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Modelling and measuring the effect of nitrogen catch crops on the nitrogen supply for succeeding crops

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Abstract

Nitrogen catch crops are grown to absorb nitrogen from the rooting zone during autumn and winter. The uptake of N (N_{upt}) from the soil inorganic N pool (N_{min}) to a pool of catch crop nitrogen, will protect the nitrogen against leaching. After incorporation, a fraction (m) of the catch crop nitrogen is mineralized and becomes available again. However, not all available nitrogen present in the soil in the autumn is lost by leaching during winter. A fraction (r) of the nitrogen absorbed by the catch crop would, without a catch crop, have been retained within the rooting zone. The first year nitrogen beneficial effect (N_{eff}) of a catch crop may then be expressed by

$$N_{eff} = m^* N_{\rm upt} - r^* N_{\rm upt}$$

The soil-plant simulation model DAISY was evaluated for its ability to simulate the effects of catch crops on spring N_{min} and N_{eff}. Based on incubation studies, parameter values were assigned to a number of catch crop materials, and these parameter values were then used to simulate spring N_{min}. The model was able to predict much of the vairiation in the measured spring N_{min} ($r^2 = 0.48^{***}$) and there was good agreement between the measured and the simulated effect of winter precipitation on spring N_{min} and N_{eff}.

Scenarios including variable soil and climate conditions, and variable root depth of the succeeding crop were simulated. It is illustrated that the effect of catch crops on nitrogen availability for the succeeding crop depends strongly on the rooting depth of the succeeding crop. If the succeeding crop is deep rooted and the leaching intensity is low, there is a high risk that a catch crop will have a negative effect on nitrogen availability. The simulations showed that the strategy for the growing of catch crops should be adapted to the actual situation, especially to the expected leaching intensity and to the rooting depth of the succeeding crop.

Introduction

The general concern about nitrate pollution from arable soils emphasizes the need for more efficient ways of nitrate management, including the cycling of N via crop residues, catch crops and improved adjustment of the fertilizer application rates.

A catch crop is grown to absorb nitrate from the root zone during autumn and winter, and thereby reduce nitrate leaching. To achieve the optimal environmental and economical effect of catch crops, they should reduce the need for nitrogen fertilizer inputs. However, the effect of catch crops on N availability for succeeding crops may vary from strong positive effects (Elers and Hartmann, 1987; Sørensen and Thorup-Kristensen, 1993; Thorup-Kristensen, 1994a) to significant negative effects (Jensen, 1991, 1992; Muller et al. 1989). Large differences have been observed between catch crop species in their effect on N availability for succeeding crops (Elers and Hartmann,

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1987; Jensen, 1991; Muller et al., 1989; Sørensen and Thorup-Kristensen, 1993; Thorup-Kristensen, 1993b, 1994a).

The effect of catch crops on N supply for a succeeding crop depends on several factors and processes, e.g. rooting depth of the catch crop (Thorup-Kristensen, 1993a), climate, soil type and rooting depth of the succeeding crop (Thorup-Kristensen, 1993b), the content of nitrate in the soil, the biomass production of the catch crop, and the mineralization of N from the catch crop (Jensen, 1991, 1992). To select the most optimal catch crop species and management strategy under a given set of environmental conditions requires an integrated evaluation of several processes simultaneously.

Such an evaluation may be supported by simulation models which are able to predict the effects of catch crops on the nitrogen cycle in the soil-plant system, e.g. the simulation model DAISY (Hansen et al. 1991). In the DAISY model, the catch crop N uptake (N_{upt}) is a transfer of N from a pool of soil inorganic nitrogen (N_{min}) to a pool of catch crop nitrogen. The resulting change in each of these pools will directly influence the simulated N availability for the succeeding crop. The reduction of the N_{min} pool by a catch crop will reduce the N availability for the succeeding crop, as a fraction (r) of the assimilated N would otherwise be retained in the rooting zone and be available for the succeeding crop. This effect has been termed preemptive competition (Thorup-Kristensen, 1993b). The simultaneous addition of the same amount of N to the catch crop N pool will increase the nitrogen availability for the succeeding crop, as some fraction (m) of this nitrogen will be mineralized and thus returned to the plant available N_{min} pool. Based on such considerations Thorup-Kristensen (1993b) found that the combined effect of catch crop N uptake on N availability for a succeeding crop (N_{eff}) can be expressed as

$$N_{eff} = N_{upt} * m - N_{upt} * r \tag{1}$$

In the model r is not the same for all catch crop nitrogen uptake. It depends on both when and where the N is assimilated. Nitrogen that is available in the early autumn and at great soil depth is much more likely to be lost, and will thus have a lower r value than nitrogen available e.g. in the early spring in the topsoil. On the contrary, the value of m is the same for all catch crop nitrogen, as its effect on mineralization does not depend on where or when it was assimilated.

