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Modelling the turnover of ^{15}N-labelled fertilizer and cover crop in soil and its recovery by maize

A. HADAS[a], T. A. DOANE[a], A. W. KRAMER[b], C. VAN KESSEL[b] & W. R. HORWATH[a]
[a]*Department of Land, Air and Water Resources and* [b]*Department of Agronomy and Range Science, University of California, Davis, CA 95616, USA*

Summary

The rate at which available nitrogen (N) is released from organic materials in soil is often measured by applying ^{15}N and following its recovery by the growing crop. However, the turnover of labelled N in soil modifies the ratio of labelled to unlabelled available N and thereby affects the uptake of ^{15}N by plants. The recovery of labelled N by maize was measured in a field experiment under three management systems, with one ^{15}N-labelled input in each: (1) conventional, with fertilizer side dressing, (2) low input, with vetch as a cover crop and fertilizer side dressing, and (3) organic, with vetch and composted manure. The NCSOIL model, which simulates C and N turnover in soil, was modified to include relevant processes related to the maize crop, and used to estimate the decomposition rate constant of vetch in the field by optimizing the simulated dynamics of labelled N uptake by maize against the measured results. A large input of C from mineralizable soil organic matter and root deposition was necessary to account for the recovery of fertilizer N by maize. Optimization of labelled N recovery in the low input system resulted in two optional rate constants for the decomposition of vetch: rapid decomposition (0.4 day^{-1}) of a labile vetch pool (49% of total vetch N), or slow decomposition (0.008 day^{-1}) of a single vetch pool. In the simulated organic system, where manure and vetch were incorporated at the same time, only a rapid decomposition of the labile component of vetch accounted well for the recovery of vetch N by maize. The prolonged recycling of N mineralized from the vetch, and its mixing with fertilizer side dressing in the low input system, reduced the recovery of vetch N even though it was mineralized rapidly. This demonstrates the difficulty in assessing the availability of N from organic materials.

Introduction

Continuous arable cropping depends in many situations on maintaining a sufficient quantity of organic matter in soil. It may be achieved by growing cover crops to be incorporated as green manure, by returning crop residues to the soil, and by adding animal manure and industrial by-products. All these materials contain nitrogen (N), which is made available to plants by microbial decomposition, but they also enhance the turnover of carbon (C) and N and the recycling of inorganic N in soil. Predicting how much N is likely to be released by these processes is important, so that we can estimate how much fertilizer to apply for a crop in addition to the organic materials.

The release of N from organic materials should be synchronized with the demands of crops. To do that we must understand the factors that affect the rates of decomposition of these materials and the fate of N after its release. Incubation experiments with soil have shown a wide range of decomposition rates, mostly calculated from the net mineralization of C or N. Usually there is an initial rapid mineralization, after which mineralization becomes much slower (Azam *et al.*, 1993; Ajwa & Tabatabai, 1994; Nicolardot *et al.*, 1995; Quemada & Cabrera, 1995). Rates vary with the composition of the organic residues, the experimental conditions, and the nature of the soil. In field experiments, the amount of N from leguminous residues or cover crops available to the subsequent crops ranges between 20 and 60% of initial N content (Hesterman *et al.*, 1987; Mahler & Hemamda, 1993; Jensen, 1994b). It varies with the time between the incorporation of the residue and planting, and with amounts of fertilizer added to the crop. Estimates of it also depend on the technique used to assess the availability of the N. A rapid initial decomposition of cover crops, or release of N to soil microbial biomass, has also been observed in the field, although the release does not always correlate with crop uptake (Bremer & van Kessel, 1992; Jensen, 1994a; Hu *et al.*, 1997).

The recovery of ^{15}N from residues or fertilizers by plants, or as inorganic labelled N in soil, often underestimates the

Correspondence: Aviva Hadas, Institute of Soil, Water and Environmental Sciences, A.R.O., The Volcani Center, Bet Dagan 50250, Israel. E-mail: ahadas@agri.gov.il
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availability of the labelled N; the difference method (comparison of no N added to added N) always records more (Azam *et al.*, 1993; Kramer *et al.*, 2002). The discrepancy results from the recycling of inorganic N, during which labelled N added to the soil partly substitutes for unlabelled N in the soil, so that more unlabelled inorganic N remains in the soil, although rates of N transformation have not changed. Jenkinson *et al.* (1985) called this phenomenon the 'apparent added N interaction', which they distinguished from real 'added N interaction', when the addition of N does change the rates of N transformation. Processes that remove inorganic N independently of its content in the soil, such as immobilization, denitrification, and uptake by plants (if it is not limited by lack of available N), cause an apparent interaction. Computer models that simulate the turnover of C, N and ^{15}N in soil, such as NCSOIL (Molina *et al.*, 1983, 1990; Hadas & Molina, 1993), account for both real and apparent added N interaction.

The dynamics of ^{15}N recovery by a crop is the outcome of the daily uptake of labelled and unlabelled N, which depends on the $^{15}N/^{14}N$ ratio in the available N in soil during crop growth. The amount of available N from different sources in soil is controlled largely by microbial decomposition of organic materials and the recycling of inorganic N. These processes, which often interact, are difficult to measure, but they can be simulated by NCSOIL in a way that accounts for their interactions and overlap. In the field the amount of inorganic N in the root zone is depleted by the growing crop through uptake and enhanced immobilization by carbon deposited from the roots (Whipps, 1990; Qian *et al.*, 1997), and by leaching. These processes can be added as simple functions to NCSOIL, which can then be used to simulate the turnover of labelled N in soil and uptake by plants in a field. This keeps the interpretation of the recovery of labelled N by the growing crop focused on the microbial transformation and recycling of N in soil.

Using computer simulation of a field experiment, in which the recovery of ^{15}N-labelled fertilizer or vetch by maize was measured during the growing season, we aimed (i) to quantify the turnover of labelled N and the ^{15}N enrichment of soil inorganic N, and (ii) to estimate the rate of decomposition of vetch and manure, and so understand better the effect of soil processes on the availability of added N to the crop.

Materials and methods

Field experiment

The experiment was done in the SAFS (Sustainable Agricultural Farming System) plots, at the University of California at Davis. Clark *et al.* (1998) and Kramer *et al.* (2002) described the site and its characteristics. Briefly, the plots, established in 1988, have been continuously under organic (ORG), low input (LI) or conventional (CONV) management. In the LI and ORG plots a cover crop of vetch (*Vicia* sp.) is typically grown in the winter, preceding each summer cash crop in a 4-year crop rotation (tomato, safflower, maize, beans). The N treatments consist of fertilizer alone in CONV, cover crop and a moderate amount of fertilizer in LI, and cover crop and composted poultry manure in ORG, on which synthetic chemicals are prohibited.

