Operational Optimization of Organic Fertilizer Application in Greenhouse Crops

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Abstract

Organic fertilizers are the only fertilizers used in organic greenhouse horticulture. The nitrogen (N) in these fertilizers must be mineralized before it can be taken up by the crop. This makes it a challenge to minimize N losses while ensuring that adequate N is available to the crop at all times. The objective of our work was to develop an operational method to determine optimal fertilizer strategy (timing of applications, kind and amount of fertilizer for each application). We developed the model LinFert, in which mineralization and loss of N are linearly related to the amounts of fertilizer applied, and which can thus be optimized using linear programming. Cumulative mineralization and loss of N simulated with LinFert matched closely the equivalent numbers simulated by a detailed process-based model describing water movement as well as transport, uptake, mineralization and denitrification of nitrogen. We conclude that optimization runs with LinFert will be helpful to farmers when current fertilizer strategies are fine-tuned, and when in the future fertilizer strategies are needed that put greater emphasis on reducing nitrogen loss.

INTRODUCTION

Organic fertilizers are the only fertilizers used in organic greenhouse horticulture. The nitrogen (N) in these fertilizers must be mineralized before it can be taken up by the crop, which means that the application of fertilizer must take place a certain amount of time before the crop needs the nitrogen. There are two uncertainties involved in deciding on the application of organic fertilizer: how much time does it take for the N to be mineralized, and how much N does the crop need until the next application. These uncertainties can be addressed by applying liberal amounts of organic fertilizer, but this is costly and easily leads to large losses of N through leaching and denitrification. Thus there is a need for an advisory tool that (1) evaluates whether a proposed fertilizer strategy will result in sufficient availability of mineral N, and (2) given boundary conditions, finds the fertilizer strategy that results in the lowest cost or the lowest loss of N. Here fertilizer strategy is defined as decisions taken before the growing season about the kinds of fertilizer used, the times of application and the amounts applied.

Intkam is a model that simulates potential (light-limited) crop growth and can thus be used to calculate the time course of crop N demand (Marcelis et al., 2006). OSmanSoil is a model that simulates the time course of mineralization of organic matter in the soil and the movement and transformations of mineral N in the soil (Heinen, 2005). With these two models it is possible to evaluate a given fertilizer strategy. It is also possible to use these models to find an optimal fertilizer strategy, but execution time makes interactive optimization impractical. Let us assume there are 10 moments during a growing season at which we want to consider applying one or more fertilizers. Let us further assume that at any given moment there are 2 fertilizers to choose from. This is a simplification of the real situation, because many more moments and fertilizers are possible. A random-search optimization algorithm such as that of Price (1983) could then be used to find the amounts of each fertilizer to be applied at each moment that lead to the lowest cost or the lowest loss of N. Such an optimization could, however, require 10,000 or more evaluations, which, even if a simulation run takes only one second, would take several hours, which precludes interactive use. An alternative and faster method would be to discretize the amounts of fertilizer to be applied and consider only, for example, 10 amounts. Then, a full evaluation of the simple example would require only 1000 simulations or approx. one quarter of an hour, which is still too slow for interactive use. Therefore, interactive optimization requires a faster model, a faster optimization algorithm, or a combination of the two.

The models mentioned above are too slow for the purpose of optimization because they describe the modeled system in greater detail (in terms of resolution in time and space and in terms of the processes that are represented in the models) than is needed for optimization. This was recognized by Ten Berge et al. (1997) who developed a summary model of crop growth and soil N supply to optimize fertilizer applications in rice. Our case is simpler than that of field-grown rice: greenhouse farmers aim for potential growth and thus potential N uptake, so that the optimization model needs to consider only mineralization and losses.

When the function to be optimized can only be evaluated by running a complex simulation model, a random-search optimization algorithm may be used (Hendrix, 1998). A random-search optimization is typically slow and there is no way of knowing whether the optimum found is local or global. Thus, when optimization is the main purpose of the model, many authors have developed linear models. Linear models can be optimized efficiently (Chvatal, 1983).