Table 1. Compartments of organic matter in the DAISY model

Compartments	Sub-compartments
The plants (crop)	Shoot and root
Soil organic matter (SOM)	SOM1 and SOM2
Soil microbial biomass (SMB)	SMB1 and SMB2
Added organic matter (AOM)*	AOM1 and AOM2

*E.g. a catch crop.

Thus, the equation will be

$$N_{eff} = N_{upt} * m - \sum_{layers} \sum_{days} N_{upt} * r_{ij} \tag{2}$$

where r_{ij} is the fraction of the nitrogen absorbed by the catch crop from the ith soil layer at the jth day that would have been retained until spring as N_{min} within the root zone of the succeeding crop.

The aim of this work is to test the ability of the DAISY model to simulate the effects of catch crops, especially the effect on N supply for a succeeding crop as affected by preemptive competition and mineralization. The model is also used to simulate the perspectives of various catch crop strategies in order to improve the management of catch crops to optimize the nitrogen supply for the succeeding crop.

Materials and methods

The model

The DAISY model simulates nitrogen (N), carbon (C), water and energy dynamics in the soil-plant-atmosphere system including crop growth and net uptakes of C, N, and water by the crop plants (Hansen et al., 1991). The organic matter in the soil-plant system is divided into four measurable compartments (Table 1).

Each of these compartments is considered as a continuum of e.g. organic matter turnover rates which vary with soil, crop rotation and soil fertility management. Simulations of a variety of agronomic conditions were predicted satisfactorily with an equal set of C turnover rates, if each of the compartments SOM, SMB, and AOM were divided into two sub-compartments (Hansen et al. 1990, 1991). The C and N turnover between and within the compartments SMB, SOM, and AOM are illustrated in Figure 1. The simulation is based on the assumption that the

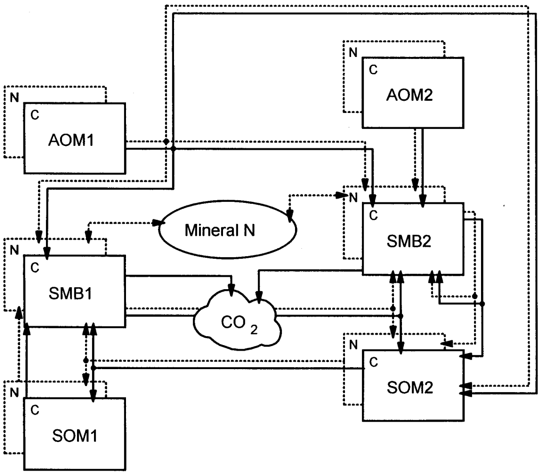

Figure 1. Interrelations between soil organic matter pools considered in the DAISY model. SOM1 and SOM2: Resistent and labile dead soil organic matter. AOM1 and AOM2: Resistent and labile added organic matter (e.g. catch crop residues). SMB1 and SMB2: Soil microbial biomass with slow and fast decay rates respectively. Solid lines show C dynamics, dotted lines show N dynamics.

desorption-dispersion-dissolvement process of the soil organic matter into the soil solution constitutes the rate limiting step in the turnover of soil organic matter (Nielsen et al. 1988). The microbial mediated net C turnover within the various C pools can then be expressed by first-order reaction kinetics, which includes the effects of temperature, soil moisture and soil type. The C turnover is restricted by N availability only if the soil is depleted of inorganic N in the soil layer considered.

The net N mineralization rate which is an integrated part of microbial mediated C dynamics may then be expressed by

$$\xi_m = -\sum_{pools} \frac{1}{[C/N]_i}\frac{dC_i}{dt} - \sum_{pools} \frac{1}{[C/N]_j}\frac{dC_j}{dt} \tag{3}$$

The net change in C content within the ith microbial biomass pool may then be expressed by

$$\frac{dC_i}{dt} = \sum_{pools} f_j^i E_i k_j C_j - m_i C_i - k_i C_i \tag{4}$$

For an explanation of symbols see Table 2.

Parameter estimation

Values for the parameters controlling the turnover of catch crop material in the DAISY model were estimated from an incubation experiment with catch crop materials of ryegrass (*Lolium multiflorum*), winter rye (*Cecale cereale* var. 'multicaule') and phacelia (*Phacelia tanecetifolia*) (Thorup-Kristensen, 1994b). In this experiment, catch crop materials were incubated in pots in a glasshouse, where the soil was kept at 15 °C and the soil water tension at pF = 2. Ryegrass was then grown in the pots and N mineralization was determined from the N uptake in the ryegrass five times during the experimental period of approx. five months. For further details, see Thorup-Kristensen (1994b).

