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Modelling the change in soil organic C and N and the mineralization of N from soil in response to applications of slurry manure

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Abstract

A computer simulation model of the turnover of organic matter in soil was adapted to simulate the change in soil organic C and N contents of soil during several years following annual additions of farm slurry to maize fields. The model proved successful in estimating the build-up of both C and N in soil and the leaching of N to ground-water in response to applications of slurry ranging from 50 to 300 tons per hectare per year. The model was then used to estimate the build-up of organic matter in soil under crops of fodder maize that were grown using the excess of manure produced during the last 20 years in the Netherlands. The build-up of organic matter from these applications was estimated to lead to about 70 kg extra nitrogen mineralized ha^{-1} yr^{-1}. As a result of legislation manure applications have decreased and are expected to decrease further in the immediate future. Calculations suggest that after 10 years of manure applied at rates no longer exceeding the amount needed to replace the phosphorus removed by crops, the extra mineralization of N will still be between 45 and 60 kg ha^{-1} yr^{-1}. If manure applications cease altogether then the extra mineralization will be about 25–30 kg N ha^{-1} yr^{-1}.

Introduction

Nitrogen from manure is partly taken up directly by crops, partly lost to the atmosphere and natural waters and partly assimilated in organic matter. The exact proportions following each pathway depend on the nature and composition of the manure, the ability of the crop to extract nitrogen, the nature of the soil, and the weather conditions during the weeks after application. The interaction of all these processes is naturally rather complex but Lund and Doss (1980) and Liang and Mackenzie (1992) showed that organic N in soil increased during several years of manure application. This extra organic matter can contribute to extra mineralization (Dilz et al., 1990; Magdoff and Amadon, 1980; Motavelli et al., 1992; Ndayegamiiye and Côté, 1989; Powlson et al., 1989). The decline in mineralization and soil organic matter once applications stop or are reduced has not been quantified.

The fate of this organic matter and its contribution to mineralization are of great importance to agriculture in the Netherlands and in particular growers of fodder maize who have been applying large amounts of slurry to their crops for the last 20 years. Legislation in the Netherlands, both in place and proposed, restricts the timing, delay before incorporation and amount of applications of animal slurry. From 1996 farmers must apply no more slurry to their soils than is sufficient to maintain phosphorus levels in soil. Naturally this will restrict the amount of nitrogen applied too. In the past, however, without the benefit of this legislation, excess slurry has been applied leading to a large increase in the organic matter in soil and a surplus of N mineralization over crop requirement in the winter months. We decided to examine the build-up of organic matter in soil and subsequent increase in N mineralization in response to slurry applications during the last 20 years. To do this we compared the predictions of a computer model which simulates the change in organic matter

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content of soil in response to inputs with measurements from two long-term experiments studying slurry applications. Having shown that the model could estimate changes in soil organic C and N and the leaching of N we calculated the likely fate of organic manures applied to maize fields between 1975 and 2005.

Methods

The model

There are three main parts to this computer simulation model: (i) water movement, that is leaching and evaporation, (ii) crop growth, development and nitrogen uptake, and (iii) organic matter turnover in the soil. Different components of the model have already been described elsewhere (leaching: Addiscott and Whitmore, 1987; organic matter turnover: Bradbury et al., 1993; crop growth: Whitmore, 1995), so the most important aspects of the model only will be described here along with the specific adaptations for slurry and the growth of maize.

Leaching

The model divides the soil into a series of uniform horizontal layers each 50 mm deep. Within each is a mobile and immobile compartment containing amounts, W_m (mobile water) or W_r (retained or immobile water), of water per unit area. Incoming rain displaces an equal amount of W_m (and the nitrate it contains) and this displacement is followed by equilibration between the compartments. Because in practice nitrate diffuses between the compartments, some is held back by the model after complete equilibration of the water; the effect of ped sizes on nitrate diffusion was estimated by Addiscott et al. (1983). Upward movement of water by evaporation takes place from both compartments, taking nitrate with it. As the soil dries this evaporative demand cannot be met entirely from the liquid phase, so that vapour movement becomes more important, reducing the amount of nitrate transported.

Addiscott (1977) assumed that half the water held more tightly than 15 bar tension excludes anions; the division between mobile and immobile water was made at 2 bar so that for a 50 mm layer W_m and W_r are calculated in mm per layer as follows:

$$W_m = 50(\theta_{0.05} - \theta_2) \qquad (1)$$

$$W_r = 50(\theta_2 - \frac{1}{2}\theta_{15}) \qquad (2)$$

where $\theta_{0.05}$, θ_2 and θ_{15} are the percentage amounts of water (by volume) held by the soil at tensions greater than 0.05, 2 and 15 bar, respectively.

Crop growth and N uptake

Dry matter production is estimated from a simple relationship with incoming radiation based on a proposal by Green and Vaidyanathan (1986) for cereals. Maize is assumed to produce 1.2 g dry matter m^{-2} for every MJ m^{-2} radiation intercepted.

