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Management effects on topsoil carbon and nitrogen in Swedish long-term field experiments—budget calculations with and without humus pool dynamics

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Abstract

The annual input and output of nitrogen (N) to and from agricultural land is relatively small compared with the total stock of organic N in soil. However, the long-term humus N pool dynamics is seldom considered in fertilisation planning, and thus N surpluses in budgets are considered as losses. In this paper, we analyse the consequences of this assumption and investigate how observed data precision affect the precision of model projections. We used available data sets from long-term agricultural field experiments in Sweden (topsoil C and N concentrations, crop yields as well as soil type and climate data) for calculating topsoil C and N mass dynamics. ICBM/2N, a simple C and N soil model (available at: www.mv.slu.se/vaxtnaring/olle/ICBM.html), was used for calculating soil organic matter balances. We parameterised this model for two field trials, and for specific crops, using available data and educated guesses and compared the results with those obtained from the conventional approach, not including humus pool C and N dynamics. In spite of the corrections for bulk densities, etc., the soil carbon measurements were too variable for a critical model validation or a sensitive test of the effects of including pool dynamics. In other words, we had to rely on the model assumptions for the projections and soil data could only be used to obtain general means, e.g., for the whole duration of the experiment. We think this is a general problem, not limited to this data set and model. We also show, at least in principle, how estimates of organic N pool dynamics can be used to produce improved N balance sheets for individual crops. For example, the apparent N use efficiency by sugar beet increased from 58 to 99% when organic N pool dynamics were included.

Keywords: Soil nitrogen; Soil organic matter; Long-term experiments; Model; Nitrogen balances; Simulation

1. Introduction

Nitrogen (N) losses from agriculture is a major environmental as well as economic problem. Therefore, national and international programs have been introduced to reduce these losses (Albertsson et al., 1999; SNV, 1997). Field or farm N balances are often used to identify situa-

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tions where the risks of losing large amounts of N to the environment are high, i.e., farms or fields with a high calculated surplus. However, possible changes in soil organic matter (SOM) are seldom included in the balances, although topsoil organic N ("humus N") may be of the order 10 t ha^{-1}, and a 1% annual change corresponds to 100 kg, which in turn is in the same order of magnitude as the annual N fertilisation dose. Annual changes in SOM content are usually very small if compared with the total amount of SOM, and changes measured over a few years are difficult to detect due to spatial heterogeneity and lack of sensitivity of analysis. Even if the measurements cover a sufficiently long period to detect statistical significant changes of SOM, we need a model to do any additional forecasting, e.g., steady-state pools (Andrén and Kätterer, 1997).

The Introductory Carbon Balance Model (ICBM) family of models is based on generally agreed core concepts such as first-order decomposition kinetics and a low number of carbon (C) and N pools. The basic idea is to create simple, analytically solved models (Andrén and Kätterer, 1997; Kätterer and Andrén, 2001). In this paper, we used ICBM/N to estimate the changes of N in SOM under different management regimes. The model parameters were calculated from the results of Swedish long-term experiments (Mattsson, 2001; Kirchmann et al., 1994). We then used the model to calculate changes in soil organic N pools over a 30-year period and compare system N balances with and without including these changes. We also show how these estimates of organic N pool dynamics can be used for improved N balance sheets for individual crops.

2. Methods

2.1. The model

The ICBM family of analytically solved soil carbon and N models are described in detail by Andrén and Kätterer (1997), Kätterer and Andrén (1999, 2001) and only a very brief description will be given here.

The ICBM was developed as a minimum approach for calculating soil organic C balances in a 30-year perspective. There are two C pools, young (Y) and old (O). Crop residues and organic manure are input to Y and during decomposition of this material some C will be respired and lost as carbon dioxide and some will enter the O pool, according to the value of the humification parameter (h). Thereafter, this C model has been developed to fit different needs. For example, functions describing changes in SOM-N have been included. In this study, we use a model assuming two pools of young C and N, respectively, and one pool of humus C and N, respectively (ICBM/2N). Different parameter values, e.g., input to the soil, can be set for each year. The ICBM/2N model is available as an Excel spreadsheet or SAS program at www.mv.slu.se/vaxtnaring/olle/ICBM.html.

2.2. The experiments

Results from two long-term experiments have been used.