Microplots of 4 m^2 were demarcated within each of four replicates of the SAFS plots (1224 m^2 each) where maize was to be grown. Within the microplots one of the sources of N applied to the different farming systems was labelled with ^{15}N: the fertilizer in the CONV system, vetch or fertilizer (two microplots) in LI, and vetch in the ORG system. The fertilizer (220 kg ha^{-1} urea N for CONV and 90 kg ha^{-1} for LI) was applied as a side dressing 36 days after planting maize on 29 and 30 April. Composted turkey manure was incorporated in the ORG system 4 days prior to planting. The rate of manure application was 14.5 t ha^{-1}, containing 3280 kg organic C and 340 kg N; 80 kg of the total N was extractable as NH_4^+-N and 890 kg of the organic C was extractable in hot water (80°C for 1 hour). The vetch (labelled and unlabelled) was incorporated in the LI and the ORG treatments 1 week prior to planting. Small differences in the composition of the vetch, grown separately for the different microplot treatments (^{15}N-labelled vetch was grown in 9-m^2 areas in the main plots of LI and ORG by applying ^{15}N-labelled $(NH_4)_2SO_4$), resulted in slightly different quantities of dry matter and total N applied to the different treatments, as shown in Table 1. Insoluble C and N in the vetch were determined in hot-water-extracted material. Extractable N included NO_3^--N (0.055% of dry matter, approximately 2 kg ha^{-1}). All inputs were applied at similar rates and times as in the main plots. The plots were

Table 1 Concentrations of N and C in the vetch and in the hot-water-insoluble residue, and quantities applied in the LI and ORG treatments. *V is ^{15}N-labelled vetch

Treatment	Biomass applied		Total vetch		Insoluble residue			Vetch N applied		Vetch C applied	
	Fresh	Dry	N	C	DM	N	C	Total[a]	Insol.	Total	Insol.
	/t ha^{-1}		/% DM			/% residue DM		/kg ha^{-1}			
LI - *V	18.2	3.64	3.3	39	70	2.38	39.7	120	61	1420	1010
LI - V	18.2	2.91	3.46	39	70	2.49	39.7	101	51	1135	810
ORG - *V	15.1	3.1	3.4	39.1	72	2.41	40.7	105	54	1212	908

[a]Including NO_3^--N, 2 kg ha^{-1}.

furrow-irrigated according to need, approximately 11 times during the 153 days that the maize was growing.

The management systems have accumulated different amounts of soil organic matter (SOM) over the years. Averages for the main plots in the experiment, in the top 15 cm of soil, before incorporation of vetch and manure, were 0.91, 1.08 and 1.14% organic C and 0.100, 0.116 and 0.123% total N in CONV, LI and ORG, respectively.

Plants were sampled at 10-day intervals between 40 and 90 days after planting to determine the uptake of total N and ^{15}N. Outside the microplots 1-m plant rows were harvested for measurements of dry matter production and N content of the plants. In the central area of the microplots five plants were chosen at random, and small discs were taken from the second new leaf of each plant for atom-% ^{15}N analysis by dry combustion–continuous flow isotope-ratio mass spectroscopy. Analyses of individual plants, done in July, indicated that enrichment in ^{15}N did not vary among different plant components, and therefore the second leaf reflected the atom-% ^{15}N in the whole plant. At harvest the whole central areas of the microplots were harvested for yield, dry matter, and the contents of N and ^{15}N. The proportion of total N in the maize derived from the ^{15}N-labelled inputs (%NdfI) was calculated from the enrichment of the maize:

$$\%\text{NdfI} = 100 \times (^{15}\text{N atom \% excess in maize})/(^{15}\text{N atom \% excess in labelled input}),$$

and total uptake of input-derived N was calculated from total N uptake and %NdfI.

Inorganic N in soil, before and several times during maize growth, was measured in samples of the top 30 cm, taken outside the microplots. After harvest 15–20 cores to 30 cm were sampled across the rows in the central area of each microplot, and a single core to 90 cm. Inorganic N and ^{15}N were measured in the topsoil samples and total N and ^{15}N in all samples.

Computer simulation

The computer model NCSOIL (Molina *et al.*, 1983; Hadas & Molina, 1993) simulates the turnover of C and N in soil amended with organic residues, including the flow of labelled C and N among organic and inorganic pools. The model comprises several organic pools differing in their functions and role in defining the fate of added C and N. The microbial biomass (Pool 0 and Pool I) feeds on added organic residues and on mineralizable, slightly humified organic matter (Pool II), and releases metabolites to Pool II. Each organic pool, i, is defined by its C contents, C_i, its C:N ratio, $R_i = C_i/N_i$ (where N_i is its N content), its decomposition rate constant, k_i, and its microbial use efficiency (the fraction of decomposed C that is incorporated into the microbial biomass). It decomposes following first-order kinetics:

$$-(\mathrm{d}C_i/\mathrm{d}t) = k_i C_i. \tag{1}$$

The gross N mineralization is given by

$$-(\mathrm{d}N_i/\mathrm{d}t) = k_i N_i = -(1/R_i)(\mathrm{d}C_i/\mathrm{d}t). \tag{2}$$

The last expression shows the dependence of N mineralization on the rate of decomposition of C and on the C:N ratio, and we present it this way to maintain the spirit of NCSOIL. The rate of gross N immobilization is the rate of incorporation of C into the microbial biomass divided by the C:N ratio of the biomass. The model can be used to derive unknown properties of soil pools or organic inputs, such as potentially mineralizable N (PMN) in soils or rates of decomposition of residues, by optimizing simulated values against measured dynamic data (Barak *et al.*, 1990; Hadas *et al.*, 1993, 1998; Hadas & Portnoy, 1994).

To use NCSOIL for quantifying the processes in soil that control the dynamics of labelled N uptake by a crop, we made the following assumptions and modifications in the model.

1 Nitrogen in the plant is an integrative measure of available N in the root zone; the amounts of labelled and unlabelled N taken up by the plant each day result from their relative contents in the pool of inorganic N in the soil.

2 Labelled (input) N unaccounted for, measured at harvest, results from loss of N by leaching and denitrification.

3 Temperature and moisture were similar in all systems; during maize growth (May–August) average temperatures and moisture were near optimal. Decomposition rate constants of soil organic pools were therefore set at the usual values (Molina *et al.*, 1983, 1990).

4 Units of pool concentrations were kg ha^{-1}, the same as the major inputs applied to the field or the measured uptake of N by the plants. Conversion from mg kg^{-1} to kg ha^{-1} was done by using a bulk density of 1.2 g cm^{-3}. Concentrations of inorganic N in the top 30 cm, before N was added to soil, represented the initial available N in the root zone; most of it was in the top 15 cm.

5 Uptake and leaching of N were added to NCSOIL as simple processes that withdraw inorganic N, each to its own pool.

6 Leaching was activated on each day of irrigation, simulating a 'leaching fraction', which was a predetermined fraction of the NO_3^- in the soil. The amount of labelled N leached was proportional to its content in the pool of NO_3^-. The fraction leached was adjusted to give cumulative leaching of N that fitted the loss of N observed experimentally. We set the leaching fraction to 0.1 in this study.

7 Denitrification was activated on the day after irrigation, on the assumption that the moisture content of the soil exceeded that at field capacity and that oxygen in the irrigation water had been depleted. The rate of denitrification is proportional to the available C or the respiration rate.

8 The N uptake function was obtained from measurements, six times during the growing period at 10-day intervals. We had to assume that the uptake rate between measured points was linear. Daily uptake was limited by the amount of available N in the soil, but at the end of each 10-day interval the calculated cumulative uptake was verified against the measured uptake by the plants. Uptake withdrew NO_3^- and NH_4^+ proportionally to their amounts in the pool of available N, and labelled N withdrawn was proportional to its content in each of the two inorganic forms of N.