Of the two processes considered here, mineralization and N losses, there are several simple models available for mineralization. The model of Janssen (1984) states that under constant conditions – in terms of temperature and water content – mineralization is a first-order process. It follows that the amount of N mineralized, from a certain amount of organic matter, and during a given period of time, is linearly dependent on the initial amount. This observation is the cornerstone of Nutmatch (Bos and Ten Berge, 2005). The objective of the work reported here is to formulate a linear model of the availability of mineral N to the crop for use in greenhouse situations that can be used to optimize greenhouse fertilizer strategy in an interactive manner.

MATERIALS AND METHODS

Derivation of LinFert

In order to obtain the highest possible yield, greenhouse temperature and soil nutrient status are manipulated in greenhouse horticulture in such a way that they do not limit crop growth. Crop growth rate is then limited only by light. The amount of N (N) that must be available for crop growth can then be calculated using a dynamic model of crop growth. In this study we used Intkam (Marcelis et al., 2006).

The amount of N that is taken up during day p of the simulation is U_p and is expressed in kg N per hectare (we use the subscript "p" (for "period") to denote the time scale, e.g., days, because the derivation that follows can be applied to periods of arbitrary length). U_p is taken from the mineral N in the soil at the beginning of the day (N_p, kg ha^{-1}) plus the N that is mineralized from organic matter during day p. The organic matter may have been present in the soil at the start of the season (soil organic matter) or it may be added during the growing season as organic fertilizer.

The amount of N mineralized from organic matter during day p is

$$\sum M_i f_{pi} \quad (1)$$

where M_i = the total amount of N (kg ha^{-1}) in the i-th pool of organic matter (soil organic matter, or an application of organic fertilizer), and f_{pi} = the fraction of M_i that is mineralized during day p.

Mineral N that is not taken up during day p is partially lost to leaching and denitrification. We assume that in a greenhouse irrigation will be so as to keep the soil wet, but not so plentiful as to cause much leaching. We assume that under these conditions the loss of mineral N to leaching and denitrification can be expressed as a fraction of the amount of mineral N in the profile at the end of the day:

$$N_{p+1} = x_p\,(N_p + \sum M_i f_{pi} - U_p) \quad (2)$$

where x_p is the fraction of mineral N available at the start of ($p+1$). The amount of mineral N at the beginning of the simulation (N_1, kg/ha) is the measured amount of N_{min} at the beginning of the first day.

In order to realize potential (light-limited) growth, the availability of mineral N on every day must be equal to or greater than the potential uptake of N:

$$N_p + \sum M_i f_{pi} \geq U_p \quad (3)$$

Here we limit ourselves to the case of three periods. Recursive substitution (2) into (3) leads to:

$$\begin{aligned} &N_1 + \sum M_i f_{1i} && \geq U_1 \\ &x_1(N_1 + \sum M_i f_{1i} - U_1) + \sum M_i f_{2i} && \geq U_2 \\ &x_2[x_1(N_1 + \sum M_i f_{1i} - U_1) + \sum M_i f_{2i} - U_2] + \sum M_i f_{3i} && \geq U_3 \end{aligned} \quad (4)$$

Considering two applications of organic fertilizer (M_1 and M_2) and reordering of terms, yields:

$$\begin{aligned} &M_1(f_{11}) &&+ M_2(f_{12}) &&\geq U_1 - N_1 \\ &M_1(x_1 f_{11} + f_{21}) &&+ M_2(x_1 f_{12} + f_{22}) &&\geq x_1 U_1 + U_2 - x_1 N_1 \\ &M_1(x_2 x_1 f_{11} + x_2 f_{21} + f_{31}) &&+ M_2(x_2 x_1 f_{12} + x_2 f_{22} + f_{32}) &&\geq x_2 x_1 U_1 + x_2 U_2 + U_3 - x_2 x_1 N_1 \end{aligned} \quad (5)$$

These equations are linear in M_i and can thus without further manipulation be used as constraints in a linear programming optimization (Chvatal, 1983).