2.2.1. Ultuna

This experiment is located in central Sweden close to Uppsala (59°48′N,17°38′E). It was started in 1956 to investigate the long-term effects of regular application of various types of organic material. The soil is a clay loam with 365 g/kg clay, 419 g/kg silt and 225 g/kg sand. The crops are cereals, oil seed and some years root crops (Kirchmann et al., 1994). The climate is cold temperate and semi-humid. The mean annual precipitation in nearby Uppsala during 1961–1990 was 544 mm and the mean annual air temperature was 5.7 °C (SMHI, 2000). The Ultuna experiment was included mainly because it is well designed and probably the most investigated experiment in Sweden regarding changes in soil C and N. The original ICBM was preliminarily calibrated using results from this experiment, and other models have also been applied here (see Andrén and Kätterer, 1997 and papers cited therein). In this paper, the changes in soil N will be described using the ICBM/2N model.

2.2.2. Fjärdingslöv

This experiment is located in southern Sweden (54°24′N, 13°14′E) on a sandy loam with 100–200 g/kg clay (Kirchmann et al., 1999). The experiment started in 1957 and was initiated to investigate the long-term effects of different fertiliser application rates in two-crop rotations. One rotation including ley and manure and one without are compared at different levels of N fertiliser application (Table 1). The yearly precipitation and mean temperature over a 30-year period in the area (data from nearest meteorological station) were 590 mm and +8.1 °C, respectively (Carlgren and Mattsson, 2001). The Fjärdingslöv experiment was included to investigate if it is possible to isolate the effect of ley cropping on C and N mineralisation. The ley has a high potential for transpiration and thus the soil under a ley is usually drier during the growing season than that under cereals (see, e.g. Paustian et al., 1990), making the conditions less favourable for mineralisation.

2.3. Calculations

To be able to run the ICBM/2N model, 18 initial values and parameters are needed. The parameters k_y, k_o, q_b and e_y were assumed to be constants and values calculated by Andrén and Kätterer (1997) were used (Table 2). The humification coefficients (h_l and h_r) govern the fractions of each Y-pool entering O and were assumed to be 0.125 and 0.31, respectively (Andrén and Kätterer, 1997). For all treatments, the initial mass of topsoil C had to be established. Total C concentrations and soil density data are available both for Ultuna (Kirchmann et al., 1994) and Fjärdingslöv (Kirchmann et al., 1999). First, the young carbon has to be calculated (Y_{0l}, Y_{0r}), then the remaining C fraction is assumed to be in the old pool (O_0). For Ultuna, values from Andrén and Kätterer (1997) were used for initial amount of young C ($Y_{0l} = 3$ t ha^{-1}).

At Fjärdingslöv, Y_{0l} was set to the calculated mean steady-state pool for Y (Y_{ss}) originating from the input of crop residues during the two first crop sequences (8 years) in the treatment regarded to have most similarities with the conditions before the experiment started (Table 1, B2, moderate N fertilisation, no manure). By including two crop sequences, the Y_{0l} will be a mean value of the most common crops in the area and two sequences give some reassurance against possible bias from years with exceptionally low or high yields. The Y_{ss} is dependent on the amount of crop residue input, but also on r_e. Therefore, both Y_0 and r_e were optimised simultaneously. In these applications, we assumed that the young and refractory pool (Y_{0r}) only consisted of manure, and thus the initial value was assumed to be zero for all treatments. At Fjärdingslöv, the first C analysis is from 1962 and because farmyard manure had been applied once in 1958 the treatments not receiving manure were thus assumed to be the most similar to initial (1957) conditions.

Records from the experiments give the input of C and N in manure and other organic amendments (Kirchmann et al., 1994; Mattsson, 2001). Inputs of some crop residues, such as straw, were possible to calculate from measurements in the experiment, others, like roots, stubble and chaff, had to be calculated by using allometric relationships (linear regression) between C and N in harvested products and other plant parts. For cereals, information given by Andrén et al. (1990), Flink et al. (1995), Kätterer et al. (1993), Olofsson (2000) and Paustian et al. (1990); for oil seed, Mueller et al. (1997), Olofsson (2000) and Petersen et al. (1995); for sugar beet and other root crops, Mattsson (1991), Olofsson (2000), Svanberg (1962) and Vandendriessche (2000) and for leys, Andrén et al. (1990) and Paustian et al. (1990) were used. With the help of these relationships, we estimated yearly inputs

Table 1
Crop rotation and mean annual amount of fertiliser N applied at Fjärdingslöv

Rotations		Fertilisation	
A[a]	B[b]	Treatment	Fertiliser N (kg ha^{-1})
Barley	Barley	0	0
Ley	Oil seed	1	50
Winter wheat	Winter wheat	2	100
Sugar beet	Sugar beet	3	150

[a] Manure added, grain straw and beet tops removed.
[b] No manure added, all crop residues returned.

