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Modelling the release and loss of nitrogen after vegetable crops

A.P. WHITMORE

DLO Research Institute for Agrobiology and Soil Fertility, Oosterweg 92, P.O. Box 129, NL-9750 AC Haren, The Netherlands
(fax: +31-50-5337291; e-mail: a.p.whitmore@ab.dlo.nl)

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Abstract

A computer model is described that is able to simulate the mineralization-immobilization turnover of nitrogen derived from vegetable crop residues added to soil. Once mineralized, N is subject to loss from soil in the model by leaching and denitrification. That the mineralization part of the model works well is demonstrated with reference to some pot experiments in which residues from Brussels sprouts, leeks, cabbage or spinach were mixed with either a sandy or clay soil and incubated at 20 °C under optimal moisture conditions for 48 weeks. The release of mineral N was measured at intervals during the experiment and was strongly dependent upon the amount of N added in the crop residues: spinach (C:N = 6) released most nitrogen and most quickly, the other residues (C:N = 13–15) released N more slowly. With adaptations for field conditions, the model was then used to elucidate the fate of nitrogen remaining after field vegetables. The dynamics of both mineral and organic N remaining in soil were traced with this model. After spinach, much nitrate leaches to groundwater; sprouts, however, appear able to immobilize or denitrify what little mineral N remains at harvest reducing the loading of N in percolating water.

The model suggests that during the last 40 years over winter losses of nitrate after cabbage almost always exceeded the EC drinking water limit of 11.3 mg NO_3-N l^{-1}: in some years by a factor of four. Since mineral N remaining in soil at harvest is shown to have most influence on leaching losses, measures taken to reduce unused mineral N will probably benefit groundwater quality most.

Keywords: computer model, immobilization, leaching, mineralization, nitrogen, vegetable residues

Introduction

Modern day vegetable farming can no longer afford to be careless in its use of fertilizer. Where a vegetable crop requires a large amount of nitrogen this must be supplied if profitability is to be maintained, but account can be kept of any N that remains behind in soil after harvest. This idea has been adopted in the mineral bookkeeping legislation under discussion in the Netherlands. Accounting for this nitrogen can be complex because of the lability of most forms of N in the soil. A part of the unused N is free in soil in one of the mineral forms: nitrate or ammonium, another part remains behind in the crop residues. Whether mineral nitrogen remaining in the soil at harvest leaches, denitrifies, survives to be taken up by the following crop, or is incorporated into soil organic matter is not straightforward to say; it varies from season to season. What happens to nitrogen in crop residues once the harvestable parts are removed is just as hard to say. The residues usually break down quickly. Nevertheless, their nitrogen may be mineralized or immobilized and when mineralized the fate of this N is just as difficult to predict as that of native mineral nitrogen. These questions are most easily addressed in relation to each other with the help of computer simulation models. In this article a computer model is first tested against some experimental data from an incubation study. After it is shown to be satisfactory, it is used to illustrate how much and how soon losses of nitrogen, particularly through leaching, can occur in the field.

Methods

Experimental

Pot Experiments

Fresh vegetable crop residues (30 g), from plants grown in soil-less media, were added to moist, sieved soil (300 g) in pots according to the following scheme: (i) cabbage (9.2% dry matter, C:N = 15, NO_3-N = 1.31%), (ii) spinach (6.2% dry matter, C:N = 6, NO_3-N = 1.32%), (iii) leeks (6.4% dry matter, C:N = 14, NO_3-N = 0.21%), (iv) sprouts (12.5% dry matter, C:N = 13, NO_3-N = 1.16%), (v) a control with no addition. The dry weight of the leeks seemed unreasonably low; R. Booij (personal communication) has measured 11.4% dry matter in whole leeks. The dry weight of all soils including controls, was determined immediately after addition; because un-dried residues were added to the pots, the differences between control and treatments allow the dry weights of the additions to be checked. From these calculations: cabbage, 9.5%; leeks, 11.6%; sprouts, 14.5%, spinach, 4.3%. The discrepancy in the moisture content of the leeks is too great to ignore and Booij's value of 11.4% has been preferred. Two different soil types were used: a sandy soil from the experimental farm in Haren in the North of the Netherlands, and a clay soil from the Bouwing experimental farm in Wageningen. Both soils were stored and used field moist; they were kept at a temperature below 5 °C until use. Details of the soils, including original moisture contents, are given in Table 1. Total N in crop and soil was measured by the Kjeldahl method (Deijs, 1961); pH of soil was measured in KCl. All crop samples were dried for 24 hours at 70 °C to retain nitrate; spinach dried at this temperature was found to contain 28.9% C. Apart from this, carbon in crops was not measured but because the other crops were also dried at the same temperature, they have also been assumed to contain 30% C in dry matter. Pots were incubated at a constant temperature of 20 °C and the moisture contents of the soils kept constant