Nitrogen uptake and rooting depth are estimated using a simplified logistic function (Whitmore and Addiscott, 1987)

$$Y = (A^{-\frac{1}{n}} + e^{-kx})^{-n} \qquad (3)$$

where Y is the nitrogen uptake or rooting depth, n distorts the symmetry of the curve and was set at 1.5 for all processes, k is a rate constant and x is thermal time (the accumulation of the average daily temperature above 0 degrees centigrade each day). The parameter A is the maximum value Y is allowed to take: 260 kg N ha^{-1} for N uptake, 150 cm for the rooting depth. The amount of root in each layer declines with depth exponentially in the manner proposed by Gerwitz and Page (1974). Uptake from each layer depends on the quantity of N available in the proportion of each layer that is defined to be accessible to roots by the exponential relationship (Addiscott and Whitmore, 1987).

The model also predicts development, grain production and nitrogen content of the grain but because maize in the Netherlands is predominantly grown for fodder, less attention has been paid to the goodness of fit of this section of the model. Returns of C in crop residues to soil in roots and stubble were assumed to be a constant 0.8 t ha^{-1} each year. Maize was grown for fodder in this series of experiments and we expect the amount of residues left in soil to be a minimum; similarly, because almost all the dry matter was removed, year to year variation in the amount of residue remaining should also be small. Crop development follows that proposed by Weir et al. (1984); the parameters used came from Van Diepen et al. (1988). The allocation of assimilate to roots is: 50% between sowing and emergence, 30% until stem extension and 10% until anthesis following Van Keulen and Seligman (1987) who made measurements of the growth of spring barley. After anthesis, root growth ceases and senescence of the plant begins. Between anthesis and harvest a maximum of 15% of the total carbon in the plant is lost during senescence most of it towards the end of the crop's life. Nitrogen in senescing above-ground parts is made available to the growing grain and root nitrogen appears in the soil as the roots decompose. Throughout growth a proportion of the assimilate is exuded through roots into soil. This amount can vary from year to year depending upon the time between certain growth stages but on average was found to be just over 2 tonnes C ha^{-1} in total for cereal crops (Swinnen, 1994). Bradbury et al. (1993) assume about 2.3 t ha^{-1} annual C input to soil in the form of senescence, exudates and harvest residues. Swinnen (1994) showed that during active growth, wheat and barley roots exude and slough off an average of 1.5 times their daily growth; his total estimate of the input of C was 2.3 t ha^{-1}. Exudation from maize is less per unit of dry matter produced than barley but slightly more in total (Liljeroth et al., 1994). By adding 1.0 times the daily modelled growth of root to soils we obtained exudation of between 1.3 and 1.6 t C ha^{-1} annually, which added to the 0.8 t ha^{-1} from harvest residues gives a total C input of 2.1–2.4 t C ha^{-1}. The C:N ratio of exudate was taken to be 40.

The turnover of organic matter

The fundamental structure of the organic matter model and parameters used is as proposed by Bradbury et al. (1993) with two important differences. In the original formulation this model used the same C:N ratio of 8.5 for both microbial biomass and older organic matter (humus) but here the biomass has a C:N ratio of 5 and the older humus 10. In this study the time-step of the model is one day whereas in the original it was one week. A systematic fitting procedure (Stol et al., 1992) was used to derive the best estimates of the daily rate constants knowing the original weekly ones. Rate constants used throughout the organic matter build-up study were derived independently of all data in this article. Carbon and nitrogen from plant residues (stubble, senescing crop and roots) or organic manure decompose in soil to produce microbial biomass and humus. A proportion (α) of the carbon entering the soil becomes microbial biomass and a further proportion (β) becomes humus. The remainder (1-α-β) is respired and lost from the soil as CO_2. The proportion of clay in soil determines the values of α and β. Nitrogen flow follows carbon, but where there is insufficient N in the residues or manure to effect their full

Table 1. Some properties of the two soils in the calibration at the start of the experiments

Site	pH-KCl	Organic matter (%)	Total N (%)	Rooting depth (cm)
Maarheeze	5.2	2.9	0.11	40–80
Heino	4.6	4.2	0.14	70–100

incorporation into soil, mineral N is immobilized. If there is insufficient mineral N in soil, decomposition is reduced until enough is available. Full details of the flow and the derivation of α and β can be found in Bradbury et al. (1993). For the sandy soils used in both the calibration and the build-up study (α+β) was set at 0.34.

Once the consumption of carbon is known the demand for oxygen in soils can also be calculated assuming the respiratory quotient remains close to unity; if the soil is waterlogged then the model uses simple zero-order kinetics (with respect to nitrate) to reduce any nitrate present in soil in order to supply the demand for an electron acceptor (Bradbury et al., 1993). In this way denitrification is already corrected for temperature. Denitrification is not permitted below 5 °C, nor unless the soil is saturated for 3 (sand soil), two (loam) or one (clay) consecutive days.

Nitrogen is deposited on land from the atmosphere. In part this is soluble N in part particulate (e.g. Goulding, 1990). For convenience we have assumed that all the N is deposited in rainfall. The 49 kg ha^{-1} deposited is in accordance with current estimates of total (particulate plus soluble) deposition in the Netherlands (Stouthart and Leferink, 1992).

Bulk density was assumed to alter with organic carbon content of soil according to a relationship derived by Whitmore et al. (1992) for 36 separate soils in the UK.

$$\text{Bulk density} = 1.728 - 0.271 \times \sqrt{(\%\,\text{carbon})} : \quad r = -0.906 \quad (4)$$

The results to be presented in this article fall logically into two phases First a demonstration that the model can simulate real data taken from two experiments that measured the effects of long-term applications of manure to maize fields and secondly model calculations to estimate the build-up of organic matter generally during the last 20 years and the likely consequences this will have for mineralization from soil in the near future.