Rate of Mineralization

In the above equations, the mineralization factors f_{pi} are of crucial importance. The starting point for the calculation of these factors is the formula of Janssen (1984):

$$Y_t = Y_0 \exp\,[4.7 * \{(a + t\,T_c)^{-0.6} - a^{-0.6}\}] \quad (6)$$

where Y = the total amount of N in a quantity of organic matter (kg ha^{-1}), Y_0 = the initial amount of N in a quantity of organic matter (kg ha^{-1}), a = initial age of the organic matter (years), $T_c = 2^{(T-9)/9}$ = a temperature correction factor with T = actual temperature (°C), and t = duration of mineralization period in years. Note that the temperature correction factor can only be used in this way for a constant T during the period considered. In LinFert, the f_{pi} are calculated as $(Y_{p+1} - Y_p)/Y_0$ with eq. 6 appropriately parameterized for each application of organic fertilizer. It is implicitly assumed that mineralization is not limited by the soil water status.

Optimization

LinFert can be run with one of two objective functions. First, minimization of cost of fertilizer application leads to

$$\text{minimize}\ (\sum M_i P_i) \quad (7)$$

where P_i is the price (€ t^{-1}) of fertilizer M_i (in LinFert, P_i includes the cost of applying the fertilizer).

Second, the model may be used to find the fertilizer application plan that leads to the lowest possible N loss. Here, the number of terms in the objective function depends on the number of days (periods) considered. For example, the objective function for a simulation with three periods is

$$\text{minimize}\ (\sum M_i f_{1i}(1 - x_3 x_2 x_1) + \sum M_i f_{2i}(1 - x_3 x_2) + \sum M_i f_{3i}(1 - x_3)) \quad (8)$$

Additional Constraints on the Optimization

In addition to the necessary constraints defined above (the amount of mineral N in the profile must be sufficient to allow uptake of N at the potential rate), the following additional constraints are imposed on the optimization.

1. Lower Bound on N_{min}. In order to ensure unimpeded uptake of N by the crop, we don't want the amount of mineral N to drop below a certain value:

$$N_p \geq S \text{ (for } p \geq 2) \quad (9)$$

which holds for all N_p except N_1 because the latter is given by the starting conditions of the simulation. For two applications of organic fertilizer, and after substitution and reordering of terms, this leads to a new set of constraints:

$$\begin{aligned}
&M_1(f_{11}) && + M_2(f_{12}) && \geq S/x_1 + U_1 - N_1 \\
&M_1(x_1 f_{11} + f_{21}) && + M_2(x_1 f_{12} + f_{22}) && \geq S/x_2 + x_1 U_1 + U_2 - x_1 N_1 \\
&M_1(x_2 x_1 f_{11} + x_2 f_{21} + f_{31}) && + M_2(x_2 x_1 f_{12} + x_2 f_{22} + f_{32}) && \geq S/x_3 + x_2 x_1 U_1 + x_2 U_2 + U_3 - x_2 x_1 N_1 \quad (10)
\end{aligned}$$

In the extreme case that $S = 0$, the above equation is reduced to eq. 5.

2. Upper and Lower Bounds on Applied Amount. It is impractical to apply very small or very large amounts of an organic fertilizer at any given time. Therefore, the LP decision variables that hold the amount of fertilizer applied are defined as "semi-continuous" with upper and lower bounds that can be defined separately for each fertilizer.

3. Maximum Number of Applications of a Fertilizer. It is not realistic to apply a particular fertilizer more than a certain number of times on a crop. This constraint is implemented by introducing a binary variable B_{it} for each combination of fertilizer and application time. These variables are subjected to the constraints:

$$M_{it} \leq L\, B_{it} \quad (11)$$

where M_{it} = the amount of fertilizer M_i (t/ha) applied at time t, L is a large number (we use 99999) and binary variable B_{it} is only allowed to become 0 or 1. If $M_i > 0$, B_{it} is forced to 1 (note: if $M_i = 0$, eq. 10 imposes no constraint on B_{it}). The constraint that M_i may be applied at most n_i times can now be expressed as:

$$\sum B_{it} \leq n_i \quad (12)$$

4. At Most 170 kg N from Manure. EU regulations stipulate that at most 170 kg N ha^{-1} may be applied using manure.

5. Apply at Least *x*% at *t*=0. It may desirable from the point of view of maintenance of soil organic matter to include a slowly decomposing fertilizer such as farm yard manure in the fertilizer plan, even if other fertilizers are preferable from a financial point of view.