Table 2
Parameters, symbols, constants and dimensions in the ICBM/2N model

Parameter	Symbol	Constants	Dimension
Initial C mass of the 'young and labile' pool (from crop residues)	Y_{0l}		kg
Initial C mass of the 'young and refractory' pool (from organic amendments)	Y_{0r}		kg
Initial C mass of the 'old' pool	O_0		kg
Annual C input to soil, labile part (from crop residues)	i_l		kg per year
Annual C input to soil, refractory part (from organic amendments)	i_r		kg per year
Decomposition rate constant for young pool	k_y	0.8	Per year
Decomposition rate constant for the old pool	k_o	0.006	Per year
Humification coefficient, fraction of 'young and labile outflux to O (crop residues)	h_l	0.125	Dimensionless
Humification coefficient, fraction of 'young and refractory' outflux to O (organic amendments)	h_r	0.31	Dimensionless
External response factor that affects out flux from 'young' and 'old'	r_e		Dimensionless
Initial N mass of the 'young and labile' pool	Y_{0N_l}		kg
Initial N mass of the 'young and refractory' pool	Y_{0N_r}		kg
Initial N mass of the 'old' pool	O_{0N}		kg
Quality, C/N ratio of labile input, i_l	q_{i_l}		Dimensionless
Quality, C/N ratio of refractory input, i_r	q_{i_r}		Dimensionless
C/N ratio of soil organism biomass	q_b	8	Dimensionless
C/N ratio of the 'humification', the influx to O	q_h		Dimensionless
Efficiency, the fraction of C flux from Y allocated to organism growth	e_y	0.4	Dimensionless

of C and N in crop residues (i_l, q_{i_l}) and organic amendments (i_r, q_{i_r}) (Table 3). The r_e factor includes all abiotic effects on the decomposition rates. Any effects of climate, cultivation, soil types, fertilisation and crops are included in this factor. For all included treatments at both locations, r_e was calculated by optimising the simulations to measured soil C amounts using a least-squares procedure.

The C/N ratio of the influx to O (q_h) was assumed to be constant at any location and not changed by treatment. Therefore, only one value was calculated for each site. In Ultuna, the bare fallow could be considered to only contain the O-pool, since no input had been added to Y for decades. Therefore, a mean value of soil C/N measurements during 1975–1991 in the fallow treatment could be used. In Fjärdingslöv, no bare fallow treatment was included, so q_h was calculated by optimising (least squares) the model to measured values of total soil N in the most "normal" treatment (B2, no manure and moderate N fertilisation). To estimate initial values for N in the soil pools (Y_{0N_l}, Y_{0N_r}, O_{0N}), measured values could not be used due to their high variability. Instead, calculated values for O_0 and q_h were used to estimate O_{0N} ($O_{0N} = O_0/q_h$). Y_{0N_l} was calculated from the inputs in a way similar to that used for Y_0, and Y_{0N_r} was assumed to be zero (no manure before the experiment). Thereafter, N balances for the whole experimental period could be calculated and finally balances for individual crops.

Table 3
Calculated soil N amounts in the topsoil (0–20 cm) 1956, mean C annual input ($i = i_l + i_r$) and optimised external response factor (r_e) in a long-term organic matter experiment at Ultuna, Sweden

Treatments	Soil N (Mg ha^{-1})	i (Mg ha^{-1} per year)	r_e
No N, no crop	4.82	0.0	1.4
No N, +crop	4.85	0.73	1.2
Calcium nitrate	4.88	0.82	0.8
Straw	4.92	2.46	1.0
Green manure	4.72	2.67	0.7
Farmyard manure	4.85	2.61	0.9
Straw+N	4.99	2.71	0.7

Soil C data from Kirchmann et al. (1994).