9 Cumulative deposition of C by roots was estimated as a fraction of the aboveground dry matter. This fraction was adopted from Qian *et al.* (1997) according to the morphological stages of the maize. Assuming shoot C to be 42% of dry matter, we estimated the deposition of C by the roots as 24% of aboveground C up to 40 days after planting, and thereafter 19%, 15%, 11%, 10% and 9% for 50, 60, 70, 80 and 90 days after planting, respectively. The daily rate of deposition of C was constant between sampling dates, and equalled 1/10 of the cumulative quantities of C deposited within each 10-day interval (as with N uptake). Root deposition created a labile residue pool of C that decomposed at a rate of 0.1 day^{-1}, in the range obtained by Bottner *et al.* (1999).

We used the measured %NdfI and the uptake of N from the labelled input for the best fit of simulated to measured data as a function of time, while we optimized unknown parameters related to the rate of N release from organic sources. The quantities of PMN and C in the soil (Pool II) were optimized in the CONV system, where PMN was the only source of N that diluted the ^{15}N-labelled fertilizer N. In the LI and ORG systems two N inputs were applied, of which one was labelled with ^{15}N. We assumed that PMN, the second unlabelled N source, was proportional to total N in the top 15 cm soil layer, and used the proportion found for the CONV system also in the LI and ORG systems. Decomposition rate constants of vetch, including labile (hot-water-extractable) and recalcitrant components, were optimized simultaneously for the two LI treatments, where either vetch N or fertilizer N was labelled. The decomposition rate constant of manure was optimized in the ORG system, where the rate parameters of vetch (labelled) and PMN were already known.

The best fit of simulated values to measured data is defined as the minimum weighted sum of squares of residuals, represented by a χ^2 value:

$$\chi^2 = \frac{1}{D}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{n=1}^{N}\left[\{Y_{jmn} - Y_{jmn}(A)\}/S_j\right]^2, \qquad (3)$$

where J is the number of measured variables used for the optimization, M is the number of sampling times, and N is the number of the experimental treatments. The quantities Y_{jmn} are measured values, $Y_{jmn}(A)$ are the corresponding simulated values with the set of NCSOIL parameters A, S_j is the standard deviation of the measured Y_j, and D is the number of degrees of freedom, given by $D = JMN - a(A)$, where $a(A)$ is the number of optimized parameters in A. In our study $J = 1$ (either %NdfI or uptake of input-derived N), $M = 7$ (six sampling times plus time zero), $N = 1$ (in CONV and in ORG) or $N = 2$ (in LI), and $a(A) = 1$.

The simulation period was 100 days, beginning when vetch was incorporated in soil, 6–7 days before planting of maize. Timing of irrigation (seven times during the simulated period), fertilizer application and plant samplings were as done in the field. Inorganic N content in the top 30 cm, determined outside the ^{15}N microplots during the simulation period, and loss of labelled N at harvest, served as additional checkpoints to verify the simulation results.

Results and discussion

Measured plant data

The largest production of dry matter and uptake of N by maize were measured in the CONV system (Table 2). From 90 days to harvest, 153 days after planting, loss of plant material was observed in CONV and a small loss of N in LI. Labelled N contents of the plants differed greatly with treatment and time, depending on the time that labelled N was applied and on the availability of N from each source. The fertilizer was applied only 3–6 days before the first sampling date, therefore up to this date the maize took up most of its N from other available sources. The N in the vetch, which was incorporated 42 days earlier, was partly available during the early part of the growing season. Between 40 and 50 days after planting the fertilizer was the major source of available N; it increased significantly its proportion in the plants and diluted the labelled N in plants derived from vetch.

The availability of N from soil organic matter and added organic materials and the isotopic dilution of inorganic N in soil, which controlled the recovery of labelled N by the maize, were determined by the simulation.

Net mineralization of soil N (finding PMN)

The mineralization of organic matter that diluted the ^{15}N-labelled fertilizer N in the CONV system is a function of Pool II in NCSOIL. The N content of Pool II (PMN) and its C:N ratio were determined by optimizing the simulated uptake of labelled fertilizer N in plants against measured results in the CONV treatment. Inorganic N measured in the top 30 cm before planting, and starter fertilizer (7 kg N ha^{-1}) applied at planting, were also unlabelled.

The rapid increase of N derived from fertilizer in plants between 40 and 50 days after planting, and its continuous dilution thereafter (Table 2), indicated that the amount of unlabelled available N in soil was fairly small when the fertilizer was applied, and that labelled fertilizer N was recycled rapidly thereafter. To account for this dynamics of isotopic dilution, a large C:N ratio of Pool II was obtained by the optimization, which could not be justified without supporting

Table 2 Dry matter production and total N uptake by plants, measured in the main SAFS plots, and N derived from ^{15}N-labelled input (%NdfI) measured in the ^{15}N microplot treatments. V* is labelled vetch and F* is labelled fertilizer

	Treatments			
Days after planting[a]	CONV	LI - V* + F	LI - V + F*	ORG
	Aboveground dry matter /kg ha^{-1}			
40	201	150	150	242
50	1316	869	869	1059
60	3952	2740	2740	3455
70	9756	6067	6067	5828
80	11920	10161	10161	9662
90	14334	12274	12274	10973
153	13189	12561	12561	13854
	N uptake /kg ha^{-1}			
40	9	7	7	11
50	42	28	28	36
60	108	67	67	86
70	208	116	116	103
80	242	135	135	144
90	251	179	179	147
153[b]	206	161	130	188
	^{15}N-labelled-input-derived N /% of plant N (SE)			
40	18 (3.1)	26.6 (1.3)	5.4 (0.9)	18.9 (0.8)
50	69 (6.5)	16.5 (1.0)	33.2 (1.6)	17.8 (0.5)
60	64 (4.4)	11.3 (0.8)	32.4 (4.6)	14.2 (0.4)
70	59 (5.3)	11.8 (1.1)	29.7 (2.9)	14.0 (0.1)
80	57 (3.4)	11.8 (0.4)	27.1 (4.7)	13.8 (0.8)
90	53 (3.9)	12.5 (0.7)	26.2 (3.9)	11.9 (0.2)
153	43 (1.2)	14.2 (1.3)	20.3 (2.4)	10.5 (0.3)

[a]CONV and ORG were sampled at 39, 49, ..., etc. days after planting, LI at 41, 51, ..., etc. days.
[b]N uptake at harvest (153 days after planting) was measured in the microplots.

data on the mineralization of C. An upper limit of the C:N ratio of Pool II was therefore set at 25, within a range that has been reported when mineralization of both C and N were measured (Houot *et al.*, 1989; Hadas *et al.*, 1993). The size of Pool II was optimized with a C:N ratio of 25 and also with a C:N ratio of 10, the most commonly accepted value for soil organic matter. With the C:N ratio of 25 the optimized PMN values were slightly larger, and the simulated results fitted better (smaller χ^2) the measured fertilizer-derived N in plants (Table 3). The PMN values obtained by optimizing against %NdfI (%N in maize derived from fertilizer) were smaller than those obtained by fitting to fertilizer N uptake. The model overestimated the %NdfI in plants from 70 to 90 days after planting in an effort to minimize deviations from 40 to 50 days, when the plants were very small but the %NdfI was large (Figure 1). The relative weight of the early stage data was