Table 1. Properties of the experimental soils in the pot experiments

Soil	Moisture (%)	[1]OM (%)	pH	Mineral Particles in soil (%)				N (%)	$CaCO_3$ (%)
				< 2 μm	2–50 μm	50–210 μm	>210 μm		
Sand	12.6	2.89	7.16	4.4	2.6	77.6	15.4	0.106	0.6
Clay	27.1	3.25	6.98	48.4	45.1	5.4	1.1	0.168	0.4

[1] Organic Matter

for 11 months by sealing them with a thin, air-permeable but water-impermeable plastic film; sufficient pots were set up to allow the entire contents of duplicate pots to be sacrificed after 1, 3, 6, 12, 24, and 48 weeks. Ammonium and nitrate in soil extracts (1M KCl) were measured colorimetrically. Fibre in plant samples was measured by the method of Van Soest (1967); tannins were not measured.

A model of the decomposition of crop residues

There are two main parts to this computer simulation model: (i) water movement, *i.e.* leaching and evaporation, and (ii) organic matter turnover in the soil. Different components of the model have already been described elsewhere (leaching: Addiscott & Whitmore, 1987; organic matter turnover: Bradbury *et al.*, 1993, Whitmore & Groot, 1994, Whitmore, 1995) but the most important aspects of the combined model will be described here. That the turnover model works well with vegetable residues will be shown with reference to the pot experiments; the validity of the combined leaching and organic matter turnover model has been demonstrated with field results from England (Addiscott and Whitmore, 1987), from Germany (Whitmore, 1995) and the Netherlands (Whitmore *et al.*, 1991; Van Erp *et al.*, 1993).

The turnover of organic matter

The fundamental structure of the organic matter model and parameters used is as described by Whitmore (1995). Carbon and nitrogen from plant residues and stubble, senescing crops and roots 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 $(1 - \alpha - \beta)$ 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 to effect their full incorporation into soil, mineral N is immobilized. If there is insufficient mineral N in soil, decomposition is reduced until enough is available. Recent changes to the model allow both the C:N of the products to vary and the efficiency with which the biomass uses C, $(\alpha+\beta)$, to change; in this way more carbon can be decomposed per unit of nitrogen where necessary. 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 the calibration and the prediction $(\alpha+\beta)$ was set at 0.32 and in the clay soils

0,43. Mineralization of N from residues using this model can be calculated during any time t as:

$$N = C\left\{\frac{1}{Z} - \frac{\alpha}{X} - \frac{\beta}{Y}\right\} \qquad (1)$$

where N is the amount of nitrogen mineralized (positive) or immobilized (negative), C is the amount of carbon in the residues that decomposes in time t, Z is the C:N of the residues, X the C:N ratio of the biomass (assumed constant at 5) and Y the C:N of the soil organic matter (assumed 10 initially). With these figures N will be zero in the sand soil (*i.e.* all the nitrogen in the residues is immobilized but none from the soil) when Z is about 20. The values of α and β will vary from soil to soil, and so will mineralization from soil as opposed to that from residues, because different soils supply N over and above what is calculated in equation (1) from residues. For this reason the critical range of Z where mineralization switches to immobilization may be thought of as between 20 and 25 (*e.g.* Whitmore, 1994).

Equation (1) implies that the amount of N mineralized (or immobilized) follows a hyperbolic relationship with the C:N of the added plant material. Titulaer (1994) quoting earlier work by Van Dijk (1981) showed that a similar relationship holds for animal manures added to soil. Figure 1 plots the amounts of N that mineralized in experiments carried out by a number of different authors. The data used in Figure 1 are not intended to be exhaustive but they illustrate the hyperbolic relationship nicely. The data chosen followed incubations of about two months' duration at room tem-