3. Results

In the analysis of the long-term SOM experiment at Ultuna, treatments with well-defined crops had a r_e factor between 0.7 and 1.0 (Table 3). For bare fallow, the calculated r_e was 1.4. The no-fertiliser treatment was intermediate with $r_e = 1.2$. q_h was calculated to be 8.49. Measured and simulated soil C values are presented in Fig. 1. The saw tooth pattern is created by the biannual application of organic amendments. At Fjärdingslöv, the soil analysis data were very variable and although the information was too small to allow a proper statistical analysis, the apparent difference between mean soil C measurements was so small that we decided to use the mean over all four fertiliser rates in the ley/manure rotation. The r_e value for this rotation was 1.0. In the rotation without ley, the calculated r_e values were 1.3, 1.5, 1.6 and 1.1 for fertiliser rates 0, 1, 2 and 3, respectively. q_h was optimised to 8.75. Model fit to measured soil C data is presented in Figs. 2 and 3. The application of manure every 4th year is the reason for the regular pattern with peaks in Fig. 2.

The yield differences between industrial N fertiliser rates were much smaller in the ley and manure rotation compared with the rotation without ley and manure. The grain yield increase at the highest N level compared with zero fertiliser was 48% in the ley and manure rotation and 78% in the rotation without ley and manure. At Fjärdingslöv, the N balances, not including soil N dynamics, showed a N deficiency with no or low N fertilisation and gradually increasing surplus with increasing N fertilisation (Table 4). Including changes in soil N reduced the deficiency for the low N fertilisation and reduced the surpluses for high N fertilisation. Table 5 shows results from model calculations of N balances for crops in the rotation without manure and medium N application (treat-

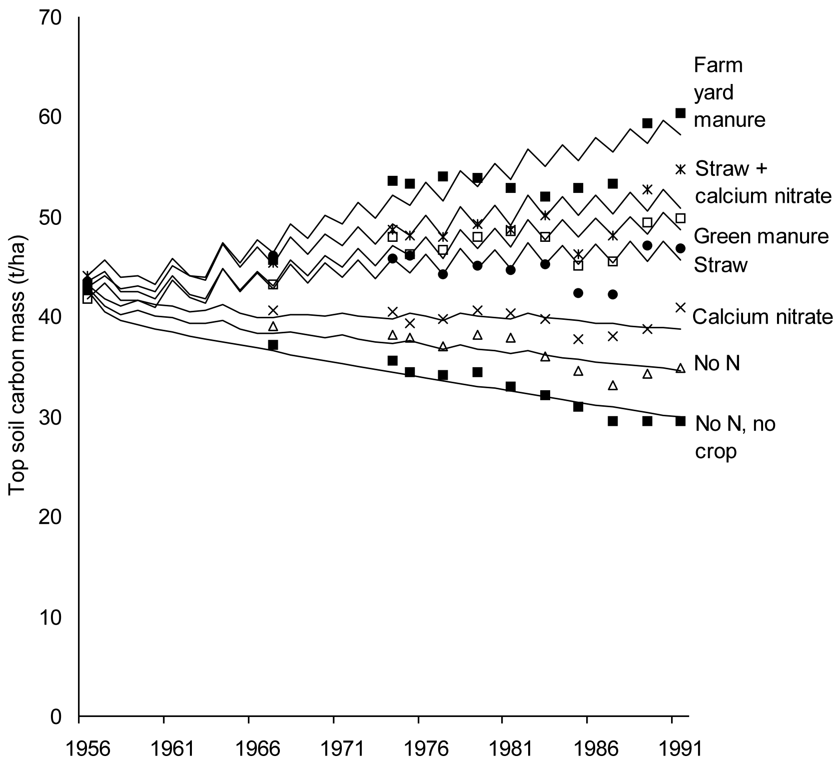

Fig. 1. Model fit to topsoil C data from Kirchmann et al. (1994) for seven treatments. The lines are model predictions, and the symbols indicate data.

