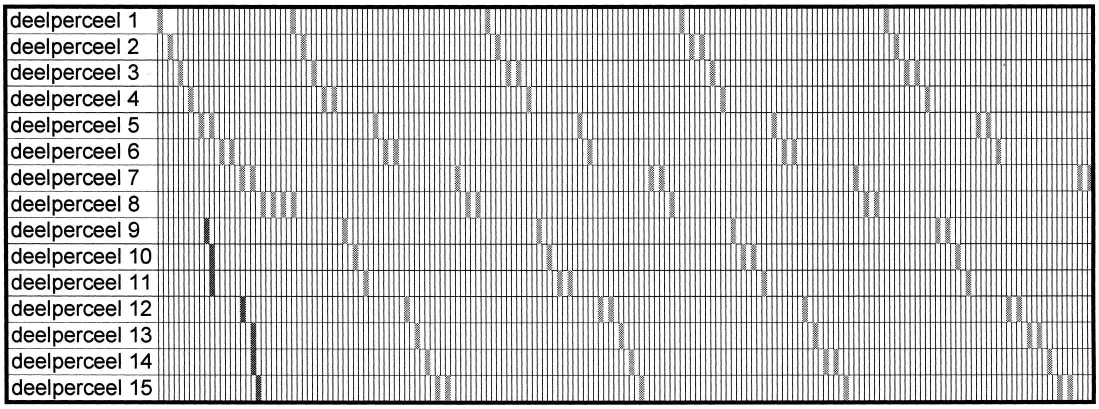

Fig. 3. Simulated grazing and mowing calendar (grey = grazing; black = mowing, deelperceel = an area of 1 ha).

(mainly for nitrogen) and the area requirement of the farm under the environmental constraints considered. Depending on the system boundaries, these balances can be calculated at cow, field or farm level as illustrated for the nitrogen balance in Fig. 4. As the output also distinguishes between the area with and without nature protection constraints, the trade-offs between farm economic, environmental and nature protection objectives can be calculated as will be illustrated in Section 4.

2.5. Model validation

The definition of validation is to study whether a model is a good representation of the system analysed. However, a validated model is never to be considered as a perfect model as the only perfect model is the reality itself (Kleijnen, 1995). The feed requirement and uptake module are based on an already validated model developed by Jarrige (1988). The grass growth

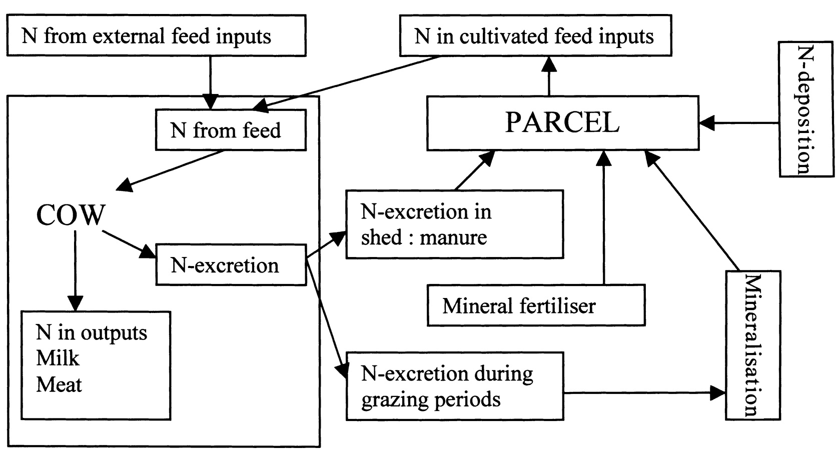

Fig. 4. N-flows at cow,parcel and farm level.