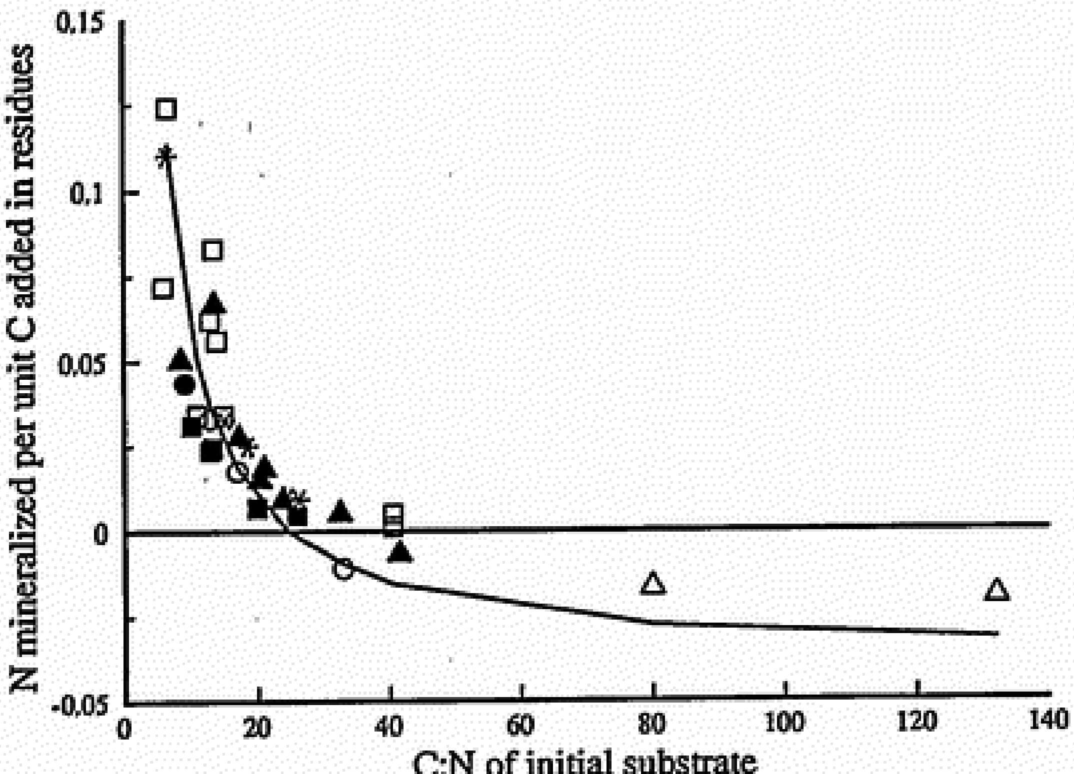

Figure 1. The relationship between nitrogen mineralized (or immobilized) and the carbon to nitrogen ratio of added organic matter after approximately 10 weeks. The data comes from the following sources: *, Franzluebbers *et al.*, 1994; ○, Zagal & Persson, 1994; △, Nieder & Richter, 1989; ■, Jensen, 1929; ▲, Chae & Tabatabai, 1985; ■; Thorup-Kristensen, 1994; ●, Whitmore (this study and unpublished) and Whitmore and Groot (1994). The solid line is the theoretical relationship derived from Equation (1).

perature or the equivalent. Suitably longer time intervals were chosen for the data derived from the field experiments conducted at ambient temperatures. No account of differences in soil type was made in deriving the theoretical line based on Equation (1).

The model also keeps track of the consumption of carbon and production of CO_2. Hence the consumption of oxygen in soils is also known; if the soil is waterlogged then the model uses simple zero-order kinetics to reduce any nitrate present in soil in order to fulfil 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 water-holding capacity is filled to the 50 mbar limit (Addiscott & Whitmore, 1987) for three (sand soil), two (loam) or one (clay) consecutive days respectively.

Modelling the effects of temperature and moisture – field simulations

The pot experiments were maintained at constant temperature and within the optimum range of moisture contents for decomposition; in the field some reckoning must be held with how dry or how cool the soil is. Both factors tend to decrease the observed rate of mineralization. In using this model for field simulations the rate constants that determine the decomposition of organic matter in soil were reduced when the soil was cooler than 20 °C or much drier than field capacity. Where T_k is the effect on the rate of decomposition, B a constant, T_B a base temperature (i.e. 20 °C) and T the absolute temperature, Addiscott & Whitmore (1987) give:

$$T_k = e^{-B\left(\frac{1}{T} - \frac{1}{T_B}\right)} \tag{2}$$

T_k is 1.0 (*i.e.* no effect of temperature on rate) when T is T_B. Addiscott (1983) showed that the constant B was about 7000°K^{-1} for native organic matter in Rothamsted soils but several authors have stated that quality modifies the effect of low temperatures on the decomposition of crop residues (Nicolardot *et al.*, 1994; Vigil & Kissel, 1995; De Neve *et al.*, 1996). At 28 °C for example the decomposition of glucose was 4.7 times faster than hollocellulose (a kind of hemicellulose) but at 5 °C it was 17.6 times faster (Nicolardot *et al.*, 1994); a relative change of a factor of four. These rates give values of B of 5521°K^{-1} (activation energy, E_a: 45.9 kJ mol^{-1}) and 7702 °K^{-1} (E_a 64.0 KJ mol^{-1}) for glucose and hollocellulose respectively. Because of the difficulty of expressing the idea of one mole of crop residues and the dubious validity of applying the universal gas constant R where $B = E_a/R$ to crop residues, the semi-empirical constant B in (2) has been preferred. A value of 5500°K^{-1} was thus used in the present model for the decomposition of readily decomposable materials in soil, such as green residues and microbial biomass, but a value of 7700°K^{-1} for old organic matter (humus) or the fibre component of the residues.

The effect of moisture on decomposition can be deduced from Equation (3), given by Bradbury *et al.* (1993):

$$M_k = 1 - \frac{(1 - M_{15})((\theta_{0.05} - \theta) - (\theta_{0.05} - \theta_1))}{((\theta_{0.05} - \theta) - (\theta_{0.05} - \theta_1))};\ \theta \le \theta_1 \qquad (3)$$
$$M_k = 1; \qquad \theta > \theta_1$$

Where M_{15} is the reduction in decomposition rate at 15 bars tension, θ is the current moisture content of the soil, and $\theta_{0.05}$, θ_1 and θ_{15} the moisture content of the soil at 0.05, 1.0 and 15.0 bars tension respectively. If the soil is more moist than θ_1 then M_k takes a maximum value of 1.0 based on work by Stanford & Epstein (1974) who showed that drying soils had little effect on mineralization until the soil dried beyond one bar tension. It is clear that $0 \le M_k \le 1$. These factors M_k and T_k multiply each of the rates of decomposition of organic matter. There is no interaction between them.

Addiscott (1977) and Addiscott & Whitmore (1987) describe the leaching component of this model. The soil is assumed to be divided into a series of horizontal layers, each with a capacity to hold water. Incoming rainfall displaces water from one layer to the next but within layers nitrate can be protected from displacement within aggregates. The division between aggregate and inter-aggregate water is made at two bars tension and the total available water was calculated for the soils used here from data given by Wösten *et al.* (1987).

Nitrogen is deposited on land from the atmosphere. In part this is dissolved 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 each year is in accordance with current estimates of total (particulate plus soluble) deposition of N in the Netherlands (Stouthart & Leferink, 1992) and is taken to be deposited uniformly each month.

Das *et al.* (1995) pointed out that the use of mean daily temperatures can be misleading at temperate latitudes where one of day or night is normally longer than the other. Mean temperatures in the field simulations were accordingly calculated by weighting maximum temperatures with day-length and minimum temperatures with night-length.

Assessment of the fate of N after harvest in the field simulations

With daily values of rainfall, evaporation and temperature the model was used to make a number of simulations for different field crops; these were chosen to make a contrast between crop residues poor or rich in nitrogen, crops harvested early in the season or late, those leaving much or little in the way of dry matter in soil at harvest or those leaving much or little mineral N in soil. They may be thought of, and are named in Table 2, as cabbage, spinach, leeks and Brussels sprouts but it is important to realize that any one field crop may deviate from what has been given here. Note that the N contents of the residues have been taken from Smit (1994); these values are more representative of field crops than the plants grown on soil-less media for the pot experiments. All N was assumed to be in organic forms in these field simulations, *i.e.* the residues themselves contained no nitrate. In the series of pot experiments outlined above all the residues had relatively narrow C:N ratios. Whitmore

Table 2. The vegetable crop residues used in the simulation study.