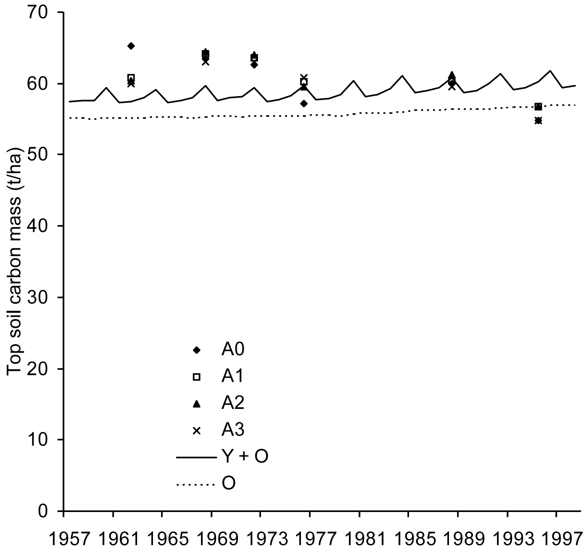

Fig. 2. Model fit to topsoil C data from Fjärdingslöv (Mattsson 2001) for mean of ley treatments. The lines are model predictions, and the symbols indicate data. O, old soil carbon; $Y+O$, total soil carbon. For explanation of treatments, see Table 1.

ment B2). For two crops, barley and sugar beet, the results changed drastically when soil N dynamics were included. If only input–output is considered for barley (61 kg N ha^{-1} is exported and 66 kg N ha^{-1} is applied), the balance is close to zero. However, mineralisation of SOM and crop residues from the preceding sugar beet crop add another 102 kg N. Considering that the total crop uptake is 109 kg N, the result is a surplus of 59 kg N. The situation is almost the opposite for sugar beet where 140 kg N is applied as fertilisers and 84 kg N is exported with the beet. In the tops, another 114 kg N is accumulated, giving a total crop uptake of 198 kg N. The net mineralisation is contributing only 55 kg N, means that the N balance is close to zero.

Including changes in soil N considerably altered the balances for treatments at Ultuna (Table 6). The balance increased in the treatments with bare fallow, unfertilised and calcium nitrate. The balance decreased for treatments receiving organic materials (straw, green manure, farmyard manure and straw+calcium nitrate).

4. Discussion

4.1. From measured C concentration to estimation of mineralisation rates

The experiences from both experiments are that we need high-precision long-term soil N and especially C data to validate a soil C and N model which is surprisingly scarce. Firstly, the experiments have to be kept free from unaccounted sources of C contamination, such as wind- or water-transported straw or leaf debris. Thereafter, soil sampling and analyses have to be done in such a way that a value close to the "true" value in the soil can be obtained throughout the experiment. There is a high spatial variation in soil C concentration, and this has to be dealt within the sampling design—bulked sub-samples, many replicates, stratified sampling, etc. Different soil C analysis methods can give different results and a change of equipment can introduce systematic error, even if both methods are calibrated similarly.

Table 7 shows that two sets of carefully analysed sub-samples taken from the same soil sample using two methods can give very different results. The fact that in this comparison the overall means were more similar than individual measurements indicates that there was a random factor involved, e.g., differences due to sample preparation. Once obtained, values for C concentrations then have to be converted to mass values which requires additional knowledge about bulk density and cultivation depth (topsoil depth), information that is frequently lacking. The effects of these errors are sometimes very clear. If calculated C amounts for 1974 and 1975 in the Ultuna experiment (Fig. 1) are compared, the C amounts for some treatments seem to have been reduced drastically during 1 year. The treatment with green manure apparently lost 1.7 t C ha^{-1} and also the treatments with bare fallow and calcium nitrate lost more than 1 t C ha^{-1}. This is much more than a model would indicate, but it is difficult, even with a good model to give exact predictions of the amount of C mineralised in a single year. However, an increase in C can never be larger than the input (providing all inputs have been accounted for) and there will