Demonstration phase

In the 1970's and 80's two long-term experiments were carried out on the application of organic manures to fodder maize in the Netherlands; one was at Maarheeze and the other at Heino (Schröder, 1985a, 1985b). Both experiments were carried out on land which formed the perimeter of medieval villages. Agricultural practice in those days was to allow the animals to graze far and wide away from the village during the day, but pen them on the perimeter at night to collect their manure. During the winter, manure from stalled animals was also spread on the perimeter fields. In this way the depth of fertility was slowly increased and the soils nowadays contain fertile humus to a greater depth than agricultural soils of more recent origin. For this reason we calibrated our model against the changes in organic matter in the top 40 cm of soil. Both soils are loamy sands with less than 5% clay. Some other properties of the soils are shown in Table 1.

At both sites we modelled the effects of 6 experimentally applied rates of cattle slurry (annually: 50, 100, 150, 200, 250 or 300 tonnes ha^{-1}). Schröder (1985a, b) reports the amounts of N and C in these manures, N and C in soil, N in leachate and the dates of application; the mean composition is shown in Table 2. Maize was sown each year towards the end of April except at Heino in 1979 when a crop of grass was sown instead. The grass received no organic manure. No catch crops were sown between the maize crops at either site. The maize crops were assumed to return an average of 0.81 tonnes C ha^{-1} annually and 0.014 tonnes N ha^{-1} in roots and stubble at harvest. These data are averages derived from several sources: Anderson (1988), Foth (1962), Klimanek (1991) and Thom and Watkin (1978). Organic matter in soil was recorded intermittently at both sites so that we began the model with organic matter measurements made at Heino in November 1975 and compared its simulations with measurements made of organic matter in 1980 and 1982 (assuming C in organic matter is 58%, e.g. Sommerfeldt et al., 1988) and with measurements made of organic N in 1980. At Maarheeze we initiated the model with data from November 1975 and compared it with measurements of organic C in 1978, 1979, 1981 and September 1982. The maize was assumed to introduce 3 kg N ha^{-1} from seed each year. The grass crop at Heino in 1979 was assumed to return 5000 kg C ha^{-1} (Schröder, 1985a). No measurements were made of ammonia volatilization but since these were slurry applications, we assumed 50% of all added N was in the ammonium form (Schröder, 1985a, b) and that 30% of this would volatilize. Döhler (1992) has shown that losses of slurry remaining on the surface of soils for two days can reach 30% from pig slurry and 50% from cattle slurry. At best our assumption of 30% is an average and will in fact vary from year to year, site to site and application to application.

Addiscott and Whitmore (1987) assessed the goodness of fit of their model with reference to the mean difference between simulation and measurement and whether or not this was significantly different from zero, the correlation between measurement and simulation and the number of simulations lying within a specified range greater than or less than the observations: for example 5 tons C ha^{-1}. The mean difference assesses whether or not the simulations differ systematically from the measurements and the correlation coefficient estimates how well measurement and simulation are associated with one another throughout the full range of the measurements. Since measurements are themselves limited by sampling or analytical error (often about 5% for organic C or N) it is reasonable to test to what extent the simulations fall within a given range. These experiments were not replicated so that the lack of fit technique recommended by Whitmore (1991) cannot be used.

Organic matter build-up during the last 20 years and decline during the next 10

The question we set ourselves to answer was: how much have manure inputs contributed to the build-up of organic matter in soils, how much does this extra organic matter contribute to mineralization of nitrogen and what is the fate of this organic matter likely to be in the near future. To do so we made simulations, using our model calibrated against the data described in the previous section, of the turnover of manures added from 1975 to the present day. As manure application rates to maize are not known accurately, we estimated them on the basis of published statistics of animal numbers and the area of maize grown (Anonymous, 1993), and average values for manure production per animal. Farms in the Netherlands have become increasingly specialized during the last 20–30 years so we discriminated between pig-rearing and dairy farms, supplying pig and cattle slurry to their maize respectively. In 1988 legislation came into force that restricted applications during the winter months and we altered the timing of applications accordingly. The associated amounts of N and P_2O_5 applied in manure were estimated using

Table 2. Average composition of the slurry applied to the experiments at Heino and Maarheeze (taken from Schöder 1985a, b)

Site	Dry matter (%)	Organic matter (%)	Total nitrogen[a] (%)
Maarheeze	11.4	8.5	0.51
Heino	9.4	6.9	0.50

[a] Mineral N in slurry set at 50%.

Table 3. Estimated amount of manure and the N and P contained in it, applied to maize grown on dairy or pig-rearing farms between 1975 and 2005; amounts before 1994 are based on known number and area of maize, amounts from 1995 onwards are best guesses

Year	Type of farm					
	Dairy			Pig-rearing		
	Manure application rate (M^2 ha^{-1})[a,b]	Associated N (kg ha^{-1})[b]	Associated P_2O_5 (kg ha^{-1})[c]	Manure application rate (m^3 ha^{-1})[a,b]	Associated N (kg ha^{-1})[b]	Associated P_2O_5 (kg ha^{-1})[c]
1975	79	348	142	47	259	221
1978	92	405	166	51	281	240
1981	89	392	160	58	319	273
1984	61	268	110	62	360	291
1987	59	260	106	79	444	250
1990	50	220	90	53	335	250
1993	46	202	83	46	286	204
1996	42	183	76	22	139	103
1999	37	165	67	24	149	90
2002	36	158	65	18	111	65
2005	36	158	65	18	111	65