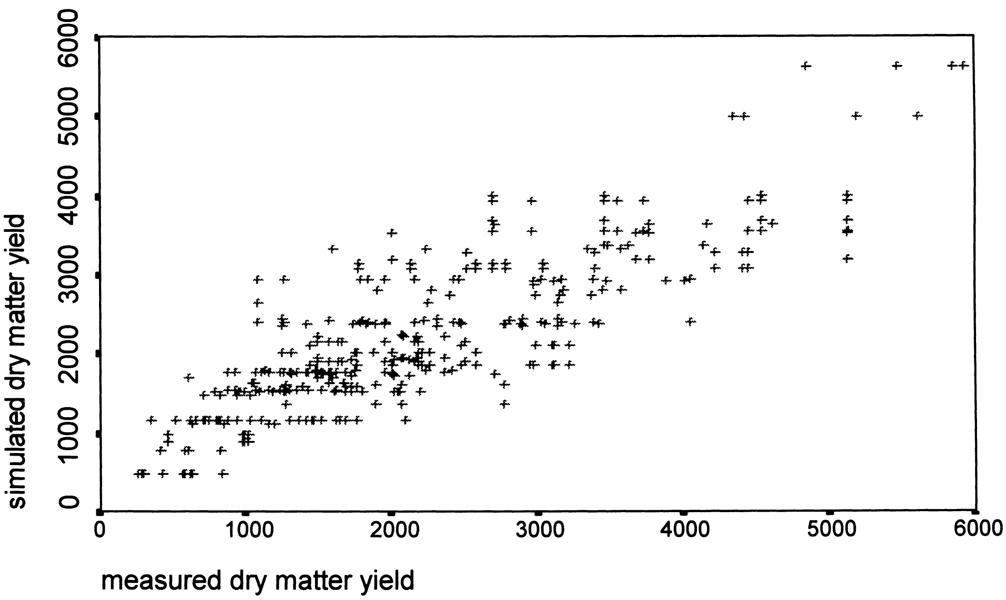

Fig. 5. Simulated and realised dry matter output for experimental grass plots.

module has been validated with field data. In Fig. 5, the simulated results from the non linear grass growth equation are plotted against experimental data obtained in field experiments. As can be derived the correspondence between field and simulated results is satisfactory as the plotted points are located near the 45° axis. Regression coefficients between 0.85 and 0.95 (depending on the year) allow to conclude that the model is sufficiently valid.

At farm level the model has been validated by comparing for five farms the model results with their real performances. In Table 1 the main indicators are compared. These results reveal that the production results (in ton milk per hectare) simulated are slightly higher while the compound feed and nitrogen input are somewhat lower than in practice. This is normal as in the model some optimisation is performed with regard to input use. But the fact that the differences are not too high and can be explained, leads to the conclusion that also at farm level the performance of the model is quite acceptable and that its use for comparing management strategies under different conditions is allowed.

Table 1
Comparison of simulated and observed results on five farms

Criterion	Farm1	Sim1	Farm2	Sim2	Farm3	Sim3	Farm4	Sim4	Farm5	Sim5
Ton milk ha^{-1}	15.9	16.9	13.9	14.1	20.0	20.1	11.4	12.5	8.5	8.5
N from compound feed (kg)	3888	3143	2495	1653	3191	2911	5087	3062	3403	1462
N from mineral fertiliser (kg ha^{-1})	81	90	165	165	146	118	131	72	182	133
N in output (kg ha^{-1})	110	106	180	181	136	142	74	82	54	57
N-surplus (kg ha^{-1})	230	217	207	167	311	262	283	194	295	189

3. Results

To analyse the influence of environmental constraints the model has been applied to an average Flemish farm holding 42 cows, 23 units of young stock and with an dairy production of 6800 l in the first lactation and 7500 l from the second lactation on. For this typical farm the economic results, the nitrogen balance and the area under nature protection were calculated for different conditions.

Fig. 6 illustrates the effect of a restriction on the N-input. The figure indicates that restrictions down to about 280 kg N on pastures and 440 kg N on 100% mowed grassland do not cause high income decreases per hectare, but are able to considerably reduce the N-surplus. Further constraints, however, cause high income losses per hectare and require sinificantly more area to maintain the output level of the farm. This result is already a first indication that the simulation model can support the setting of environmental standards by calculating the trade-offs between economic losses, reduction of environmental surplus and increase in area necessary to maintain production levels.

A second example of the use of the simulation model is given in Fig. 7 where the influence of the production per cow is simulated. This figure indicates that an increase in the production per cow leads to an increase in the nitrogen surplus per hectare. On the other hand, the area necessary to produce the same output decreases considerably and also the N-surplus per 1000 l of milk. This shows that in practice a trade-off exists between maintaining a basic environmental quality (N-surplus per hectare) and nature protection objectives effects (the less possible land under production).