The parameter values were determined using a curve fitting procedure, where the parameter values describing the catch crop material were varied and the combination giving the best fit between observed and simulated data was chosen. A fixed value for the turnover rate of AOM2 (k_{AOM2} = 0.4 d^{-1}) was chosen. This was based on results indicating that the turnover rate of easily decomposable plant material is in the order of 0.3–0.8 d^{-1} (Bremer et al. 1991; Ladd et al. 1992, 1995; Marstorp and Kirchmann, 1991), and simulations showing that the model output was insensitive to changes in turnover rate within this range (Figure 2). Therefore only the values of the three other parameters of the plant material (k_{AOM1}, f_{AOM}^{AOM1} (C) (fraction of AOM carbon assigned to AOM1), and f_{AOM}^{AOM1} (N)) were estimated by curve fitting.

When the field results were simulated, C and N from the catch crop materials were distributed between AOM1 and AOM2 by using the values of f_{AOM}^{AOM1} (C) and f_{AOM}^{AOM1} (N), determined for each catch crop species by the curve fitting procedure described above. Thus, the C/N ratios of both the AOM1 and AOM2 pools were allowed to vary with plant nitrogen content.

The conditions of the simulations

To test the ability of the DAISY model to simulate the effect of catch crops on N supply for the succeeding crop, model simulations were compared with six years of field data on catch crops from two sets of experiments (Sørensen, 1992; Thorup-Kristensen, 1993b). Both sets of experiments were made with high N availability, thus both the N uptake of the catch crops (70–170 kg N ha^{-1}) and the N$_{\text{min}}$ measured in November without catch crops (115–260 kg N ha^{-1}) were high.

Data on catch crops of phacelia, Italian ryegrass and control plots were available from all six years, whereas data on winter rye was available only from

Table 2. List of main symbols

Symbol	Description	Units
ξ_m	nitrogen mineralization rate	kg N m^{-3} d^{-1}
$[C/N]_i$	C/N ratio of SMB1 or SMB2	none
C_i	C content in SMB1 or SMB2	kg C m^{-3}
$[C/Nl_j$	C/N ratio of SOM1, SOM2, AOM1, or AMO2	none
C_j	C content of SOM1, SOM2. AOM1, or AOM2	kg C m^{-3}
t	time	d
f_j^1 (C)	partitioning coeff. of C from substrate pools between SMB pools	none
f_i^j (N)	partitioning coeff. of N from substrate pools between SMB pools	none
E_i	Substrate utilization efficiency for net growth	none
k_j	decay rate coefficient of SOM and AOM pools	d^{-1}
k_i	decay rate coefficient of SMB1 and SMB2 decomposition (death)	d^{-1}
m_i	rate coefficient of SMB maintenance respiration	d^{-1}

two years. From four of the six years, data from catch crops sown at two different dates (mid July and mid August, Sørensen (1992)) were used in the simulations. In the last two years all catch crops were sown in early August (Thorup-Kristensen, 1993b). From these two years the data include results from plots where catch crops were grown, but the aboveground plant material was removed before soil tillage, and from plots where no catch crops had been grown, but where catch crop plant material was incorporated. In the present treatment of the data, the results of Italian ryegrass and winter rye have been pooled and considered as grass catch crops.

Model simulations were made using measured values of soil ammonium and nitrate-N (in four soil layers of 25 cm down to 100 cm), plant dry matter and plant nitrogen content at the time of autumn incorporation as starting conditions. Actual weather data were used as model input. Measured and simulated results were compared at the date of spring soil sampling in April each year.

Parameters describing the turnover of the plant material were obtained from the mineralization measurements under controlled conditions (Thorup-Kristensen, 1994b), as described above. For the first four years of experiment where plant nitrate-N content was not measured (Sørensen, 1992), nitrate-N was assumed to constitute 25% of total plant N in phacelia, 10% in Italian ryegrass and 5% in winter rye, in accordance with the results of Thorup-Kristensen (1993b, 1994a).

Simulation of ‘r’ values of Equation (1)

Scenarios of the nitrogen availability effect of catch crops were simulated as affected by

- Winter precipitation and drainage
- Water holding capacity of the soil
- Date and soil depth of catch crop nitrogen uptake
- Rooting depth of the succeeding crop

The scenarios were made using varying initial conditions, and average climate conditions of either low precipitation or high precipitation areas in Denmark. Soil types were chosen to represent either a sandy soil with a total water holding capacity of 150 mm to a depth of one metre, or a typical sandy loam soil with a total water holding capacity of 300 mm to a depth of one metre.

For each combination of conditions two simulations were made with an initial difference of one kg N/ha in the considered soil layer. The results were expressed as the fraction of this difference in N_{min} still present within the relevant soil layer by 20 April in the subsequent spring. Simulations were started at 1 October, 1 December and 1 March, to estimate the r value of nitrogen which could be assimilated at various dates. To simulate the r value of nitrogen which could be assimilated at different depths, the initial difference of one kg N/ha was located either in the 0–25 cm layer or in the 50–75 cm layer.