Implementation of LinFert

LinFert is implemented using a two-step approach. First, the user enters the parameters defining an optimization run using a GUI application. Next, this application encodes the optimization and invokes an LP solver (Berkelaar et al., 2006). The solution is made visible to the user in the form of graphs and summary tables.

OSmanSoil

The experimental data available to us were insufficient to validate the new model LinFert. We therefore compared simulations by LinFert with simulations by the model OSmanSoil. OSmanSoil is a detailed, daily time step model of soil water movement, temperature, mineralization and transformations of N that has been validated earlier

(Heinen, 2005). The model also simulated relevant processes with sufficient detail in a field experiment in Naaldwijk, The Netherlands (De Visser et al., 2006).

Scenario

Simulation parameters were chosen to reflect the conditions in the experiment at Naaldwijk, The Netherlands (De Visser et al., 2006). Specifically, the crop was green pepper, planted on 18 February 2003, growing until 10 November 2003, and yielding 13 kg m^{-2} of fresh fruit. The soil was a sandy loam with an organic matter content of 7% in the layer 0-25 cm and 2.8% in the layer 25-50 cm.

Simulations

In the first set of simulations a fixed fertilizer plan was used (no optimization). This fertilizer plan was similar (but not identical) to the fertilizer plan used in Naaldwijk in 2003. Specifically, it comprised an application of 10 t ha^{-1} of farm yard manure (FYM) at the start of the simulation; an application of 1 t ha^{-1} of alfalfa straw, also at the start of the simulation; and 7 monthly applications of 0.8 t ha^{-1} of "Monterra Nitrogen+" (fertilizer details are given in Table 1). LinFert was run twice with this fertilizer plan: with measured greenhouse temperatures (average 20°C) and with a constant greenhouse temperature of 15°C. The value of parameter x_p in eq. 2 was 0.997, which was selected to match results of the detailed model. OSmanSoil was run four times with this fertilizer plan. The base run was with measured greenhouse temperatures, the effect of soil water content on mineralization switched on, and irrigation at 120% of evapotranspiration (*ET*; mm d^{-1}). The second run was with a constant greenhouse temperature of 15°C, but otherwise as the base run. The third run was as the base run, but with the effect of soil water content on mineralization rate switched off; and the fourth run was as the base run, but with measured irrigation rates.

Next, a series of optimizations was run. Details of these runs are given in Table 1.

RESULTS AND DISCUSSION

Cumulative mineralization simulated by LinFert and by OSmanSoil is shown in Fig. 1 for simulations with measured greenhouse temperature, with irrigation at 120% of *ET*, and with the effect of soil water content on rate of mineralization switched on for OSmanSoil. The two models give similar results. Regression of all values in Fig. 1 simulated by LinFert (y) on all values simulated by OSmanSoil (x) yields y = 1.04x – 0.66 with an R^2 of 0.996.

Cumulative loss of N from the profile simulated by LinFert and by OSmanSoil is shown in Fig. 2. The partitioning between leaching and denitrification simulated by OSmanSoil is also shown; LinFert gives no information about the relative magnitude of leaching and denitrification. The simulated total losses are very similar. Of course the choice of a value for parameter x_p in eq. 1 has a large influence on the results.

The difference between mineralization of N and loss of N determines the N_{min} content of the profile. Simulation results for both models are shown in Fig. 3. LinFert gives no information as to how the N is distributed over the profile. OSmanSoil does. There is a close correspondence between N_{min} simulated by LinFert and N_{min} in 0-60 cm simulated by OSmanSoil.

A constant greenhouse temperature of 15°C resulted (as expected) in lower cumulative mineralization at all times for both models and are not shown. The effect of soil water content on the rate of mineralization in OSmanSoil was negligible, both when irrigation was set to 120% of *ET* and when irrigation was input as measured (not shown).

These results indicate that LinFert describes soil N dynamics with sufficient detail to be used for strategic optimization. Results of several optimization runs are shown in Table 2. In these optimizations only "Monterra Nitrogen+" was used for application during the growing season. Prior optimization runs had shown that if more than one in-season fertilizer is offered, only the fertilizer with the most N per € is selected.