A third example of the possibilities to apply the simulation model is provided in Fig. 8 where the influence is illustrated the percentage of maize in the cattle feed ration has on the nitrogen and land balance. Accounting results at farm level do not allow to find a clear difference between farms with different percentages of maize in the cultivated area. The simulation model is able to reveal the reasons behind this because with the model a distinction can be made between maize in the summer ration (when cattle is grazing) and winter ration (when cattle is in the shed). During the summer period a higher amount of maize results in higher N-surpluses per hectare due to the lower protein content of maize that has to be

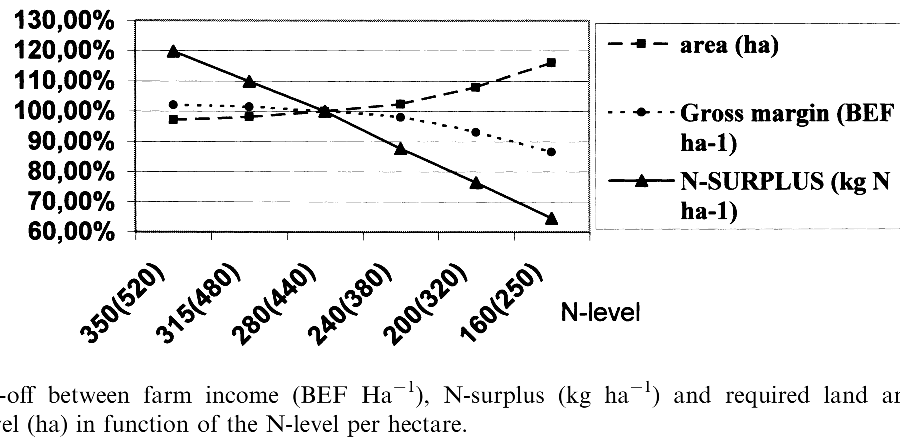

Fig. 6. Trade-off between farm income (BEF Ha^{-1}), N-surplus (kg ha^{-1}) and required land area to maintain production level (ha) in function of the N-level per hectare.

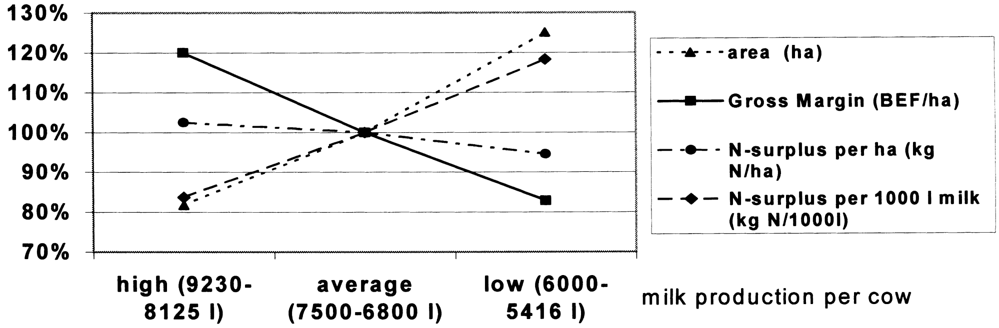

Fig. 7. Influence of yield level per cow on farm income, N-surplus per hectare and per litre and on required area.

compensated with compound feed. This has a negative influence on the N-balance. Further, the lower N-excretion coefficient of maize results in a lower manure excretion during the grazing season and thus in higher mineral N-fertilisation requirements of the grassland. Because the necessary area decreases, the overall economic result per hectare remains the same. In winter time, the simulation of increased levels of maize results in an opposite picture due to the higher uptake of maize and its higher energy content in comparison with roughage. Although also in this case more compound feed is needed, this is compensated by the lower N-requirement of maize in comparison with grassland.