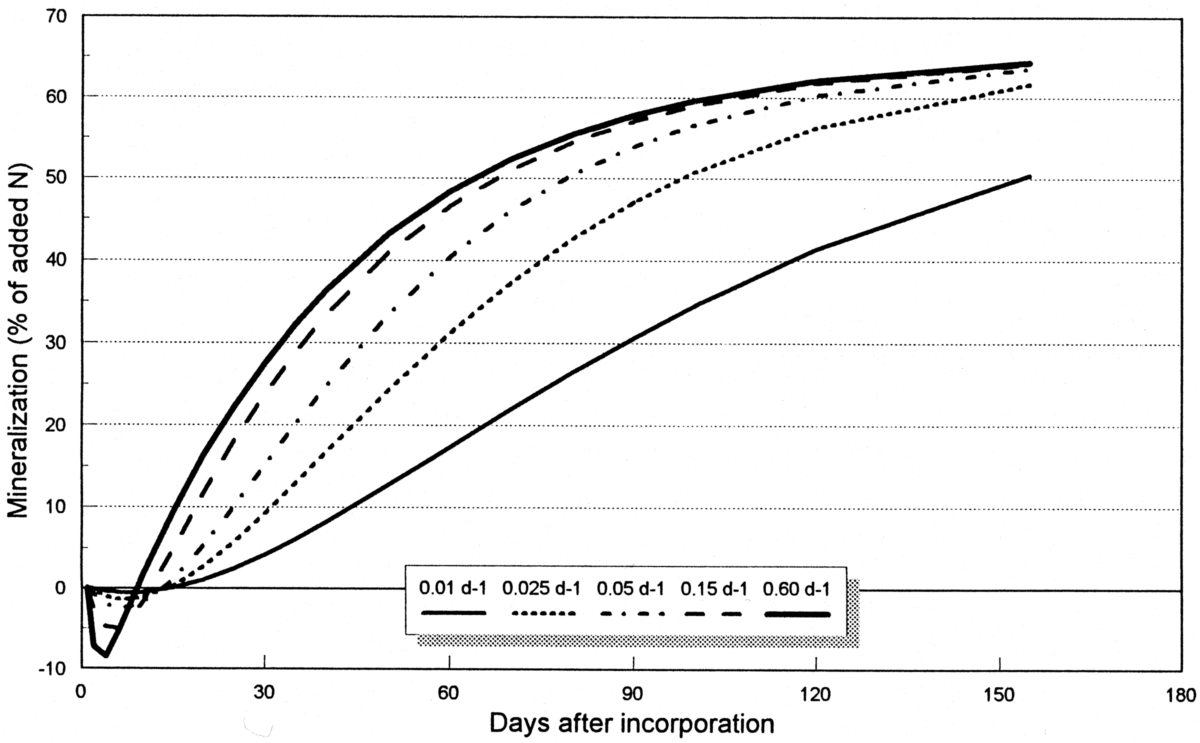

Figure 2. Sensitivity of simulated net N mineralization to varying turnover rates of AOM2.

Table 3. Parameters assigned to catch crop plant material

	f_{AOM}^{AOM1}(C)	f_{AOM}^{AOM1} (N)	C/N_{AOM1}	C/N_{AOM2}	k_{AOM1} d^{-1}
Phacelia	0.65	0.70	17.5	22.0	0.0012
It. ryegrass	0.40	0.57	11.5	22.9	0.0007
Winter rye	0.16	0.46	4.2	18.8	0.0003
Wheat straw	0.36		100.0		0.0070

*From Hansen et al. (1991), where C/N of AOM1 is fixed at 100 and the remaining N is then assigned to AOM2.

Results and discussion

Parameter estimation

With three parameter values (k_{AOM1}, f_{AOM}^{AOM1} (C), and f_{AOM}^{AOM1} (N)) to adjust in the curve fitting procedure to data on phacelia, Italian ryegrass and winter rye from the incubation experiment, a very close fit between observed and simulated data was obtained. However, some of the parameter values thus assigned seem unlikely, e.g. the value of k_{AOM1} is much lower and the value of f_{AOM}^{AOM1} (N) (Table 3) much higher for catch crops than what has earlier been used for wheat crop residues (Hansen et al., 1991).