Table 3 Potentially mineralizable N (PMN) in the CONV system, obtained by best fit of measured data to simulated dynamics of fertilizer N uptake or %N in maize derived from fertilizer (%NdfI), for two possible C:N ratios of Pool II (mineralizable SOM), and the consequent simulated net N mineralization, total N and fertilizer-derived N lost by leaching and denitrification, and labelled fertilizer N in soil after 100 days of simulation (beginning 6 days before planting)

	Fitting to fertilizer N uptake		Fitting to %NdfI	
	C:N ratio of Pool II			
Simulated variable	10	25	10	25
Optimized PMN /kg ha^{-1}	375	392	300	329
χ^2	0.0054	0.0039	0.0645	0.0493
Net N mineralization /kg ha^{-1}	141	134	108	110
N leached /kg ha^{-1}	78.4	61.2	67.3	55.6
N denitrified /kg ha^{-1}	18.9	42.6	15.9	36.3
Fertilizer N lost[a] /kg ha^{-1}	43.5	43.4	40.4	41.4
Fertilizer N in soil /kg ha^{-1}	36.4	37	30	31.9

[a]Loss of labelled N by leaching and denitrification.

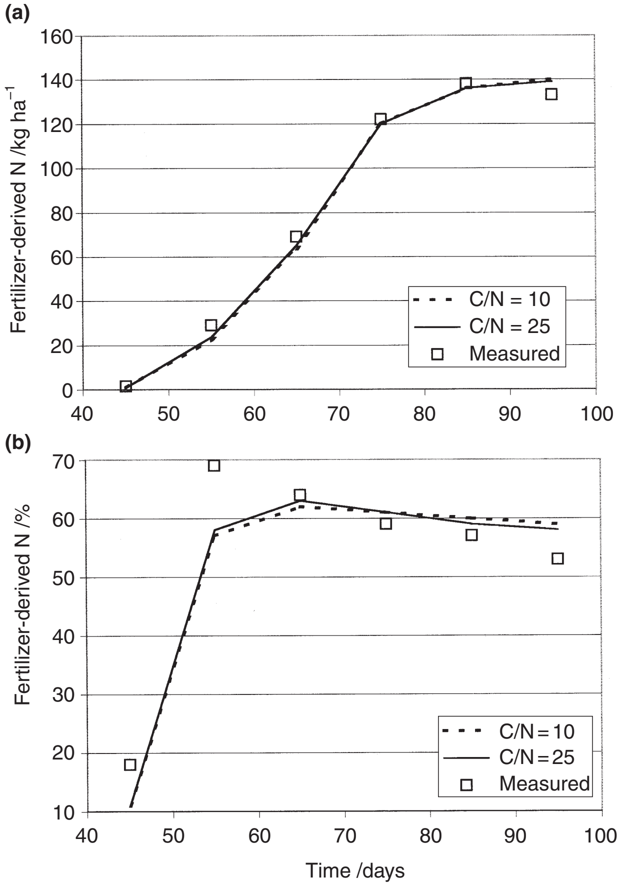

Figure 1 Fertilizer N uptake by maize (a) and per cent of maize N derived from fertilizer (%NdfI) (b) in the CONV system, measured and optimized with two C:N ratios of Pool II. The simulation began 6 days before planting; the fertilizer was applied on day 42.

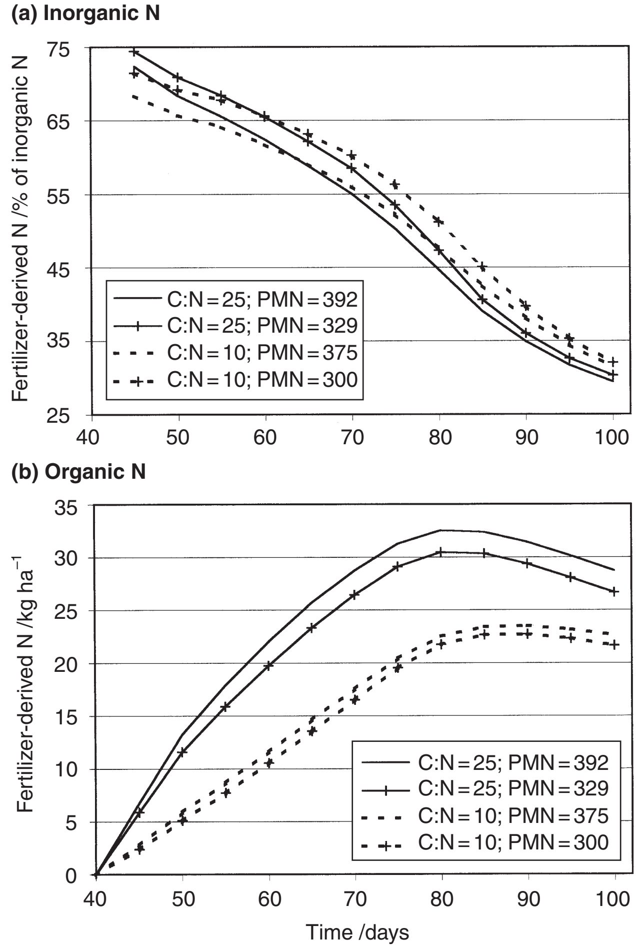

Figure 2 Fertilizer-derived N in soil inorganic N (a) and immobilized in soil organic matter (b) in the CONV system, simulated with two C:N ratios for Pool II and the corresponding optimized PMN. The simulation began 6 days before planting; the fertilizer was applied on day 42.

diminished when the uptake of fertilizer N was used to optimize the model, because the total uptake of N was small. As a result, the fertilizer uptake curve fitted the measured curve much better than did the %NdfI.

The dynamics of dilution of labelled N in the pool of inorganic N, that was available for the crop, depended on PMN and the C:N ratio of Pool II (Figure 2a). A C:N ratio of 25 caused less net mineralization of unlabelled soil N at the early stages and enhanced immobilization of labelled N. This increased the change in ^{15}N enrichment of inorganic N over time more than when the C:N ratio of Pool II was 10. Optimization against %NdfI in plants necessitated a larger enrichment of inorganic N at early growth stages, which resulted in smaller optimized PMN contents in soil; consequently the turnover of labelled inorganic N into SOM was also slower (Figure 2b).

Optimized PMN values ranged between 300 and 392 kg ha^{-1} (Table 3), which is approximately 9–12% of total N in the top 30 cm of soil, when C and N concentrations in the 15–30 cm layer are 85% of those in the 0–15 cm layer (Kramer *et al.*, 2002). Net N mineralization during 100 days of simulation ranged between 108 and 141 kg ha^{-1}, approximately half the amount of fertilizer N applied in the CONV system, while 10–14% of fertilizer N, 22–32 kg ha^{-1}, was immobilized and not available to plants during the period of rapid growth and uptake (Figure 2b).