CONCLUSIONS

LinFert describes soil N dynamics with sufficient detail to be used for strategic optimization of selection of organic fertilizers and the amount and time of their application. But the simple model is not able to partition the loss of N between leaching and denitrification, and gives no information about the distribution of mineral N in the soil profile. It is therefore prudent to interpret simulation results by LinFert with a fair degree of caution. Operationally, we first use LinFert to find the optimal fertilizer strategy for a given set of conditions, and then use OSmanSoil to simulate leaching, denitrification and the availability of mineral N.

LinFert will be helpful to farmers when current fertilizer strategies are fine-tuned, and when in the future fertilizer strategies are needed that put greater emphasis on reducing N loss.

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Tables

Table 1. Details of the organic fertilizers used.

Fertilizer	N total ($g\ kg^{-1}$)	N_{min} ($g\ kg^{-1}$)	Initial age (years)	C/N	Price €
FYM	5.58	0.71	13.9	2.2	50
Alfalfa straw	41.29	-	1.0	9.9	180
Monterra	130.00	-	0.5	3.5	400

Table 2. Details of the optimization runs described in this paper.

Case	Conditions			Outcome of optimization						
	$P_{t=0}$[1]	FYM	Alfalfa	FYM (t ha^{-1})	Alfalfa (t ha^{-1})	Monterra (t ha^{-1})	Cost (€ ha^{-1})	Leaching (kg N ha^{-1})	Denitr. (kg N ha^{-1})
1	0	yes	yes			4.4	1754	40	53
2	15	yes	yes		2.1	3.8	1900	40	54
3	15	yes	no	15.6		4.0	2374	40	54
4	15	no	yes		2.1	3.8	1900	40	54

[1]Lower bound on N applied at t=0, expressed as a percentage of total N applied.

Figures

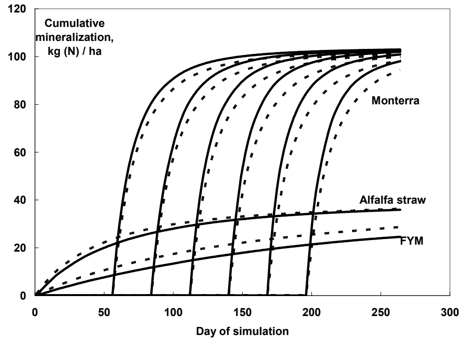

Fig. 1. Comparison of cumulative mineralization simulated by LinFert and by OSmanSoil. Solid lines: OSmanSoil; broken lines: LinFert.

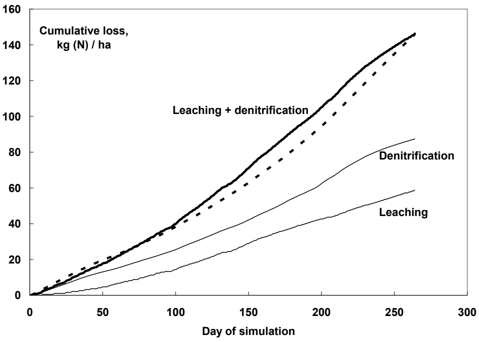

Fig. 2. Comparison of N losses simulated by LinFert and by OSmanSoil. Solid lines: OSmanSoil; broken line: LinFert.

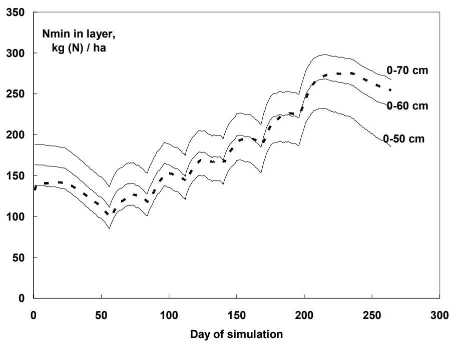

Fig. 3. Comparison of N_{min} in profile simulated by LinFert and N_{min} in selected layers simulated by OSmanSoil. Solid lines: OSmanSoil; broken line: LinFert.