Residue	Harvest	Mineral N in soil at harvest[1] (kg ha^{-1})	[1]N in residues kg ha^{-1}	[2]Fibre (%) (Fibre %N)	[1]C:N
Cabbage	end Oct	50	115	23.2 (0.25)	15
Spinach	end July	150	35	24.0 (0.25)	8
Leeks	mid Oct	125	54	29.0 (0.37)	12.5
Sprouts	end Nov	50	138	29.8 (0.34)	25

[1] Taken from Smit (1994)

[2] Fibre is the sum of lignin, cellulose and hemi-cellulose in crop residues from the pot experiments at AB-DLO

and Groot (1994) reported the success of the same model in simulating the mineralization of N from crop residues with C:N in the range 6 to 69. The amounts of mineral N in soil at harvest (start of the simulations in all cases) have also been derived from Smit (1994) and were assumed to be distributed uniformly in the top 90 cm of the soil. Simulations began at the harvest of each vegetable (dates in Table 2) The residues were incorporated in the top 25 cm of soil; leaching is defined as loss below 90 cm. Weather data from Wageningen for the winter 1993–94 and soils with properties identical to the sand and clay soils in the incubation experiments were used in the simulations. The winter 1993–94 and the autumn before it were unusually wet (Figure 2) and so the quantities of N lost in these simulations may be regarded among the greatest to be expected.

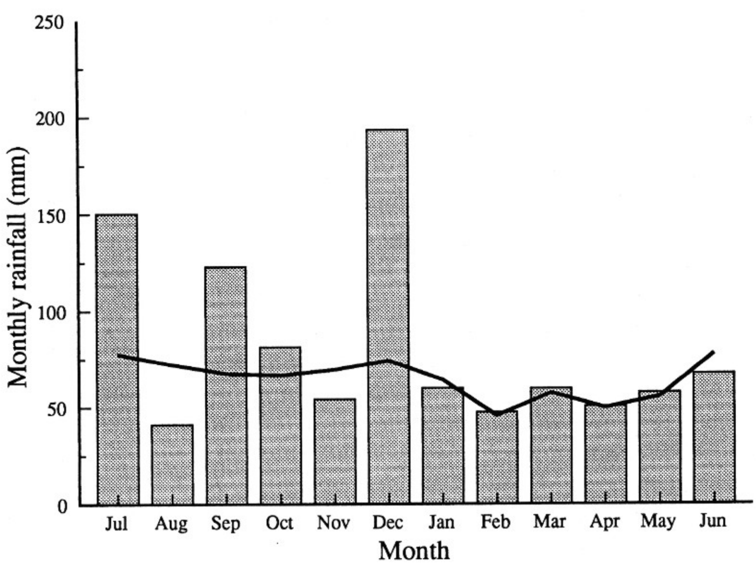

Figure 2. The mean rainfall each month at Wageningen between 1954 and 1995 (line) and the actual rainfall during the year from July 1993 to June 1994 (hatched bars).

The loss of N from under cabbage was also assessed in general by running the model against 40 years of weather data (1954 to 1995) from Wageningen and calculating the concentration of N in water draining from the soil profile both with and without the cabbage crop. The mean rainfall given each month in Figure 2 is the mean of these 40 years.

Results and discussion

Pot Experiments

Nitrogen was released from the vegetable residues in the pot experiments almost immediately and in quite large amounts (Figure 3) but this is because the C:N ratios of the residues were narrower than the critical range of 20–25 where mineralization switches to immobilization (Equation 1). Clearly, the model could simulate the release of nitrogen from these residues well; the only difference in input data between each simulation made with the same soil type was the initial amounts of carbon and nitrogen in the residues. Note that the amount of leeks added has been adjusted to agree with the amount of moisture found in this soil after amendment (see materials and methods section). Nitrate in the crop residues was assumed to feed the mineral pool directly (Whitmore and Groot, 1994). This accounts for the very large amounts of N found after 7 days in the soils to which cabbage and sprouts were added (C:N = 13–15) while the soils to which leeks were added contained far less mineral N after this time (Figure 3).

Field simulations of the fate of nitrogen in the soil at harvest and derived from residues

Figures 4 (a and b) show the predicted fate (leaching or denitrification) of N derived from vegetable crop residues alone in soil (*i.e.* excluding the mineral N found in field soils at harvest and the N mineralized during the winter from native soil organic matter). The diagrams were made by using the model to estimate the fate of nitrogen both with and without addition of residues and subtracting the latter from the former. Simulations were carried out until the end of May in order to encompass all the denitrification but leaching was usually over by April. The absolute amounts of N leached from the soils where no crop residues were incorporated (*i.e.* derived from the mineral N remaining at harvest plus mineralization during the winter) were large after all crops (Table 3). Denitrification in the bare soils without residues was much less: between 5 and 8 kg N ha^{-1}. All soils were assumed to have been left bare over the winter; a cover crop could have extracted some nitrogen. The crop residues on the other hand increase leaching by a relatively small amount (Figure 4) and the Brussels sprouts actually reduce it. Mineral nitrogen remaining in soil at harvest has the most effect on leaching; measures designed to combat this will probably reduce the amount of nitrate lost to groundwater most. After spinach or leeks, leaching losses of the mineral N present in soil at harvest and mineralized from soil organic matter afterwards can be as much as 200 kg N ha^{-1}; spinach and leeks are both crops that