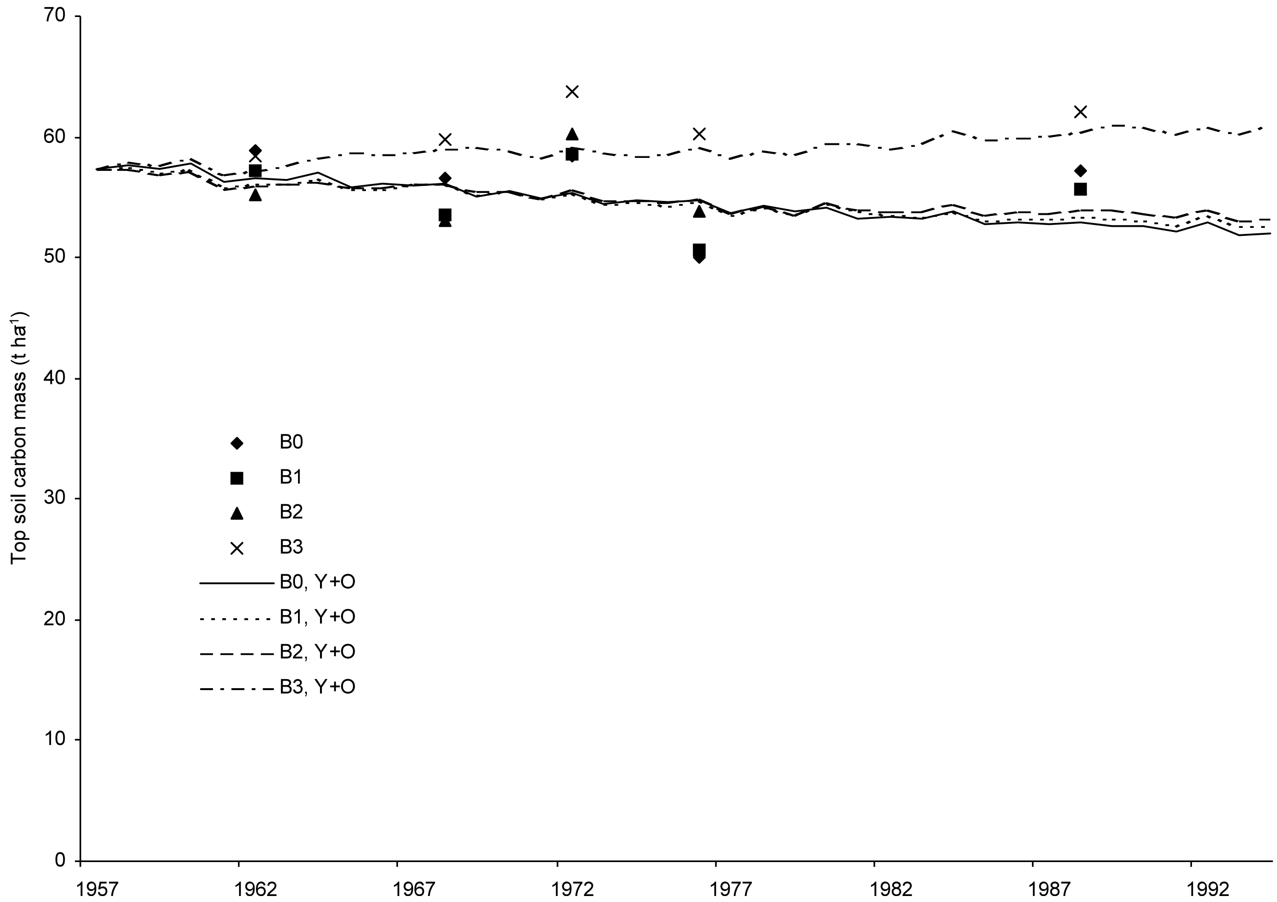

Fig. 3. Model fit to topsoil C data from Fjärdingslöv (Mattsson, 2001) for four treatments. The lines are model predictions, and the symbols indicate data. For explanation of treatments, see Table 1.

Table 4
N balances for Fjärdingslöv, 1957–1997 calculated without and including changes in soil organic N, kg ha^{-1} per year

		Treatments							
		A0	A1	A2	A3	B0	B1	B2	B3
A	Fertiliser	0	50	99	149	0	50	99	149
B	Farmyard manure	30	30	30	30	0	0	0	0
C	Deposition	6	6	6	6	6	6	6	6
D	Harvested products	87	108	133	152	39	52	69	88
E	Balance, applied − removed (A+B+C−D)	−50	−22	2	32	−33	4	36	67
F	Simulated changes in soil N	4	4	4	4	−16	−15	−13	7
G	Balance including changes in soil N (E−F)	−54	−26	−2	28	−17	19	49	60

For explanation of treatments, see Table 1.

always be some mineralisation of the existing SOM. Between 1987 and 1989, the C amount in the farmyard manure treatment seemed to increase by 5.9 t. During the same period the input was calculated to 5.6 t C. Of course, estimated C inputs are just estimates, but, e.g., weighing the manure rate and measuring its water content can be made with fairly high precision in a well-managed field experiment. In any case, the unavoidable mineralisation has still not been accounted for.