[a] Trends in animal density taken from Anonymous (1993).
[b] Trends in N content of manure taken from Anonymous (1984).
[c] Trends in P:N taken from Neeteson and Wadman (1991).

constant concentrations of N (4.4 kg m^{-3}) and P_2O_5 (1.8 kg m^{-3}) in cattle slurry but an increasing N:P_2O_5 ratio in the pig slurry (see Table 3) in accordance with the trends observed in practice (Anonymous, 1984; Neeteson and Wadman, 1991). During the 1970's it is unlikely that farmers made any allowance for the nutrient content of manure, so in 1975 250 kg; fertilizer N ha^{-1} was also applied; this we reduced gradually at a rate of 15 kg N ha^{-1} year^{-1} during the next 10 years but increased again after 1988 as manure applications were restricted. Similarly we gradually reduced the volatilization of ammoniacal N from manure from 30% to 15% during 1984–88 as we assumed that farmers became more aware of the need to incorporate quickly. The change in the amounts of manure applied and the N they contained are given in Table 3. From 1993 on we decreased manure applications in the model until their phosphorous content balanced the offtake in the plant. Full details of the calculations by which we arrive at the data in Table 3 can be found in Whitmore and Schröder (1996).

No one year of weather was completely typical of the 40 years available from 1954–1994. We therefore constructed an artificial year of daily weather data made up from months throughout the second half of this century that were close to the 40 year monthly means. Figure 1 shows the rainfall and temperatures in this artificial year together with the 40-year means for each month. Consequently year to year variation is removed from the predictions made from 1994 onwards. This is a serious objection where the aim is to estimate actual losses; Porter et al. (1995) have shown how important the effect of year to year variation in temperature can be on wheat yields. Nonetheless where the aim is to show the trend in decline of N supplying power mean weather is acceptable.

Fodder maize was grown continuously, sown at the end of April and harvested at the end of September; as in the demonstration experiments no catch crops were sown. Mineral fertilizer was applied each year at the beginning of May. For comparison the change in organic matter under continuous fodder maize grown

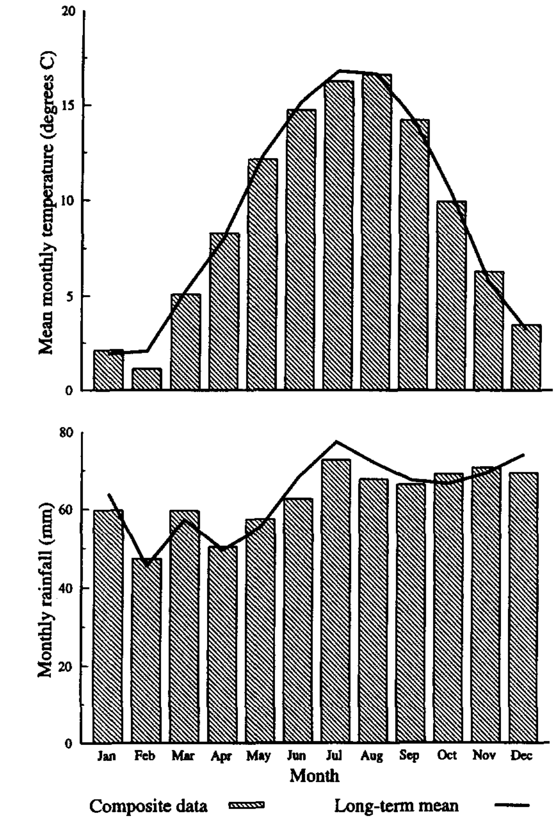

Figure 1. Long-term mean monthly rainfall and temperature data from Wageningen (1954–94) together with the monthly summaries of the year of weather chosen for the 10 years 1995–2005.

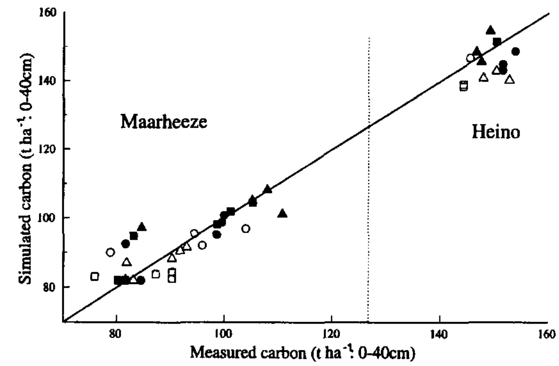

Figure 2. The measured and simulated amounts of organic carbon in the top 40 cm of soil at Maarheeze between 1975 and 1982 (left of diagram) and at Heino between 1975 and 1981 (right of diagram) as a result of annual applications of 50 (□), 100 (△), 150 (○), 200 (●), 250 (■) or 300 (▲) m^3 slurry ha^{-1}. The vertical line serves to separate the two sets of results.