These unlikely parameter values do not seem to be due to experimental errors in the incubation experiment, as the experimentally measured mineralization is in accordance with several other results. In experiments with nitrogen rich plant materials (Frankenberger and Abdelmagid, 1985; Marstorp and Kirchmann, 1991; Neely et al., 1991), the observed mineralization rates were within the same range (10–50% mineralized N) as found with the present catch crops (Thorup-Kristensen 1994b). Further, the general relationship between C/N ratio and N mineralization estimated from these data was similar to the relationship Vigil and Kissel (1991) estimated using data from eight different experiments. Furthermore, comparison of simulated carbon mineralization with experi-

Table 4. Regressions between observed and model simulated spring N_{min}

	Intercept	Slope	n	r^2
Soil layer 0–100 cm				
All data	1.9	1.04	36	0.48***
Bare soil	−21.2	1.69	6	0.93**
Phacelia	−2.2	1.22	14	0.62***
Grass	10.3	0.69	16	0.54**
Soil layer 0–50 cm				
All data	12.0	0.56	36	0.20**
Bare soil	33.3	−0.01	6	0.00
Phacelia	−1.0	0.99	14	0.25
Grass	4.4	0.59	16	0.46**
Soil layer 50–100 cm				
All data	4.9	1.24	36	0.67***
Bare soil	23.1	1.32	6	0.96***
Phacelia	17.3	1.01	14	0.57**
Grass	7.7	0.80	16	0.57***

mentally determined carbon mineralization (Bremer et al., 1991; Grant et al., 1993; Ladd et al., 1992; Marstorp and Kirchmann, 1991) indicates, that the DAISY model simulates too high N mineralization as compared to C mineralization if easily decomposable materials are added to the soil.

Simulation of effects in the field

The ability of the DAISY model to simulate the effect of catch crops was tested by comparing measured and simulated spring N_{min} after autumn incorporation of catch crops. Thus, the time of maximum leaching loss and the first five months of nitrogen mineralization after incorporation of catch crops were included in the simulation period. Soil characteristics are shown in Appendix 1.

The relationship between measured and simulated spring N_{min} was

$$y = 1.9 + 1.04x, \qquad r^2 = 0.48 \tag{5}$$

where y is simulated N_{min} and x is measured N_{min}, both in kg N ha^{-1} to the 1 m soil depth (Table 4). The best fit between observed and predicted data was obtained with bare soil (r^2 = 0.93) whereas r^2 was 0.62 and 0.54 for phacelia and grass respectively. For all crops the model was better at predicting N_{min} in the subsoil (50–100 cm) than N_{min} in the topsoil (0–50 cm). As nitrogen mineralized from the catch crops during winter will mainly affect spring topsoil N_{min}, and retention of autumn N_{min} will mainly affect subsoil N_{min}, this result indicates that the model was better at predicting year to year variation in nitrogen retention than in mineralization from the catch crop residues. This is also indicated by the fact that the bare soil results, where nitrogen retention is the most important factor, were more precisely predicted than the catch crop results where mineralization is more important and retention less important, as less autumn N_{min} is present to be either retained or leached.

Though there was a very high correlation between simulated and measured values in the bare soil plots, the predicted values were substantially higher than the measured values, especially when retention was high. This indicates that the model estimated too much retention of nitrogen.

Testing the ability of the model to estimate field mineralization from catch crops is hampered by the fact that the measured data include effects of both N mineralization and N retention simultaneously. However, in two of our experiments plots were included where catch crop material was incorporated where no catch crop had been grown (Thorup-Kristensen, 1993b). This allows direct field estimates of mineralization from catch crop residues of phacelia in the spring of 1990 and 1991 and grasses in the spring of 1991, independent of the N retention effect. The measured mineralization was 33, 14 and 11 kg N/ha, respectively, whereas the simulated values were 48, 27 and 13 kg N/ha, respectively.

A significant correlation was found between measured and model simulated N_{eff} of phacelia (p < 0.001) but not of the grasses (p = 0.075, Figure 3). For both catch crops the model simulations confirmed the experimentally observed effect that negative N_{eff} is often found in the subsoil, but not in the topsoil, an effect that can also be seen in both measured and simulated results of Alvenas and Marstorp (1993).

Further, the model was able to predict the observed result that topsoil N_{eff} was almost unaffected by winter precipitation (r^2 = 0.27), whereas the subsoil N_{eff} was closely related to winter precipitation (r^2 = 0.83). The data for phacelia is shown in Figure 4. In the subsoil (Figure 4c), both measured and simulated N_{eff} were positively correlated to winter precipitation, though the slope was significantly steeper (p = 0.015) with simulated (0.63 kg N ha^{-1} mm^{-1}) than with measured values (0.41 kg N ha^{-1} mm^{-1}). In the 0–100 cm soil layer (Figure 4a), the effect was