Results from long-term experiments are necessary for developing soil C and N models. However, the precision of the data, even from a carefully managed experiment such as that at Ultuna, was not sufficient to enable model calibration or validation. We see this problem, which is general in soil science, as the greatest obstacle along the path to better models and an increased understanding of processes in the soil. Contrary to what one perhaps would expect, soil C and N modelling leads to an urgent demand for more resources spent on high-quality long-term experiments.

4.2. Effect of management factors on r_e factor

The r_e values given in this paper for different treatments at Ultuna deviate somewhat from those presented by Andrén and Kätterer (1997). This is due to differences in: (1) estimation of i, (2) distribution of i in time, (3) estimation of C amount in soil, and (4) optimisation procedures. Probably factor (3) had the largest effect.

The calculated r_e values for treatments with reasonably productive crops were between 0.7 and 1.0. Given the large variation in measurements of

Table 5
N balances for crops in a soil fertility experiment at Fjärdingslöv, mean for a 35-year period, kg N ha^{-1}

		Crop			
		Winter wheat	Sugar beet	Barley	Oil seed
A	Fertiliser	100	140	60	100
B	Deposition	6	6	6	6
C	N removed in harvest	72	84	61	60
D	N balance (A+B−C)	34	62	5	46
E	Relative N uptake (C/(A+B))*100 (%)	68	58	92	57
F	Simulated net mineralisation from the organic N pool and previous crop residues	76	55	102	89
G	Total crop N uptake	132	198	109	123
H	N balance (A+B+F−G)	50	3	59	72
I	Relative N uptake (G/(A+B+F))*100 (%)	73	99	65	63

Table 6
N balances for Ultuna, 1956–1991, calculated without and including changes in soil organic N

	Treatments						
	No N, no crop	No N	Calcium nitrate	Straw	Green manure	Farmyard manure	Straw+calcium nitrate
A Fertiliser	0	0	78	0	0	0	78
B Organic amendments	0	0	0	27	104	86	27
C Deposition	3	3	3	3	3	3	3
D Removed plant parts	0	43	88	44	83	65	90
E Balance, applied − removed (A+B+C − D)	3	− 39	− 7	− 14	24	24	17
F Simulated changes in soil N	− 36	− 23	− 11	9	23	46	21
G Balance including changes in soil N (E − F)	39	− 16	4	− 23	1	− 22	−4

N supply and crop removal data from Kirchmann et al. (1994) (kg ha^{-1} per year).

Table 7
Measured soil C concentrations in the farmyard manure treatment, Ultuna (per cent, ±STD)

Year	Kirchmann et al. (1994)	Gerzabek et al. (1997)	Difference
1956	1.49[a]	1.52[a]	− 0.03
1967	1.60[a]	1.58 ± 0.09	0.02
1975	1.89 ± 0.04	1.91 ± 0.01	− 0.02
1977	1.92 ± 0.04	1.98 ± 0.04	− 0.06
1979	1.92 ± 0.04	2.00 ± 0.04	− 0.08*
1981	1.89[a]	1.84 ± 0.11	0.05
1983	1.86 ± 0.03	1.85 ± 0.04	0.01
1985	1.90 ± 0.02	1.96 ± 0.04	− 0.06*
1987	1.92 ± 0.04	2.03 ± 0.04	− 0.11**
1991	2.20 ± 0.06	1.94[a]	0.26
Mean	1.86	1.87	− 0.01

[a] Only pooled samples per treatment.
* Significantly different at 90% probability level (student's t-test).
** Significantly different at 95% probability level (Student's t-test).

soil C concentrations, this is probably the closest we could get to an estimate of a "real" r_e factor. It is also reasonably close to the baseline value of 1.0 for a typical crop in this region (Andrén and Kätterer, 1997).