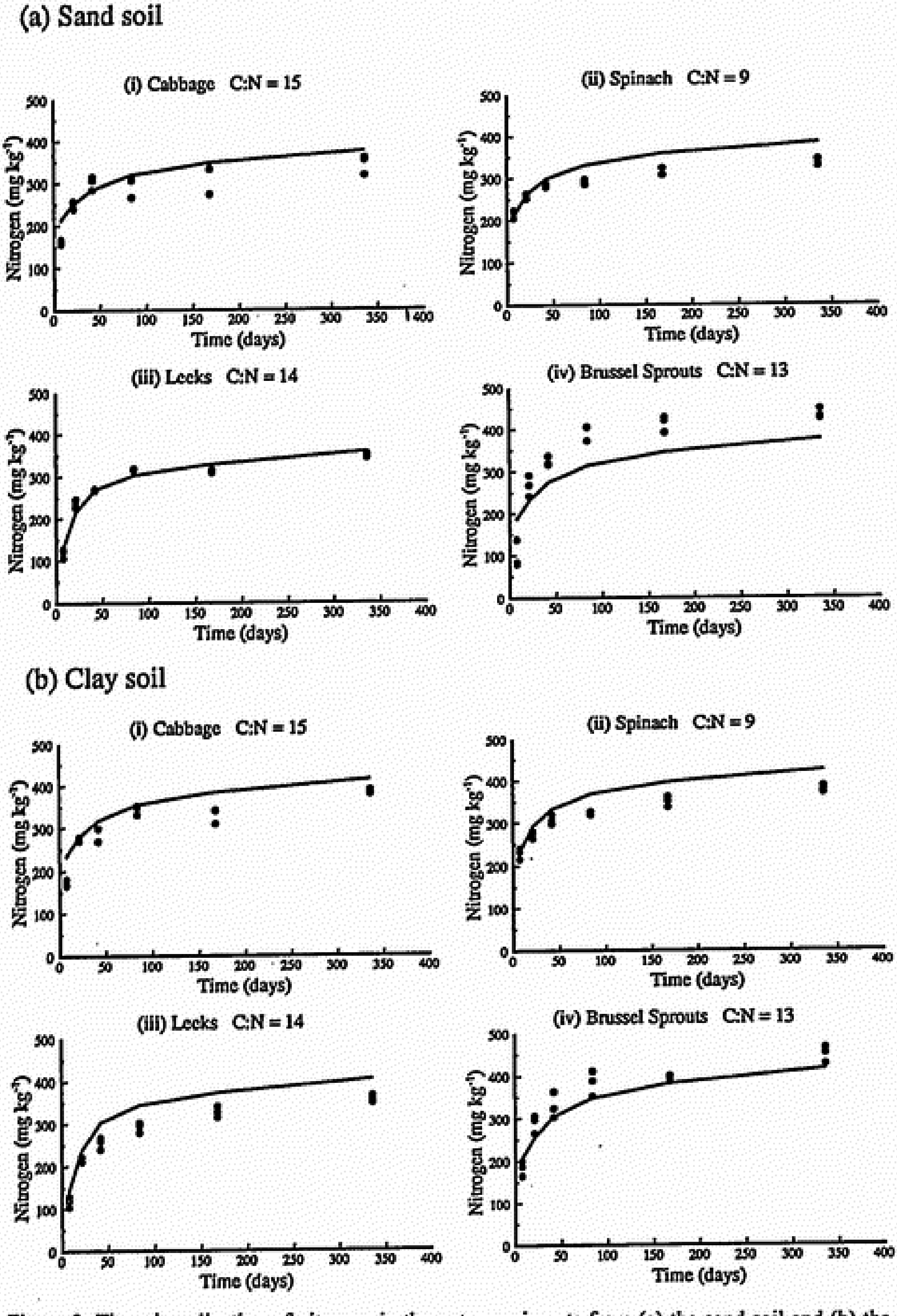

Figure 3. The mineralization of nitrogen in the pot experiments from (a) the sand soil and (b) the clay soil: (i) cabbage residues, (ii) spinach residues, (iii) leek residues and (iv) Brussels sprout residues. Points are measured data, the solid line is the simulation made with the model.