The large C:N ratio of Pool II implies a large input of C to enhance the turnover of ^{15}N-labelled fertilizer N into organic matter. Root deposition released 540 kg ha^{-1} C to the soil during maize growth, with a maximum rate of 20 kg ha^{-1} day^{-1} between 60 and 70 days after planting. These rates, estimated from the literature and from the aboveground dry matter production of maize, might have been larger; yet, when we doubled the rates of deposition of C from roots, the need for a large C:N ratio of Pool II did not change.

The dynamics of simulated inorganic N are shown in Figure 3, along with values measured to a depth of 30 cm in the field outside the microplots. Before the application of the fertilizer (on day 42 of the simulation) and at the end of the N uptake period, simulated data were closer to measured values when we used a C:N ratio of 25 for Pool II. Inorganic N in soil was not measured between days 40 and 67 (34 and 61 days after planting), when fertilization, leaching and uptake by plants caused large changes in the contents of inorganic N in the soil.

Total N in soil (organic and inorganic) derived from fertilizer after 100 days of simulation ranged between 30 and 37 kg ha^{-1} (Table 3), whereas the amount measured at harvest (60 days later) was 51 kg ha^{-1}, of which 33 kg ha^{-1} were in the top 15 cm layer and 18 kg ha^{-1} from 15 to 90 cm. The larger amount found experimentally could be attributed to the loss of 45 kg ha^{-1} plant N between 90 days after planting and harvest (Table 2), part of which may have returned to the soil.

Total simulated loss of fertilizer N by leaching and denitrification was 40–44 kg ha^{-1} after 100 days (Table 3), whereas unrecovered N from the fertilizer, measured at harvest, was 81 kg ha^{-1}. Four additional irrigation events between the end of the simulation and the harvest, and some loss of plant N, may account for this difference. Simulated leaching and denitrification were oppositely affected by the C:N ratio of Pool II, thereby compensating for each other. Loss of N via denitrification was 7–19% of fertilizer N, a range often observed in irrigated fertilized fields (Hauck, 1981; Aulakh *et al.*, 1992).

Rate of decomposition of vetch in the LI system

Decomposition rate constants of vetch were obtained by simultaneously optimizing the two LI treatments, where either vetch N or fertilizer N was ^{15}N labelled. The properties of Pool II were those that fitted best the labelled N uptake by maize in the CONV system: the C:N ratio was 25 and the PMN was corrected for LI by maintaining its proportion of total N, that was 1.16 times larger in LI than in CONV. Thus the PMN values used for LI were 455 and 382 kg ha^{-1}, 1.16 times larger than the corresponding values for CONV that fitted best the fertilizer N uptake and %NdfI, respectively.

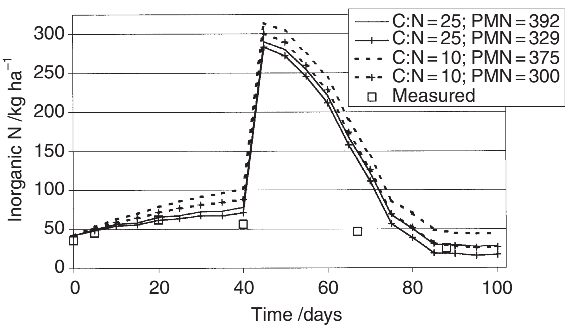

Figure 3 Inorganic N in soil in the CONV system, measured outside the microplots and simulated with two C:N ratios of Pool II and the corresponding optimized PMN. The simulation began 6 days before planting; the fertilizer was applied on day 42.

Vetch was regarded as two pools: a labile pool containing hot-water-extractable C and N, and a recalcitrant pool containing the residual non-extractable C and N. The quantities applied are shown in Table 1. Labile N was almost half of total N in the vetch, similar to values reported for vetch and lucerne (Schomberg *et al.*, 1994; Hu *et al.*, 1997). Labile C was less than 30% of total C; the C:N ratios of the labile and the recalcitrant organic components (excluding NO_3^--N) were therefore very different, averaging 6.7 and 16.4, respectively.

Inconsistent results were obtained when optimizing both labile and recalcitrant rate constants simultaneously, because of the interdependence of the two rates. Since the decomposition rate constant of the recalcitrant pool was consistently very small (mostly less than 10^{-4} day^{-1}, or less than 1% decomposed in 100 days), a rate of 10^{-5} day^{-1} was assigned to this pool, and only the rate constant of the labile pool (k_l) was optimized. In most cases a k_l of 0.4 day^{-1} fitted best the measured data of both the uptake of ^{15}N-labelled vetch and fertilizer and the %NdfI in the maize (Table 4). We also obtained much smaller k_l values, 0.017–0.019 day^{-1}, but only when optimizing against the uptake of labelled N, and only incidentally, when searching within a narrow range of initial values for k_l. The decomposition rate constant of vetch was also optimized as a single residue pool, comprising total C and N. This optimized constant (k_v) ranged between 0.0055 and 0.0082 day^{-1}, equivalent to approximately half of the vetch decomposing in 100 days, similar to the amount of labile N released from vetch with a large k_l. However, the latter released N from vetch much faster and with considerably less C (smaller C:N ratio of the labile pool), which increased the availability of vetch N during the early growth period, as observed in %NdfI in the first sampling of maize (Figure 4c,d). The uptake of vetch N was better simulated with the slow

Table 4 Optimized decomposition rate constants of the labile vetch pool (k_l) when a rate of 10^{-5} day^{-1} was assigned to the recalcitrant pool, and of a single vetch pool (k_v), obtained by best fit of simulated dynamics of ^{15}N-labelled vetch and fertilizer N uptake or %N in maize derived from the labelled input (%NdfI) to measured data in two treatments in the LI system, for two PMN contents in soil

	Fitting to labelled N uptake		Fitting to %NdfI	
	PMN /kg ha^{-1}			
Optimized parameters	455	382	455	382
k_l /day^{-1}	0.40	0.45	0.155	0.42
χ^2	0.0058	0.029	0.051	0.076
k_v /day^{-1}	0.0055		0.0082	0.0075
χ^2	0.0040		0.123	0.151

rate of decomposition (Table 4, Figure 4a), with the exception of the first two sampling dates, which had little influence on the entire curve, because total uptake of N was still very small compared with its uptake later. The simulated uptake of labelled fertilizer N was rather insensitive to the rate of decomposition of vetch (Figure 4b,d). It was more affected by PMN, particularly during the continuous dilution of labelled fertilizer N in the maize after 60 days from planting, because much more unlabelled N was mineralized from the soil organic matter than was released from the vetch. A PMN value of 455 kg ha^{-1} fitted the measured results better than 382 kg ha^{-1}. With the smaller PMN not enough N was available for the maize when optimizing k_v against labelled N uptake.