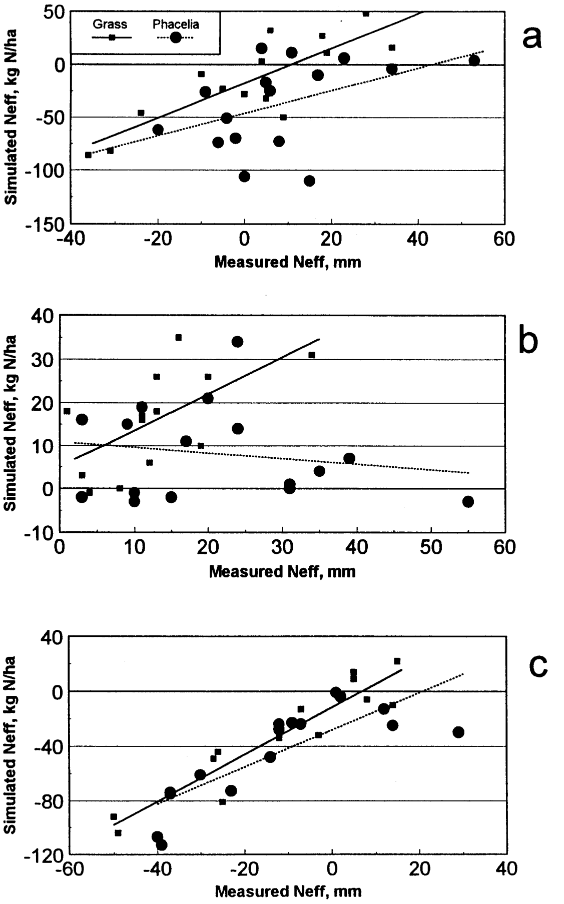

Figure 3. Simulated vs. measured N_{eff} of catch crops, (a) in the top 0–100 cm of the soil, (b) in the top 50 cm soil layer and (c) in the 50–100 cm soil layer. N_{eff} = N_{min} (catch crop plots) − N_{min} (bare soil plots).

estimated to be 0.27 and 0.73 kg N ha^{-1} mm^{-1} by measurement and simulation respectively, this difference was also significant ($p < 0.001$), showing that the model systematically overestimated the effect of winter precipitation on N_{eff}.

The negative N_{eff} found after the dry winters was mainly due to the variation in the bare soil plots, where spring N_{min} was high after dry winters and low after wet winters. After catch crops spring N_{min} was much less variable. Thus, when the precipitation was high, a positive N_{eff} was found, in some cases even in the subsoil (Figure 4). When precipitation was low, the subsoil N_{min} in the bare soil plots was high, and N_{eff} became negative. The model was able to simulate this pattern of year to year variation in N_{eff}, mainly due to its ability to predict the pattern of variation in spring subsoil N_{min} in the bare soil plots.

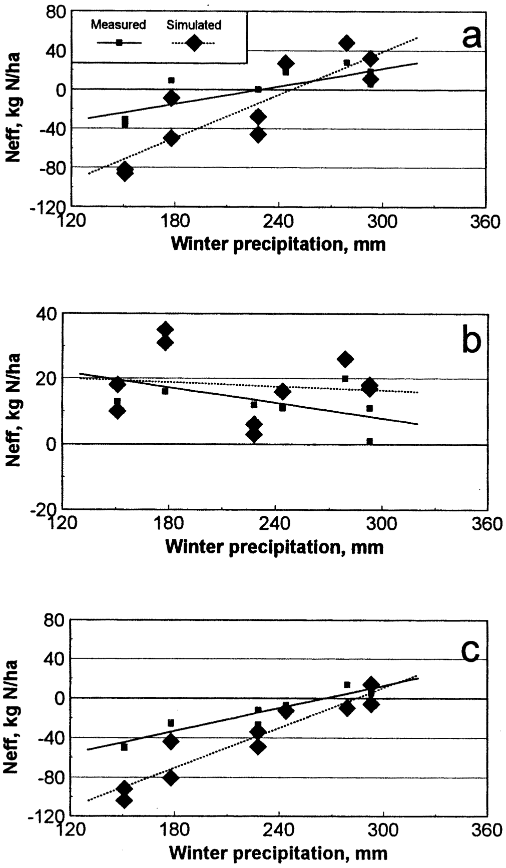

Figure 4. Simulated and measured N_{eff} of phacelia, as related to precipitation in the period from catch crop incorporation in the autumn until N_{min} measurements in the subsequent spring, (a) in the top 0–100 cm soil layer, (b) in the top 50 cm soil layer and (c) in the 50–100 cm soil layer. N_{eff} = N_{min} (catch crop plots) − N_{min}, (bare soil plots).

The comparison between simulated and measured effects shows that improvements of the simulations are needed to get a more precise prediction of the N effects of catch crops in the field. Improvements may be needed both in the measured input data, in the parametrization of the model, and in the model formulation itself. Still, the fact that the model is able to predict the general effects of catch crops and much of the year to year variation is promising, and indicates that already in its present form the DAISY model includes a reasonable treatment of the most important processes.