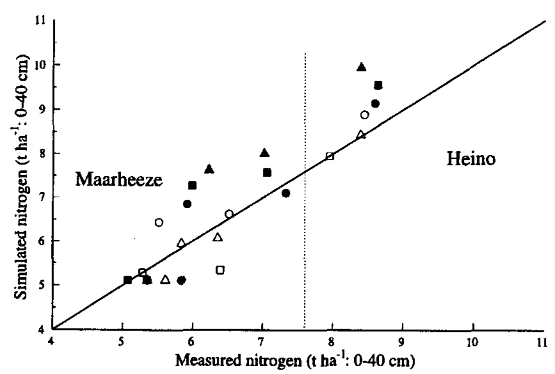

Figure 3. The measured and simulated amounts of organic nitrogen in the top 40 cm of soil at Maarheeze between 1975 and 1982 (left of diagram) and at Heino between 1975 and 1981 (right of diagram) as a result of annual applications of 50 (□), 100 (△), 150 (○), 200 (●), 250 (■) or 300 (▲) m^3 slurry ha^{-1}. The vertical line serves to separate the two sets of results.

with 250 kg mineral N ha^{-1} alone was also simulated. To see the effect of mineralization from the historical use of manure we made simulations at five-year intervals without the application of manure in that particular year. The difference between mineralization in this soil and in the soil with mineral N alone gives the effect of manure on mineralization. The organic matter level at the start of the simulations, was taken to be 1.3% C. This rather low level was chosen to ensure that there was no build-up of organic matter under the maize crop receiving mineral N alone. Organic matter levels under this treatment thus represent a true base-line.

Results and discussion

Demonstration phase

The model was able to simulate the changes in organic carbon in soil very well indeed at the two experimental sites (Figure 2). The mean difference was not significantly different from zero, the correlation coefficient was almost one and 91% of all simulations were within 10 tons ha^{-1} of the measurements (Table 4). The simulations are strikingly good for Maarheeze. Although not quite so good at Heino, the reason for this is almost certainly the fact that the pH of the soil was rather low at the start of the experiment (4.0). Jenkinson (1977) has shown that acidity in this range could reduce organic matter turnover by 85–90%; other authors have suggested even greater decreases (e.g. Hendriks, 1992). Because the pH changed during the experiment, partly as a result of the change in land use and manure application and partly because the whole field was limed in

Table 4. Statistics showing the goodness of fit of the model to the Maarheeze and Heino data

	M[a] (S.E.)	r[b]	±5[c] (0.5)	±10[c] (1)	Number of observations
Carbon	0.988 (0.840)	0.990	58%	91%	43
Nitrogen	0.245 (0.140)	0.906	54%	83%	24

[a]Mean difference between measurement (*O*) and simulation (*S*) $\sum(O\text{-}S)/N$ where *N* is the number of observations.
[b] Correlation coefficient.
[c] Simulations within ± 5 or ± 10 tons C ha^{-1} of the corresponding observation (figures in parenthesis denote simulations of nitrogen within ± 0.5 or ± 1.0 tons N ha^{-1} of the corresponding observation).

1981, we have not attempted to model the influence of pH on decomposition and consequently under-estimate the retention of organic matter at Heino. Conclusions drawn from our model should therefore be limited to soils with pH > 4.5. Organic nitrogen in soil was estimated without bias but the spread of simulations was rather greater than for organic carbon (Figure 3) and this is also clear from the small (just non-significant) mean difference and correlation coefficient (Table 4). Nonetheless the lack of bias and the excellent results for carbon encouraged us to believe that the model was reliable even with very large inputs of organic manures and over a period of several years. The measured retention of applied carbon in these soils was close to 25% of the amount added; with the model a value of 24.9% was obtained. Liang and Mackenzie (1992) found retentions of organic matter of 23.4% during 6 years of maize receiving about 30 tonnes cattle slurry each year although the amounts of C added in maize stover in their experiments were about four times greater than we have assumed here. Chater and Gasser (1970) also found a 25% retention during 18 years of manure applications to a sandy soil while Kononova (1966) reported retentions of between 25 and 33%.

Simulations of the mineral N content of soil with the model were poor (data not shown) but this is perhaps not surprising. Many of the measurements were made shortly after manure was applied; Whitmore (1995) has pointed out the difficulty of expecting models to be able to simulate the variable amounts of nitrogen found in soil shortly after fertilizer applications. An altogether more informative test of a model is its ability to simulate changes over a period of time. Schröder (1985b) published measurements of the amount of N leaching out of the Maarheeze plots using ceramic cups. This measure integrates both leaching itself, mineralization, crop uptake, returns to soil from residues and also applications of fertilizer and manure. Figure 4 compares the estimates of leaching based on measurement and modelling. The model is clearly unbiased although as with some of the organic nitrogen measurements there is a great deal of variation in the data. The results shown in Figures 2, 3 and 4 give us sufficient confidence in the working of the model to apply it more widely with the rider that any one site may well differ in any one year from the average trend we have predicted here.

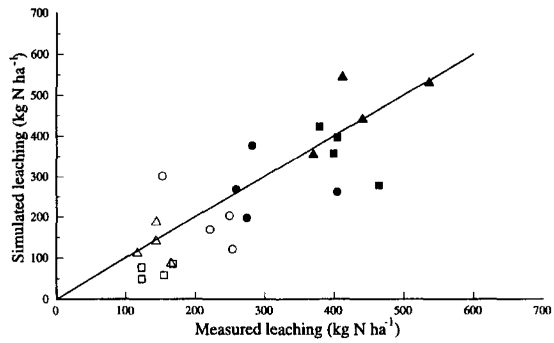

Figure 4. Comparison between modelled and calculated (from field data) amounts of nitrogen (kg ha^{-1} yr^{-1}) leaching out of soils at Maarheeze receiving annual applications of 50 (□), 100 (Δ), 150 (○), 200 (●), 250 (■) or 300 (▲) m^3 cattle slurry ha^{-1} between 1976 and 1982.