The difference in r_e values between the treatments in the Ultuna long-term experiment can be explained by the influence the crop has on the soil. The transpiration from a well-developed crop with a high leaf area index is higher than that from a poor crop, and is also much higher than the amount of water that can be evaporated from bare soil. Persson and Kirchmann (1994) used a linear function to describe changes in soil C during this period, and the fit was at least subjectively as good as that for ICBM. We think this is due to lack of precision in the measurements, but there is no proof of this. However, a linear function cannot be extrapolated outside the period of measurement—an increasing trend will continue forever. A model like ICBM will reach a steady state, or a balance point, where input equals output, which is far more realistic.

At Fjärdingslöv, the difference between the ley and manure treatment ($r_e = 1.0$) and the highest N level in the rotation without ley was small ($r_e = 1.1$). Thus, these data do not support the assumption that the ley was reducing the mineralisation. However, the ley in this rotation was only grown during 1 year out of 4, severely reducing the average long-term effect. The manure addition coupled with the ley would tend to increase r_e, since the added organic matter would increase the soil water holding capacity and thus r_e. This is typical for cropping system comparisons, where a whole set of factors are compared simultaneously which makes analysis of cause–effect almost impossible, although the overall results may be of practical value. High N-fertilisation rates, which stimulate crop growth, should also reduce the decomposition rate of organic matter. However, it was not possible to see any such effect from this material although this has been shown elsewhere (e.g., Andrén et al., 1990).

Including soil N fluxes did not seem to change the long-term N balances much in the experiment at Fjärdingslöv (Table 4). This could be a true result, i.e., the two crop rotations were not differing much from each other with respect to soil C and N dynamics. However, we think the results are mainly due to lack of data of high precision. For example, we have no good estimates of soil C mass in the individual plots before the experiment started, and had to assume one value for all plots. Kätterer and Andrén (1999) presented several cases where soil C was changing notably in similar experiments. In such cases, including soil fluxes or not will give greater differences than that found here. At Ultuna, the N balances changed markedly when the changes in soil N stocks were considered (Table 6). In the manured treatment, the balance changed from $+25$ to -23 kg ha^{-1} when soil N changes were considered. Subsoil N mining may partly account for the highly negative balance values but the precision in the data set limits the interpretation, even in this highly controlled field experiment.

4.3. Crops

By using a model such as ICBM, it is possible to distribute the N mineralisation to different years, not only using mean soil N changes for every year. In the model used here, inputs have been changed every year according to crop type and yield. It would also have been useful if it had been possible to include the effects of the weather during a specific year. However, available functions describing the weather effects on decomposition rates are complex and not generally accepted, so we used only an average climate. It is still possible to study the average effects of different crops in the rotation, over a longer period. If only input–output is considered (Table 5), barley seems to be the most efficient crop. However, when mineralisation of SOM and the large amount of residues from the crop before (sugar beet) is included, the barley crop is rather inefficient. Instead, sugar beet becomes the most efficient.

The effect of sugar beet could be due to the crop's long growing season and deep root system, taking up residual N from the preceding crop. The following barley crop can usually not utilise all N mineralised from the sugar beet residues. In the field, some gaseous or leaching losses of N will occur. When judging the risk for losses from the different crops, it would be a misleading only to look at input–output balances, as seen from the sugar beet crop. The sugar beet seems to utilise all N available in the soil. However, the sugar beet residues constitute a major risk for losses. If mineralisation starts before the following crop can utilise the N, or if it is not able to utilise all N mineralised from the residues (about 100 kg), losses can occur. The ICBM model does not predict what happens to mineral N surpluses, hence a more comprehensive model would be required to do this.

5. Conclusions

Long-term field experiments are necessary for the development of soil C and N models. At the same time, it is difficult to obtain soil C and N field data with precision sufficient for critical model validation. More emphasis is needed on precision and quality of soil C and N measurements, e.g., fewer and more clear-cut treatments, more replicates, and analyses of soil samples from different years using the same method. Combining data from experiments, information from literature and some guestimates, it is possible to at least coarsely predict soil C and N flows. However, the predictions always have to be carefully scrutinised, particularly when validation data are insufficient.

Including soil C and N dynamics (organic pool changes) can drastically alter N budget estimates. When organic soil N pools are included, calculated N surpluses were increased in treatments with no crops and reduced in treatments with large amounts of organic amendments. The calculated surplus for different crops included in a rotation can also be significantly changed.

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