Scenarios

Preemptive competition

As discussed above, the year to year variation in N_{eff} is mainly due to variation in r which varies strongly with winter precipitation. If the leaching intensity is low and most of the available nitrogen is retained in the soil also without a catch crop (r is close to 1), catch crops assimilate their nitrogen from a pool which would alternatively remain available to the succeeding crop. When this occurs, the preemptive competition effect of catch crop nitrogen uptake is strong. N_{eff} can in such situations be negative, even when there is a high net mineralization of catch crop nitrogen (Equation (1)).

If the leaching intensity is high, and little or none of the catch crop available nitrogen is retained without a catch crop (r is close to 0), nitrogen uptake by the catch crop will not occur in preemptive competition with the succeeding crop. In this situation N_{eff} is determined mainly by mineralization of catch crop nitrogen.

These considerations imply that nitrogen retention must be considered when trying to estimate the nitrogen availability effect of a catch crop. However, r will vary due to soil type, climate, and rooting depth of the succeeding crop, which is discussed in the following.

Soil type and climate

Simulations involving different soil types and climatic conditions show these to be very important factors. Table 5 shows the estimated fraction of nitrogen retained in a high leaching situation (high winter precipitation and sandy soil typical of the Western parts of Denmark) and a low leaching situation (low winter precipitation and sandy loam soil typical of Eastern Denmark), under variable conditions. At the high leaching site any soil mineral nitrogen present in the autumn has low r values, whereas at the low leaching site the retention of late autumn N_{min} may be quite high (Table 5). Similar results were obtained by Burns (1989) who simulated nitrogen retention in various soil types under English and Welsh climatic conditions, and found that simulated relative nitrogen retention varied from 0.15 to 0.48 for sandy soils and from 0.39 to 0.80 for clay soils due to variable local climatic conditions.

Root depth of the succeeding crop

The magnitude of r depends strongly on the rooting depth of the succeeding crop as well. When the succeeding crop is shallow rooted, only retention in the topsoil layers is relevant, whereas when the succeeding crop is deep rooted subsoil layers should be considered too. When deeper soil layers are included in the measurements or simulations more nitrogen will be estimated as retained, and r will be higher. This effect is also seen in the present results, comparing the 0–50 cm soil layer and the 0–100 cm soil layer (Figures 3 and 4).

The root depth of the succeeding crop can vary strongly, from approximately 25 cm for crops such as spinach (Schenk et al., 1991), onion or leek (Greenwood et al., 1982), to a metre or more for winter wheat (Burns, 1980; Strebel and Duynisveld, 1989), cabbage (Greenwood et al., 1982) or sugar beet (Strebel and Duynisveld, 1989). Table 5 shows the simulated nitrogen retention at different assumed rooting depths of a succeeding crop. In some situations this difference in r is large, e.g. with December topsoil N_{min} at the low leaching site only 18% of the N_{min} is simulated to be retained within the top 25 cm but as much as 92% is simulated to be retained within the top 100 cm (Table 5).

Such effects are also reflected in previously published results on the effect of catch crops. Elers and Hartmann (1987) found that catch crops raised the yield of the succeeding spinach crop significantly. Spinach is a shallow rooted crop (Schenk et al., 1991). On the other hand Muller et al., (1989) found that three different catch crops all led to a reduced nitrogen uptake by a succeeding sugar beet crop (deep rooted, e.g. Strebel and Duynisveld (1989)), even though their catch crops had low C/N ratios and two of them had increased spring topsoil N_{min}.

Date and depth of nitrogen uptake

The value of r further depends on both the date and depth of N uptake (Equation (2)), as also investigated by Addiscott and Darbey (1991). N present in the soil in early autumn is less likely to be retained within the rooting zone until next spring than N present at the same depth at a later date. Similarly N present in the topsoil is more likely to be retained than N present in the subsoil at the same date (Table 4).

The simulations show that the r values of spring N are so high, that allowing it to be assimilated by a catch crop will normally reduce its availability for the succeeding crop (Table 5). Thus catch crops should not be allowed to take up nitrogen in the spring. This can be avoided by incorporating the catch crop before growth is resumed in spring, or by growing catch crop

Table 5. Simulated fraction of soil mineral nitrogen retained within the rooting zone of the succeeding crop until 20 April as affected by site, initial depth of N_{min}, root depth of the succeeding crop, and date of the start of the simulation (1 October, 1 December and 1 March)

Init. depth of N_{min}	Root zone depth of suc. crop	Low leaching site[a]			High leaching site[b]		
		1 Oct	1 Dec	1 Mar	1 Oct	1 Dec	1 Mar
0–25 cm	25 cm	0.06	0.18	0.75	0.00	0.02	0.62
0–25 cm	50 cm	0.19	0.46	0.96	0.00	0.04	0.80
0–25 cm	100 cm	0.71	0.92	0.97	0.01	0.11	0.95
50–75 cm	25 cm	0.00	0.00	0.01	0.00	0.00	0.02
50–75 cm	50 cm	0.01	0.04	0.17	0.00	0.00	0.11
50–75 cm	100 cm	0.24	0.48	0.96	0.00	0.01	0.57

Simulations were made with the DAISY model (Hansen et al. 1991).