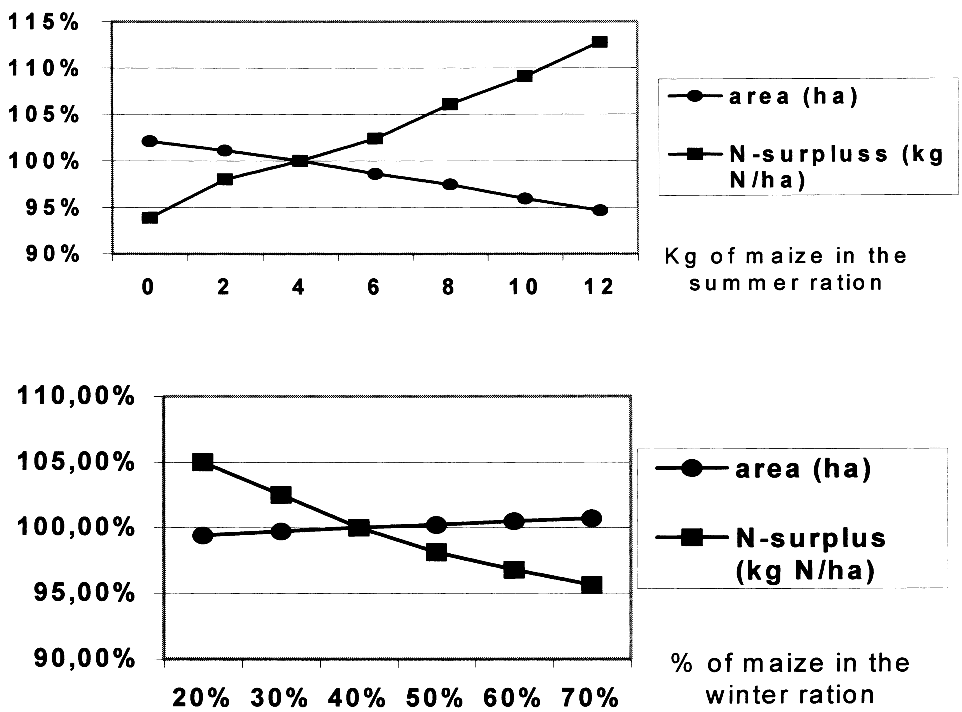

Fig. 8. Influence of maize in the feed ration in summer and winter time on the N-surplus.

Finally, the simulation model can also be used to calculate the economic losses caused by extra nature protection restrictions (such as extremely low N-levels or late mowing). Fig. 9 indicates that the effect depends on the intensity of farming. On less intensive farms, restrictions can better be introduced because of the possibility of intensification on other parcels. The figure indicates that a nature protection policy will not necessarily lead to better environmental performance of farms because to maintain their production level, farms will intensify the management of crops on fields not falling in the nature protection area.

4. Identifying the best compromise

To identify the best compromise solution, a support tool based on multi-criteria analysis has been added to the simulation programme. The best compromise can be defined as the solution closest to the ideal solution which in most cases is infeasable because of competing objectives (Duckstein and Kempf, 1981; Yu, 1973 or Zeleny, 1973). The ideal solution is defined as the point where all objectives achieve their optimal value (Romero and Rehman, 1989). In our case this is the point where N-surplus and land use should be at the minimal attainable level and farm income at its maximum level. In Fig. 10, this point is indicated in the solution space comparing the possible decrease in N-surplus with the required land area.

One way to identify the best compromise is to minimise the distance to this ideal point using the L_p-metrics (Romero and Rehman, 1989) (with W_j being the weight attached to objective j):

$$L_P(W) = \left[\sum_{j=1}^{n} \left(W_j \, d_j \right)^P \right]^{1/p}$$

with

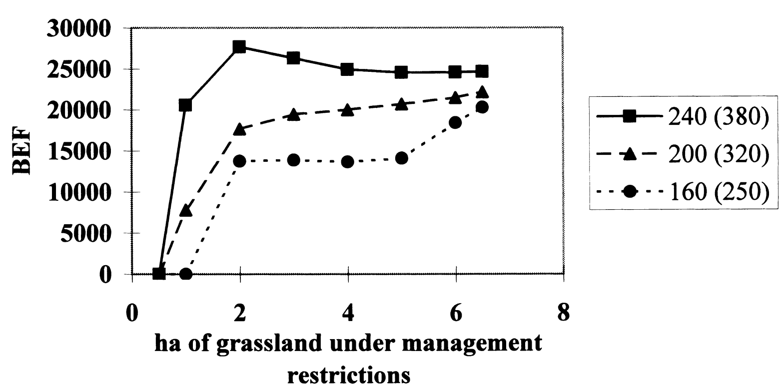

Fig. 9. Economic losses related to the number of hectares under nature management agreements for different intensity levels.