Figure 5(a) shows how the rates of decomposition of vetch affected the simulated dynamics of ^{15}N enrichment of inorganic N in the soil for the LI treatment with labelled vetch and unlabelled fertilizer, and thereby explains the uptake of N originating from the vetch. Before the fertilizer was applied (on simulation day 42), the maize withdrew N from a much more enriched inorganic N pool when the decomposition of vetch was rapid, as was observed in the %NdfI in the first

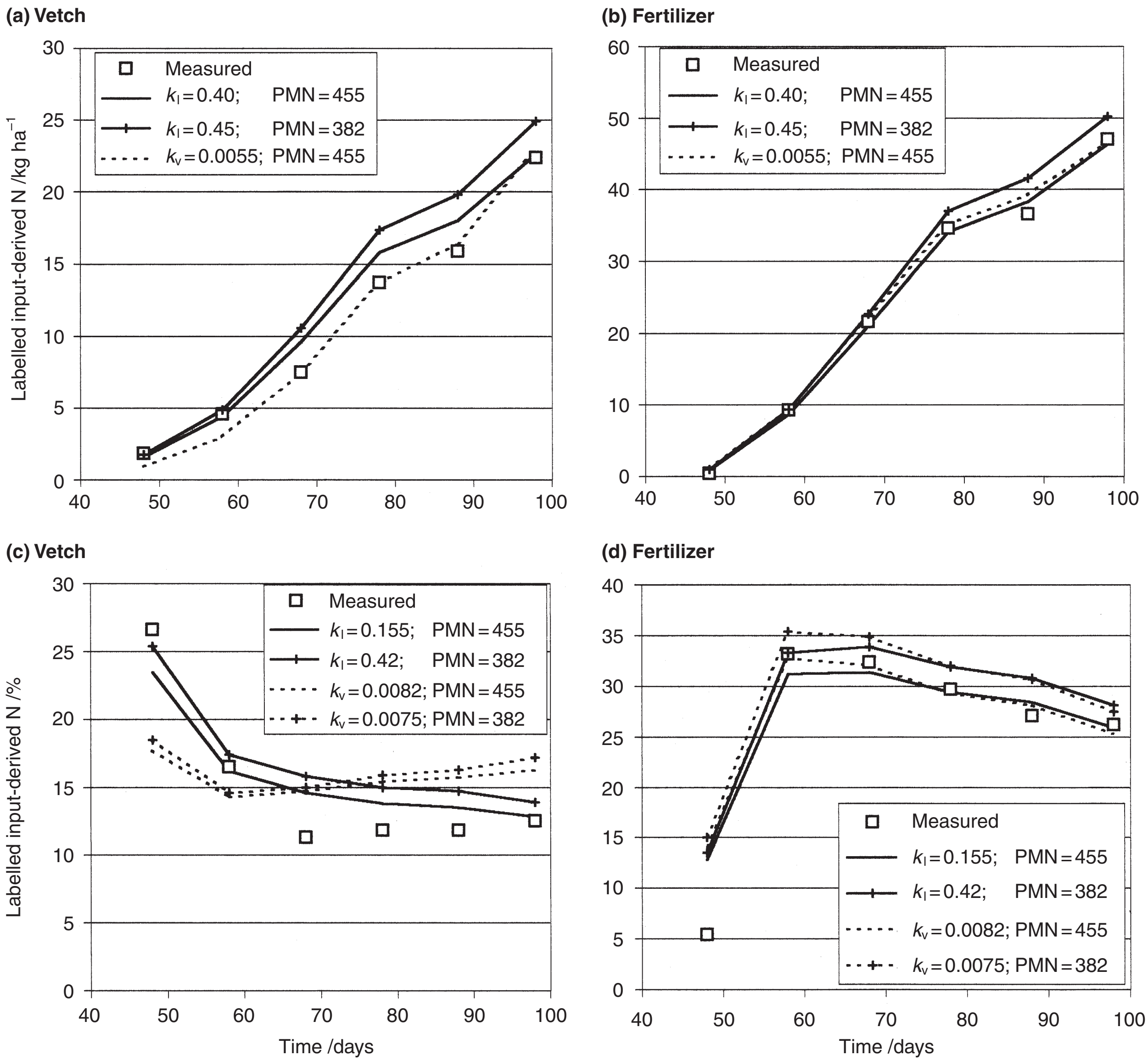

Figure 4 Uptake of N from ^{15}N-labelled vetch (a) and fertilizer (b), and per cent of maize N derived from labelled vetch (c) and fertilizer (d) in LI treatments, where either vetch or fertilizer was labelled, measured and simulated with two PMN contents in soil, and using either of two options for the vetch pools: (1) two pools with an optimized decomposition rate constant for the labile pool k_l, or (2) a single vetch pool with an optimized decomposition rate constant k_v. The simulation began when vetch was incorporated in the soil, 7 days before planting; the fertilizer was applied on day 42.

sampling of maize. Afterwards, the fertilizer diluted the labelled inorganic N and diminished the difference between the enrichments of available N in soil that were predicted by the slow and by the rapid decomposition of vetch. The rapid decomposition of the labile pool of vetch was associated with rapid immobilization of over 20 kg N ha^{-1} that was mineralized from the vetch (Figure 5b), approximately one-third of the labile pool. The fertilizer enhanced the re-mineralization of immobilized N derived from the vetch, demonstrating the apparent added N interaction (Jenkinson *et al.*, 1985), whereby fertilizer N substituted partly for vetch N in the immobilization process. By the end of the growth period, 10–15% of total vetch N had been incorporated into the soil organic matter, independent of the rate of decomposition. The long time between the incorporation of vetch and the period of plant growth, when most of the sampling was done, and the addition of fertilizer prior to that period makes it difficult to determine which of the rates of decomposition of vetch most accurately represents the process.

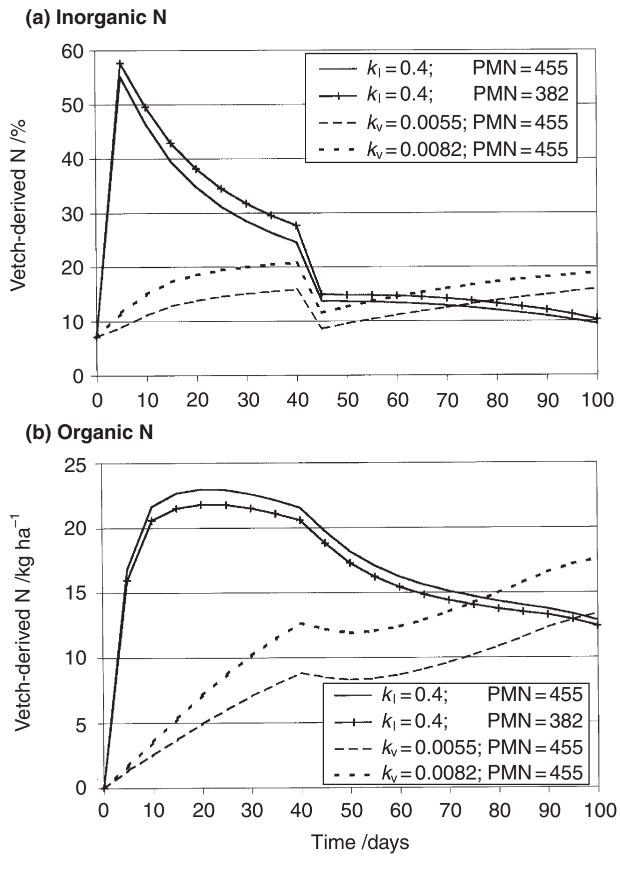

Figure 5 Vetch-derived N in soil inorganic N (a) and immobilized in soil organic matter (b) in the LI treatment with ^{15}N-labelled vetch, simulated with two PMN contents in soil and with different optimized decomposition rate constants of vetch: k_l – of the labile pool, and k_v – of a single vetch pool. The simulation began when vetch was incorporated in the soil, 7 days before planting; the fertilizer was applied on day 42.