Organic matter build-up during the last 20 years and forecasts for the next 10

Figure 5 shows the change in mineralization estimated in our model in soil receiving annual applications of pig slurry and Figure 6 soil receiving annual applications of cattle slurry. In both diagrams four series of data are plotted. Firstly, (a), the net mineralization each year (that is mineralization less immobilization) from all sources of organic matter in soil including the slurry applied within the current year. Secondly, (b), net mineralization in soil growing maize with the help

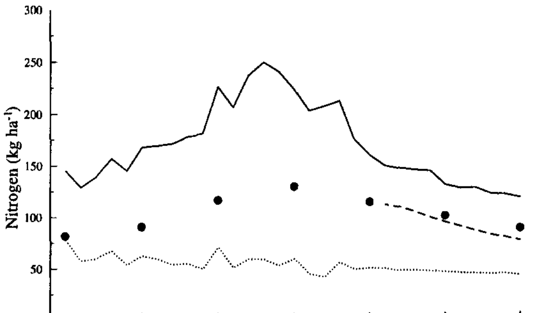

Figure 5. The annual amount of N mineralized from a sand soil as a result of (a) applications of pig slurry each year (—), (b) equivalent application of mineral fertilizer (....), (c) historical application of manure as under (a) but with no application in the current year (●), (d) historical application as under (a) but with mineral N only from 1993 onwards (- - -).

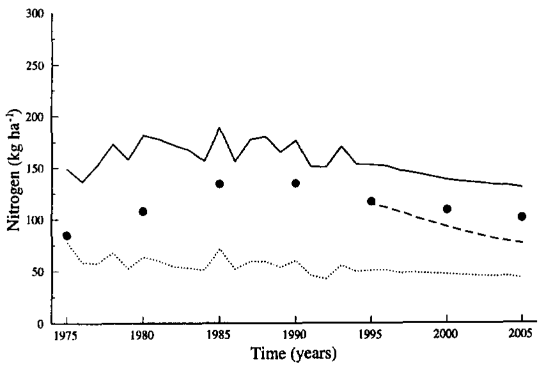

Figure 6. The annual amount of N mineralized from a sand soil as a result of (a) applications of cattle slurry each year (—), (b) equivalent application of mineral fertilizer (....), (c) historical application of manure as under (a) but with no application in the current year (●) and (d) historical application as under (a) but with mineral N only from 1993 onwards (- - -).

of mineral fertilizer only (at 250 kg N ha^{-1}). Thirdly, (c), at five year intervals, the amount of net mineralization from all sources excluding freshly applied organic manure that is to say including the effect of slurry applications in each year from 1975 onwards up to but not including the current year. Fourthly, (d), the expected decline in net mineralization from 1995 onwards if no more slurry at all were to be applied but the N supplied instead from mineral fertilizer at a rate of 250 kg ha^{-1}. The difference in mineralization between (c) and (b) gives the increase in mineralization caused by historic applications of slurry. It is clear from Figures 5 and 6 that this background mineralization increased with increasing slurry applications between 1975 and the early 90's. It is also clear that the extra mineralization in the early 90's was about 70 kg ha^{-1}' in the soil receiving pig slurry and about 75 kg ha^{-1} in the soil receiving cattle slurry. The extra mineralization endures for many years because organic matter in soil is maintained by the additions of manure at a greater level than the soils receiving mineral N alone.

By the year 2005 the extra mineralization from the pig slurry is expected to be about 45 kg N ha^{-1} and from the cattle slurry about 55–60 kg N ha^{-1}. This is despite the fact that applications of pig slurry were greater than cattle slurry between 1975 and 1993 and despite the fact that the pig slurry contains more N. As Sluijsmans and Kolenbrander (1977) have shown, cattle slurry contains a greater proportion of organic matter initially resistant to decomposition. Because it is resistant it accumulates, but because it is retained its contribution to mineralization begins to become relatively more important after many years. If manure applications are with-held completely (Figures 5 and 6: d) the decline in extra mineralization by 2005 is somewhat faster (25 kg N ha^{-1} extra mineralization from soil receiving pig slurry; 30 kg ha^{-1} from soil receiving cattle slurry). At these levels it would probably begin to become difficult to distinguish the effect of the manure from the effect of year to year variation in mineralization. The weather alone produced a range in the background mineralization in the soils receiving mineral N alone (Figures 5 and 6: c) of more than 30 kg N ha^{-1} between 1975 and 1995.