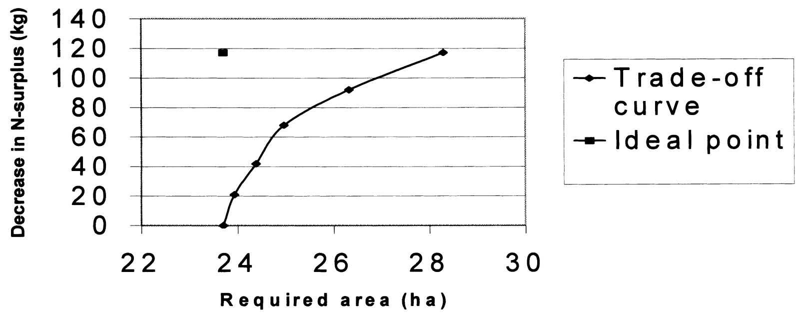

Fig. 10. Trade-off curve between decrease in N-surplus and required area for example farm.

$$d_j = \frac{|Z_j^* - Z_j(x)|}{|Z_j^* - Z_{*j}|}$$

In this formula, Z_j^* and Z_{*j} are the ideal and anti-ideal solution for criterion j, respectively. By changing the W and p parameters, different solutions are obtained reflecting different preference structures. In Table 2 the best compromise among the results obtained in Fig. 6 are determined for different weight-sets and different values of p. As can be observed, with changing values of these parameters the best compromise can change. The parameter p acts as a weight attached to the magnitude of the deviations, while W_j measures the relative importance given to the main objectives in a decision problem.

When the Euclidean distance is used ($p = 2$) and the three objectives receive the same

Table 2
Identification of compromise solutions for different weight sets

	A1	A2	A3	A4	A5	A6
Output scores						
Mineral balance in kg N (min.)	254	233	212	186	162	137
Financial balance in BF/ha (max)	122,372	121,742	119,893	117,617	111,610	103,818
Land balance in ha (min)	23.70	23.93	24.38	24.96	26.32	28.29
Solutions for $W_1 = 1$; $W_2 = 1$ and $W_3 = 1$						
L_1	1.00	0.90 [a]	0.92	0.95	1.36	2.00
L_2	1.00	0.82	0.67	0.56 [a]	0.84	1.41
L_∞	1.00	0.82	0.64	0.42 [a]	0.58	1.00
Solutions for $W_1 = 5$; $W_2 = 1$ and $W_3 = 1$						
L_1	5.00	4.19	3.49	2.62	2.21	2.00 [a]
L_2	2.23	1.83	1.45	1.01	0.94 [a]	1.41
L_∞	1.02	0.82	0.64	0.43 [a]	0.58	1.00
Solutions for $W_1 = 1$; $W_2 = 3$ and $W_3 = 2$						
L_1	1 [a]	1.02	1.34	1.74	3.09	5
L_2	1	0.82	0.71 [a]	0.72	1.30	2.23
L_∞	1	0.82	0.64	0.42 [a]	0.58	1.02

[a] ☐ Best compromise.

weight, solution 4 is the best compromise. However, when the main objective is the decrease of the N-surplus, solution 5 seems a better compromise. If more importance is attached to the financial and land balance, solution 3 comes out as the best compromise.

The L_1 and L_∞ weightings are extreme cases. Where the first is based on a separable and additive utility function, the second underlies a MINMAX utility function minimising the maximum deviation. As can be derived from the results, for the L_∞-case a stable compromise is obtained (solution A4), meaning that the weights do not change the solution. In cases where the results are more sensitive to weight changes, the weights of the decision makers can be elicited using e.g. the AHP-approach (Saaty, 1988) as illustrated in Van Huylenbroeck and Coppens (1995).

The example shows that the methodology can take into account the relative weights of the objectives in supporting the user of the programme to find the best compromise solution. Of course other multi-criteria techniques such as electre, oreste, promethee or others (see also Van Huylenbroeck, 1997) can be used and incorporated into the programme.

5. Conclusions

This paper has illustrated the added value of combining dynamic simulation and optimisation models for analysing environmental problems in agriculture. In particular the possibility to analyse the influence of separated factors makes simulation a powerful tool for decision support. The inclusion of separate optimisation routines in the simulation model allows to determine the existing possibilities for improving environmental performance at farm level without being unrealistic as is often the case with pure optimisation models. In order to support decision making, the model is supplemented with a multi-criteria tool that allows to identify the best compromise between different simulated solutions. By attaching different weights to the environmental, financial or land use balance different preference structures of decision makers can be represented and taken into account.

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