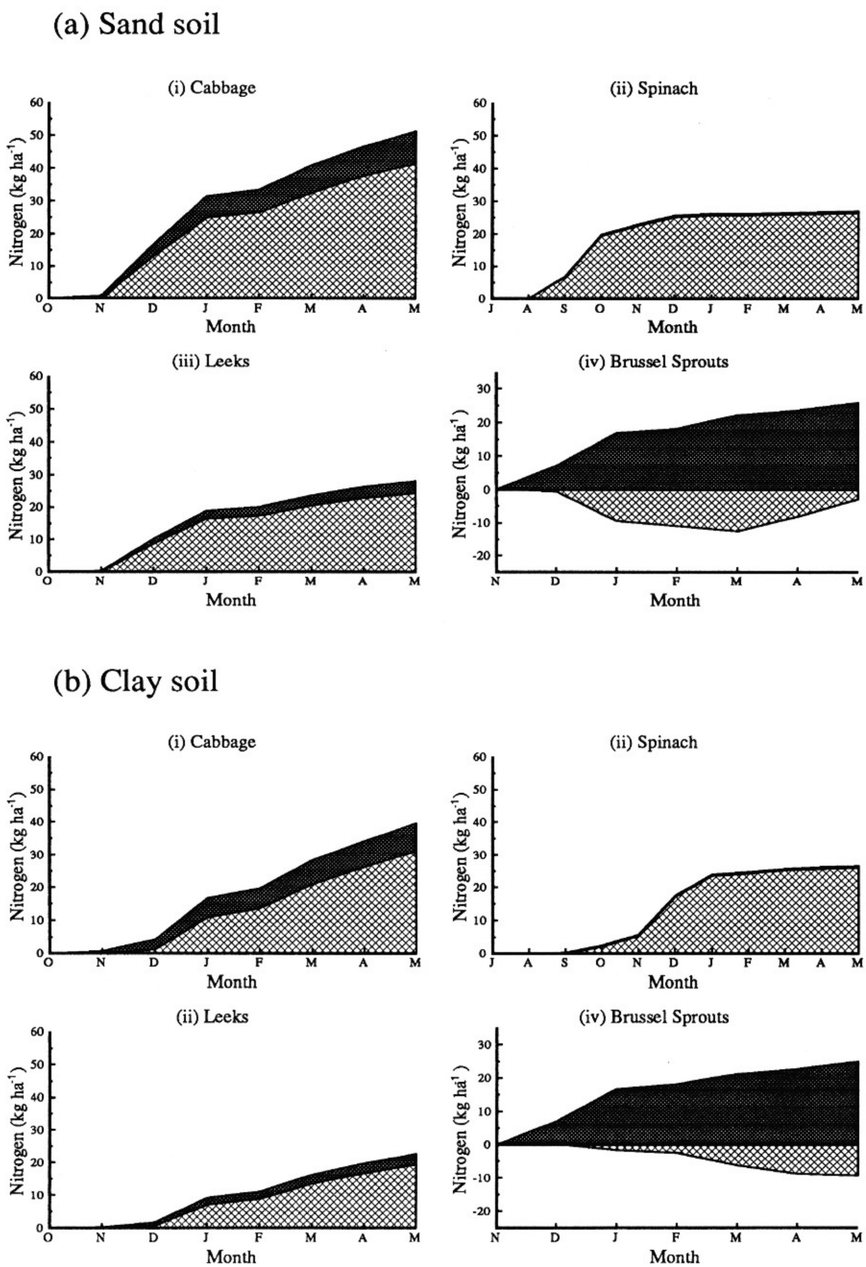

Figure 4. The fate of nitrogen derived from crop residues alone (i.e. excluding mineral N) added to soil at harvest: (a) the sand soil and (b) the clay soil; (i) cabbage residues, (ii) spinach residues, (iii) leek residues and (iv) Brussels sprout residues. Dark shading represents denitrification losses (kg ha^{-1}), hatching represents leaching losses (kg N ha^{-1}). Negative values imply a lesser amount than where crop residues were *not* applied.

Table 3. Simulations showing the total quantities of nitrogen leached (kg ha^{-1}) from soils during the winter after the harvest of vegetable crops but where the residues were removed. Leaching losses shown are thus derived from mineral N present in soil at harvest and from mineralization of native soil organic matter up to the end of May.