Inorganic N in soil that was simulated with the large rate of decomposition of vetch was clearly larger than measured in the main LI plots during the early period before fertilization (Figure 6). Measurements limited to the top 30 cm might have underestimated the available N in the root zone, especially if a large amount was released and moved below 30 cm. Inorganic N measured 25 days after fertilization was certainly too small to account for the uptake of N between 60 and 90 days after planting.

Mass balance of labelled N, measured at harvest in the LI system with ^{15}N-labelled vetch, showed that 39 kg ha^{-1} was lost, and 58 kg ha^{-1} remained in the soil, of which more than 90% was in the top 15 cm. The simulated losses of labelled N from the vetch by leaching and denitrification after 100 simulation days (60 days before harvest) ranged between 13 and 20 kg ha^{-1}, while 75–86 kg ha^{-1} remained in soil. The rapid decomposition of vetch predicted the larger loss and the smaller residual amounts of vetch N in those ranges, which were closer to the measured values. The gradual release of vetch N from soil organic matter and the additional four irrigations in the extra 60 days until harvest would probably reduce the difference between measured and simulated loss of labelled vetch N, as well as that remaining in soil.

Several studies have shown rapid decomposition of legumes, and other cover crops with low C:N ratios, shortly after incorporation. Mass loss of vetch with oats or lucerne was more than 60% in 30 days in the field (Schomberg *et al.*, 1994; Hu *et al.*, 1997). In incubation experiments cover crops released 25–30% of their N contents in 35 days (Nicolardot *et al.*, 1995; Hu *et al.*, 1997). Nicolardot *et al.* (1995) showed that the mineralization of C and N in several catch crops exhibited a two-phase curve. Net mineralization rates of the labile fraction of N, representing one-third of the N in a catch crop, ranged between 0.06 and 0.12 day^{-1}. Gross mineralization of N would

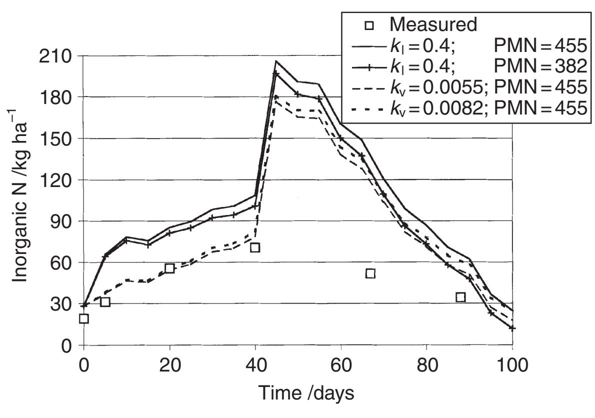

Figure 6 Inorganic N in soil in the LI system, measured outside the microplots and simulated with two PMN contents in soil and with different optimized decomposition rate constants of vetch: k_l – of the labile pool, and k_v – of a single vetch pool. The simulation began when vetch was incorporated in the soil, 7 days before planting; the fertilizer was applied on day 42.

be larger, accounting for immobilized N, which in our case was 30% of the labile N (Figure 5b). In view of these findings it seems best to assume two vetch pools, with one, the labile pool, decomposing rapidly. It corresponded well to the observed %NdfI in maize and predicted the loss and residual vetch N in soil at the end of the growth period better than the slow decomposition. Yet uncertainty remained as to whether the decomposition of vetch was rapid or slow, because the amount of inorganic N in soil was better predicted during the time between incorporation of vetch and fertilizer application when we assumed slow decomposition (Figure 6). Furthermore, the isotopic dilution of inorganic N released rapidly from the labelled vetch was substantial, and enhanced by the late application of fertilizer shortly before the uptake by maize became significant. In the ORG system, where no fertilizer was applied, this effect was avoided.

Rates of decomposition of vetch and manure in the ORG system

Manure, containing 80 kg ha^{-1} readily available NH_4^+-N, was incorporated in soil at approximately the same time as the vetch. The hot-water-extractable C in the manure was assumed to be labile (associated with the readily available manure N) and to decompose at the rapid rate obtained for labile vetch in the LI system. The PMN in the ORG system was set as 482 kg ha^{-1}, with the same ratio of PMN to total N in soil as in the LI and CONV systems. The decomposition rate constant of the recalcitrant, non-extractable component of manure was optimized by best fit of simulated to measured ^{15}N-labelled vetch N uptake or %NdfI in maize. Two possible rate constants obtained for vetch in LI were tested for the ORG system: $k_l = 0.4\ day^{-1}$ for the labile fraction with no decomposition of recalcitrant vetch, and $k_v = 0.0082\ day^{-1}$ for a single pool of vetch. When using the rate of $0.0055\ day^{-1}$ for the single pool, we obtained deviations between predicted uptake of labelled N and measured values that were very large.

The simulated uptake of vetch N and %NdfI (Figure 7) fitted the measured data much better when labile vetch decomposed rapidly ($\chi^2 = 0.0115$ and 0.0237, respectively) than when total vetch decomposed slowly ($\chi^2 = 0.0301$ and 0.246, respectively). The optimized rate constants for the decomposition of the recalcitrant component of manure (k_{mr}) were small: 0.0012 and $0.0005\ day^{-1}$ with the rapid decomposition of labile vetch and 0.0027 and $0.00018\ day^{-1}$ with the slow decomposition of vetch. The k_{mr} values were smaller when fitted against %NdfI in maize than when fitted against the uptake of vetch N. Measured %NdfI in maize declined consistently with time (Table 2, Figure 7b), a trend obtained in the simulation only if vetch N was mineralized rapidly, and the labelled inorganic N in soil was continuously diluted with unlabelled N from soil and manure, as shown in Figure 8(a). Continuous slow decomposition of vetch resulted in the opposite trend – an increasing enrichment of the inorganic N pool with N from vetch. Variations in the k_{mr} values had a small effect on labelled inorganic N if vetch was set to decompose slowly, and no effect at all if vetch decomposed rapidly (Figure 8a). Immobilization of labelled N mineralized from the vetch was larger when vetch decomposed rapidly (Figure 8b). Labile C from the manure, applied at the same time as vetch, enhanced microbial growth and early immobilization of vetch N in the ORG system in comparison with in the LI system (Figure 5b), where vetch was the only organic residue added to soil. Consequently, simulated loss of N by denitrification was larger and leaching of N was smaller in the ORG system.