The results presented here are in no way out of the ordinary. Ndayegamiye and Côté (1989) observed an increase in mineralization potential in soil receiving 120 m^3 pig slurry ha^{-1} each year for 11 years. Correcting for the temperature of their incubation this is about 80 kg N ha^{-1} extra mineralization above background. From tables given by Van Faassen and Lebbink (1990) and Kooistra et al. (1989) the effects of 8 applications of 4.5 t manure ha^{-1} (expressed as solids added) between 1966 and 1985 was worth about 45 kg N ha^{-1} to crops grown in 1987 and in 1988. Paustian et al. (1992), who simulated the effects of various additions of organic matter to soil, reported an increase of 30 kg N ha^{-1} in the amount of N recovered by wheat and barley on plots that had received 14 applications of 4 t C ha^{-1} in manure between 1956 and 1986. Dilz et al. (1990) found a residual benefit of 19, 43, 62 and 79 kg N ha^{-1} extra uptake by Italian ryegrass as a result of 11 years' application of 50, 100, 150 and 200 t ha^{-1} yr^{-1} of farmyard manure. Dilz et al. (1990) also tested a simple model developed by Sluijsmans and Kolenbrander (1977) which predicted a residual benefit of 36, 73, 109 and 146 kg N ha^{-1} yr^{-1} at the same rates of manure application. The 70–75 kg N ha^{-1} extra mineralization derived from applications of slurry of between 46 and 92 t ha^{-1} slurry thus seem very reasonable.

Conclusions

Supplying organic manures to maize during the last 20 years has almost certainly led to an increase in the N-supplying power of soil in the Netherlands. This is likely to be around 70–80 kg N ha^{-1} extra mineralization annually on average but will probably decline to half this level within 10 to 15 years if manure applications cease altogether. If manure applications are set no greater than needed to replace the phosphorus removed by crops, the extra mineralization will decrease more slowly and probably reach an equilibrium value greater than the N-supplying power of a soil that has received mineral fertilizer only. The estimates above are average values for the maize growing regions of the Netherlands; the exact levels are difficult to estimate, however, and the variability in field soils will mean that any one farm may deviate greatly from the mean prognosis. If given the correct amounts of C and N applied and removed, this model should be able to give more accurate predictions of the build-up and mineralization of N from organic matter at the field scale.

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References

Addiscott T M 1977 A simple computer model for leaching in structured soil. J. Soil Sci. 28, 554–563.

Addiscott T M and Whitmore A P 1987 Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. J. Agric. Sci., Cambridge 109, 141–157.

Addiscott T M, Thomas V H and Janjua M A 1983 Measurement and simulation of anion diffusion in natural soil aggregates and clods. J. Soil Sci. 34, 709–721.

Anderson E L 1988 Tillage and N fertilization effects on maize root growth and root:shoot ratio. Plant and Soil 108, 245–251.

Anonymous 1984 Manuring of arable land. Vlugschrift voor de landbouw nr. 357. Ministry of Agriculture and Fisheries, The Hague, the Netherlands. 12 p. (*In Dutch*).

Anonymous 1993 Agricultural Statistics 1992. Landbouw-Economisch Instituut/Centraal Bureau voor de Statistiek, The Hague, the Netherlands. 245 p. (*In Dutch*).

Bradbury N J, Whitmore A P, Hart P B S and Jenkinson D S 1993 Modelling the fate of nitrogen in crop and soil in the years following application of ^{15}N-labelled fertilizer to winter wheat. J. Agric. Sci., Cambridge 121, 363–379.

Chater M and Gasser J K R 1970 Effect of green manuring, farmyard manure and straw on the organic matter of soil and of green manuring on available nitrogen. J. Soil Sci. 21, 127–137.

Dilz K, Postmus J and Prins W H 1990 Residual effect of long-term application of farmyard manure to silage maize. Fert. Res. 26, 249–252.

Döhler H 1991 Laboratory and field experiments for estimating ammonia losses from pig and cattle slurry following application. *In* Odour and Ammonia Emissions from Livestock Farming. Eds V C Nielsen, J H Voorburg and P L'Hermite. pp 132–140. Elsevier Applied Science, London, UK.

Foth H D 1962 Root and top growth of corn. Agron. J. 54, 49–52.

Gerwitz A and Page E R 1974 An empirical mathematical model to describe plant root systems. J. Appl. Ecol. 11, 773–781.

Goulding K W T 1990 Nitrogen deposition to arable-land from the atmosphere. Soil Use Manage. 6, 61–63.

Green C F and Vaidyanathan L V 1986 A reappraisal of biomass accumulation by temperate cereal crops. Specul. Sci. Technol. 9, 193–212.

Hendriks R F A 1992 Decomposition and mineralization of peat. Report No. 199 of the DLO-Staring Centrum, Wageningen, the Netherlands. 152 p. (*In Dutch*).

Jenkinson D S 1977 Studies on the decomposition of plant material in soil. V. The effects of plant cover and soil type on the loss of carbon from C^{14}- grass decomposing under field conditions. J. Soil Sci. 28, 424–434.

Klimanek E 1991 Umsetzungsverhalten der Wurzeln landwirtschaftlich genutzter Pflanzenarten in Abhaengigkeit vom Vegetationsstadium. Archiv Acker- Pflanzenb. Bodenkd. Berlin 35, 121–128.

Kononova M M 1966 Soil Organic Matter, its Nature, its Role in Soil Formation and Soil Fertility. Pergamon Press, New York, USA 544 p.

Kooistra M J, Lebbink G and Brussaard L 1989 The Dutch programme on soil. ecology of arable farming systems. 2. Geogenesis, agricultural history, field site characteristics and present farming systems at the Lovinkhoeve experimental farm. Agric. Ecosyst. Environ. 27, 361–387.

Liang B C and Mackenzie A F 1992 Changes in soil organic carbon and nitrogen after six years of corn production. Soil Sci. 153, 307–313.

Liljeroth E, Kuikman P and van Veen J A 1994 Carbon translocation to the rhizosphere of maize and wheat and influence on the turnover of native soil organic matter at different soil nitrogen levels. Plant and Soil 161, 233–240.