[a] Winter surplus prec. approx. 175 mm. soil water holding capacity in the top meter at pF = 2 approx. 300 mm.

[b] Winter surplus prec. approx. 375 mm, soil water holding capacity in the top meter at pF = 2 approx. 150 mm.

species which will be killed during winter (Thorup-Kristensen, 1994a).

Muller et al. (1989) allowed their rye catch crop to grow into the spring, and they even applied their N fertilizer before it was incorporated. Thus the catch crop was allowed to assimilate much N with a high r value in the spring. Accordingly, the rye catch crop reduced the N uptake of the succeeding sugar beet crop with approx. 70 kg N/ha as compared to bare soil plots, even though it had a low C/N ratio.

As subsoil N is less likely to be retained within the root zone than topsoil N, preemptive competition is reduced as the depth of uptake increases (Table 5). The lower r value for subsoil than for topsoil N means that uptake of subsoil N will add more to the N_{eff} of a catch crop than assimilation of the same amount of topsoil N.

Conclusions

The simulated scenarios suggest that N_{eff} is not a factor which is determined by variations in the climate alone. The simulations show that much can be done to increase N_{eff}. This can be done by measures as adapting the incorporation time of the catch crop to the actual situation (soil type, local climate conditions and rooting depth of the succeeding crop) and by selecting deep rooted catch crops which can decrease r and sometimes increase N_{upt}. Also by choosing catch crops which maintain a low C/N ratio m can be kept high with the same effect. All together, the choices made by the farmer will determine much of the N_{eff} obtained, as also indicated by the strongly variable N_{eff} which can be obtained just by varying the choice of catch crop species (Thorup-Kristensen, 1994a).

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Appendix 1

Apart from the ‘high leaching site’ the soil used for the experiments end simulations was a Typic Agrudalf soil, with 2% organic matter, 11% clay, 14% silt, and 73% sand in the top 40 cm and 0.2% organic matter, 19% clay, 13% silt, and 67% sand in the 40–100 cm soil layer. Water retention data for the soil was obtained from Jacobsen (1989).

Table 6. Initial soil conditions, and SOM turnover rates and nitrification rate coefficient at standard conditions (10 °C, field capacity, and no clay content), used in the soil nitrogen sub-model of DAISY

Parameter	Value	Units	Reference
Initial soil conditions			
C content, 0–20 cm depth	13	kg C m^{-3}	Jacobsen (1989)
Clay content, fraction of soil	0.104	none	Jacobsen (1989)
C/N ratio	11	none	Hansen et al. (1991)
C content, 20–40 cm depth	9	kg C m^{-3}	Jacobsen (1989)
Clay content, fraction of soil	0.119	none	Jacobsen (1989)
C/N ratio	11	none	Hansen et al. (1991)
C content, 40–60 cm depth	1.5	kg C m^{-3}	Jacobsen (1989)
Clay content, fraction of soil	0.204	none	Jacobsen (1989)
C/N ratio	11	none	Hansen et al. (1991)
C content, 60–80 cm depth	1.1	kg C m^{-3}	Jacobsen (1989)
Clay content, fraction of soil	0.195	none	Jacobsen (1989)
C/N ratio	11	none	Hansen et al. (1991)
C content, 80–130 cm depth	1.1	kg C m^{-3}	Jacobsen (1989)
Clay content, fraction of soil	0.186	none	Jacobsen (1989)
C/N ratio	11	none	Hansen et al. (1991)
Fraction of C with is SOM1	0.793	None	Hansen et al. (1991)
Fraction of C with is SOM2	0.200	None	Hansen et al. (1991)
Fraction of C with is SMB1	0.004	None	Hansen et al. (1991)
Fraction of C with is SMB2	0.003	None	Hansen et al. (1991)
C-turnover rate, $dC/dt = k_i C_i$			
k_i for SOM1	$2.7\ 10^{-6}$	day^{-1}	Hansen et al. (1991)
k_i for SOM2	$1.4\ 10^{-4}$	day^{-1}	Hansen et al. (1991)
Rate coefficient of nitrification	0.1	day^{-1}	Hansen et al. (1991)

Table 7. Parameter values used in the soil water sub-model of DAISY. Simulations were made assuming a fixed ground water table at 2.5 m depth

Soil layer	% clay		Hydraulic conductivity ms^{-1}
	Low leaching site	High leaching and other simulations	
0–25 cm	4.4	10.4	5 E-8
25–40 cm	3.9	11.9	2 E-9
40–75 cm	3.4	20.4	2 E-9
Below 75 cm	3.6	18.6	2 E-9