	Cabbage	Spinach	Leeks	Sprouts
Sand	90	223	160	84
Clay	77	215	177	66

use applied N inefficiently and leave little in the way of residues behind after harvest. After cabbages or sprouts (but where the residues are removed), leaching is less – about 90 to 100 kg ha^{-1} – because both these crops extract mineral nitrogen quite efficiently from soil and leave little mineral N in soil at harvest (Table 2). Both cabbage and sprouts do, however, leave a large mass of residues in the soil in contrast to spinach and leeks, but the differences in C:N lead to very different effects on the amount of leaching. The cabbage residues with C:N = 15 increase the nitrogen leached to about 130 kg N ha^{-1} (from 90 kg ha^{-1} without residues). The sprout residues have C:N = 25, which is in the critical range (Figure 1), and decrease leaching slightly relative to a soil without crop residues (Figure 4). The extra carbon added in the sprout residues can stimulate microbial activity resulting in a greater immobilization of N than with the other residues but some extra denitrification also takes place; clearly N that denitrifies cannot leach.

Because the switch between immobilization and mineralization depends partly on soil type (factors α and β in equation 1) any crop residue with a C:N ratio of between 20 and 30 is likely to give conflicting results in field experiments in different soils: sometimes mineralization will be found sometimes immobilization. Where the carbon and nitrogen content of residues is known, computer models can help to relieve this confusion. It must be borne in mind, however, that a C:N ratio of 25 implies, as far as the model is concerned, that the residues are chopped and mixed to give an average C:N ratio. In fact, because the most resistant part of the residues (stems) usually contains least nitrogen, not chopping and not mixing nitrogen deficient sprout residues may make leaching worse than predicted here because the nitrogen from the easily decomposable fractions is lost before organisms feeding on the nitrogen-deficient, but recalcitrant, fractions have a demand for it. Even where the residues are chopped finely and mixed well, the N-rich parts probably decompose first. This can be seen in Figure 3 where the model underestimated the mineralization of nitrogen from the sprout residues. It is likely that the N-rich parts decomposed completely but even within the relatively long time-scale of this experiment, undecomposed fibre and other N deficient parts remained.

Crops such as spinach and leeks that use nitrogen inefficiently do so, at least in part, because their roots do not penetrate the subsoil, exploiting surface but not subsoil N. Leaching from these two crops may be even worse than estimated in Figure 4 if the model calculations have assumed wrongly that the mineral nitrogen at harvest was higher-up in the soil profile than it actually was. In practice, more nitrogen in the subsoil would lead to earlier and more leaching. Furthermore a good deal of nitrogen may leach during the growing season from crops with shallow roots or those that receive much irrigation.

During the last 40 years and on a soil with the properties of the sand soil in Table 1, the mean drainage of water from soil between September and May was 380 mm with a standard deviation of 88 mm; this assumes that the soils were close to field capacity at harvest which is not unreasonable given the amount of irrigation applied to many vegetable crops. With this amount of percolation no more than 40 kg N ha^{-1} may safely leach before exceeding the EC limit of a concentration of 11.3 mg N l^{-1}. It was based on calculations like this, and with a correction for denitrification and N mineralizing from native organic matter in the soil, that Goossensen & Meeuwissen (1990) recommended that no more than 70 kg N ha^{-1} should remain in soil in the autumn. Since denitrification can also be damaging to the environment, they also suggested an even lower limit of 45 kg N ha^{-1}. A mean value of through-drainage of 380 mm implies that in many years even this lower limit of 45 kg nitrogen ha^{-1} will result in water leaching from under field vegetables exceeding the 11.3 mg l^{-1} limit. During the last 40 years the mean nitrate concentration in the water draining from under the cabbage crop discussed above was 32 mg N l^{-1} with a standard deviation of 5 mg N l^{-1} and a range of 22–44 mg N l^{-1}. For reference, 568 mm of excess rainfall percolated through the soil in the winter 1993–94 on which Figure 4 is based; this value was reached or exceeded during only three of the last 40 winters. The water draining to ground from under the cabbage residues during 1993-4 contained on average 23 mg N l^{-1}.

Against a legal limit of 11.3 mg nitrogen l^{-1} these are far from trivial amounts and measures to reduce them even fractionally could have an enormous benefit. Because mineral N left in soil at harvest has most effect on leaching, reducing this will most effectively reduce losses of N. Mineral N in soil might be reduced by supplying fertilizer in small doses as and when shallow rooting crops such as leeks require it or by sowing a cover or second crop as soon as possible after spring and summer vegetables. Where possible, deep rooting crops could be scheduled late in the growing season. Applying large quantities of N-deficient crop residues may reduce leaching of N to some extent. Computer models can help quantify the benefit of these measures.

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