Lund Z F and Doss B D 1980 Residual effects of dairy cattle manure on plant growth and soil properties. Agron. J. 72, 123–130.

Magdoff F R and Amadon J F 1980 Nitrogen availability from sewage sludge. J. Environ. Qual. 9, 451–455.

Motavelli P P, Bundy L Cr, Andraski T W and Peterson A E 1992 Residual effects of long term nitrogen fertilization on nitrogen availability to corn. J. Prod. Agric. 5, 363–368.

Ndayegamiye A and Côté D 1989 Effect of long-term pig slurry and solid cattle manure application on soil chemical and biological properties. Can. J. Soil Sci. 69, 39–47.

Neeteson J J and Wadman W P 1991 Possible uses of animal manure in arable farming taking account of environmental targets. Onderzoek inzake de mest- en milieuproblematiek in de veehouderij 13. Mest en Milieu in 2000. Ed. H A C Verbeek. pp 51–88. DLO, Wageningen, Veenendaal, the Netherlands.

Paustian K, Parton W J and Persson J 1992 Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Sci. Soc. Am. J. 56, 476–488.

Porter J R, Leigh R A, Semenov M A and Miglietta F 1995 Modelling the effects of climatic change and genetic modification on nitrogen use by wheat. *In* Modelling the Fate of Agrochemicals and Fertilizers in the Environment. Eds. C Giupponi, A Marani and F Movari. pp 49–69. ESA and Unipress, Padua, Italy.

Powlson D S, Poulton P R, Addiscott T M and McCann D S 1989 Leaching of nitrate from soils receiving organic or inorganic fertilizers continuously for 135 years. *In* Nitrogen in Organic Wastes applied to Soils. Eds. J A Hansen and K Henriksen. pp 334–345. Academic Press, London, UK.

Schröder J J 1985a The effect of large applications of cattle slurry on the growth, yield and quality of fodder maize and on soil fertility; Heino (sandy soil) 1972–1982. Report no. 30. PAGV, Lelystad, the Netherlands. 151 p. (*In Dutch*).

Schröder J J 1985b The effect of large applications of cattle slurry on the growth, yield and quality of fodder maize and on soil fertility and ground-water pollution; Maarheeze (sandy soil) 1974–1982. Report no. 31. PAGV, Lelystad, the Netherlands. 101 p. (*In Dutch*).

Sluijsmans C M J and Kolenbrander G J 1977 The significance of animal manure as a source of nitrogen in soils. *In* Proceedings of an International Seminar on Soil, Environment and Fertility Management in Intensive Agriculture. pp 403–411. The Society of the Science of Soil and Manure, Tokyo, Japan.

Sommerfeldt T G, Chang C and Entz T 1988 Long-term animal manure applications increase soil organic matter and nitrogen and decrease the carbon to nitrogen ratio. Soil Sci. Soc. Am. J. 52, 1668–1672.

Stol W I, Rouse D I, van Kraalingen D W G and Klepper O 1992 FSEOPT a Fortran program for calibration and uncertainty analysis of simulation models. Simulation Report CABO-TT, no 24, CABO, Wageningen, the Netherlands. 24 p.

Stouthart F and Leferink J 1992 Mineral book-keeping (including working documents for advisor and participant). CLM, Utrecht, the Netherlands. 20+33+57 p.

Swinnen J I 994 Production and turnover of root-derived organic matter in the rhizosphere of wheat and barley under field conditions. Ph.D. thesis No. 247 of the Faculty of Agriculture and Applied Biology of the Catholic University of Leuven, Belgium. 126 p.

Thom E R and Watkin B 1978 Effect of rate and time of fertiliser nitrogen application on total plant, shoot and root yields of maize. N. Z. J. Exp. Agric. 6, 29–38.

Van Diepen C A, Rappoldt C, Wolf J and van Keulen H 1988 CWFS Crop growth simulation model WOFOST Documentation version 4.1. Centre for World Food Studies c/o AB-DLO, Wageningen, The Netherlands. 299 p.

Van Faassen H G and Lebbink G 1990 Nitrogen cycling in high-input versus reduced-input arable farming. Neth. J. Agric. Sci. 38, 265–282.

Van Keulen H and Seligman N G 1987 Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. Pudoc, Wageningen, the Netherlands. 310 p.

Weir A H, Bragg P L, Porter J R and Rayner J H 1984 A winter wheat crop simulation model without water or nutrient limitations. J. Agric. Sci., Cambridge 102, 371–382.

Whitmore A P 1995 Modelling the mineralization and immobilization, leaching and crop uptake of nitrogen during three consecutive years. Ecol. Model. 81, 233–241.

Whitmore A P 1991 A method for assessing the goodness of computer simulation of soil processes. J. Soil Sci. 42, 289–299.

Whitmore A P and Addiscott T M 1987 A function for describing nitrogen uptake, dry matter production and rooting by wheat crops. Plant and Soil 101, 51–60.

Whitmore A P, Bradbury N J and Johnson P A 1992 The potential contribution of ploughed grassland to nitrate leaching. Agric. Ecosyst. Environ. 39, 221–233.

Whitmore A P and Schröder J J 1996 Nitrogen mineralization under maize: a modelling approach. Report 55, AB-DLO Wageningen/Haren, the Netherlands. 33 p. (*In Dutch*).

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