Inorganic N in soil measured in the ORG system outside the microplots was larger throughout the growth period than in the two other systems. The simulated amounts and trends of this pool matched the measured data well (Figure 9). Available N in the soil peaked at approximately the same time as the fertilizer was applied in the CONV and LI systems, although this peak was not as large, and was reached by gradual accumulation. During the early part of the simulation, available N declined because of immobilization and denitrification. The

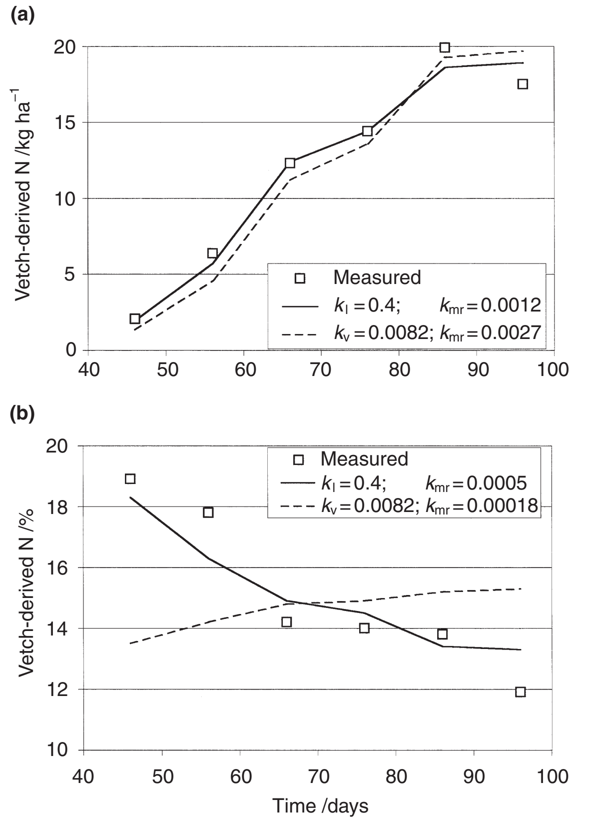

Figure 7 Uptake of ^{15}N-labelled vetch N (a) and per cent of maize N derived from vetch (b) in the ORG system, measured and simulated with two decomposition rate constants of vetch (k_l – of the labile pool, and k_v – of a single vetch pool), and the optimized rate constants of the recalcitrant component of manure, k_{mr}. The simulation began when vetch and manure were incorporated in the soil, 7 days before planting.

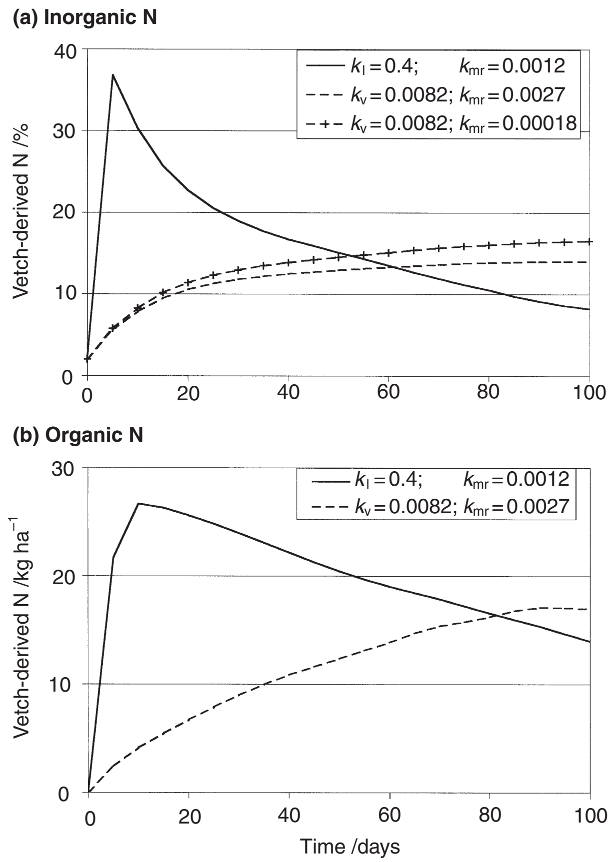

Figure 8 Vetch-derived N in soil inorganic N (a) and immobilized in soil organic matter (b) in the ORG system, simulated with two decomposition rate constants of vetch (k_l – of the labile pool, and k_v – of a single vetch pool), and optimized rate constants of the recalcitrant component of manure, k_{mr}. The simulation began when vetch and manure were incorporated in the soil, 7 days before planting.

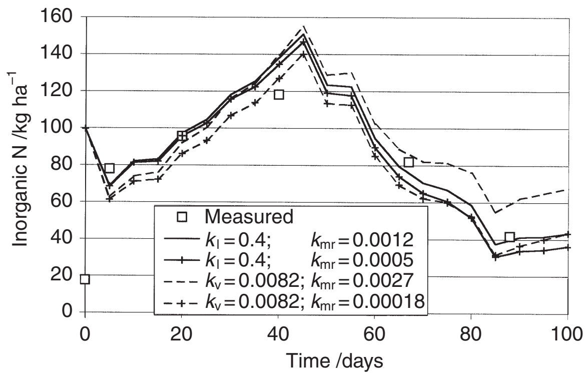

Figure 9 Inorganic N in the soil in the ORG system, measured outside the microplots and simulated for two decomposition rate constants of vetch (k_l – of the labile pool, and k_v – of a single vetch pool), and the corresponding optimized rate constants of the recalcitrant component of manure, k_{mr}. The simulation began when vetch and manure were incorporated in the soil, 7 days before planting.

best overall fit to measured data was obtained with a rapid decomposition of vetch. With the largest rate constant of recalcitrant manure, inorganic N in soil was overestimated, particularly towards the end of the maize growth.

Residual vetch N in soil was overestimated and loss of vetch N underestimated by the model, as in the LI system but to a lesser extent, and for the same reason – only half of vetch N decomposed in 100 days, whether we assumed a rapid decomposition of a labile component or a slow decomposition of the total vetch. The ORG system showed clearly that only a rapid decomposition of the labile fraction of vetch accounted well for the observed uptake of ^{15}N from the vetch.

Conclusions

By modelling the uptake of ^{15}N-labelled vetch or fertilizer N by a maize crop with NCSOIL, we could relate the recovery of labelled N by the crop to the dynamics of the isotopic dilution of available N in the soil during the growth period. This dilution depends not only on the availability of the labelled N added, but also on its recycling and mixing with other sources of N in the soil.

Intensive recycling of fertilizer N was necessary to account for its recovery by the maize in the CONV system, which implies a large input of C from mineralizable organic matter in the soil and from root deposition. The availability of N from vetch in the LI system was overshadowed by the application of fertilizer shortly before the rapid growth of the maize, 42 days after the incorporation of vetch. This management emphasized that the recycling of N mineralized from the vetch since its incorporation in soil until the uptake of N by maize was significant and had a strong effect on the recovery of vetch N by the maize. Simulation of the LI system showed that approximately half of the N in the vetch decomposed in 100 days, by either rapid decomposition of its labile component or by slow decomposition of the whole residue. However, in the ORG system, where available N from manure was applied at the same time as vetch, only rapid decomposition of the labile component of vetch could explain the observed uptake of N from the vetch by maize accurately.

Immobilization of N mineralized from vetch was larger in the ORG than in the LI system, because there was a larger input of available C from the manure. Part of the rapidly immobilized N was gradually re-mineralized and by the end of the growth period of maize 10–11% of vetch N was immobilized in LI, and 13–14% in ORG.

Simulation of available N in the ORG system also revealed that the maximal availability of N was reached at about the same time as the fertilizer was applied in the LI and CONV systems. Maximum availability of N in agricultural systems with only organic inputs may therefore be made to coincide with maximum demand by the crop, as is the principal intent of applying mineral fertilizer.

Acknowledgements

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