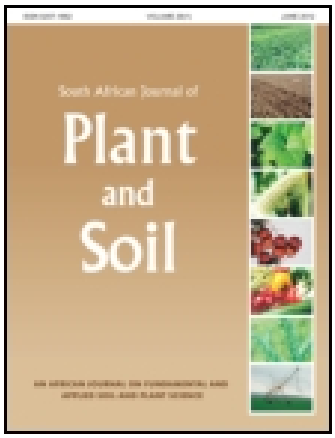

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Chickpea residue properties controlling decomposition dynamics and nitrogen availability in some tropical acid soils

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Chickpea (*Cicer arietinum*) grown in a rotation can contribute significant nitrogen (N) if its decomposition and nutrient-release dynamics are known and synchronised with the maximum demand by the succeeding crop. The aims of the study were to investigate the decomposition rates of two chickpea residues, mature (CHR) and green manure (GM), and use their properties to predict N dynamics in acid soils. The N dynamics were predicted by the NCSOIL model using neutral and acidic detergent fibres (NDF and ADF, respectively) measured by near-infrared reflectance spectroscopy (NIRS) for defining residue pools. The GM released 50–60% of total N in 84 d, whereas CHR immobilised N. Simulations based on the two residue pools indicated that NIRS predicted the carbon (C) and N dynamics reasonably well for both residues. The decay rate constants of the NDF − soluble pool varied between 0.5 and 0.2 d^{-1}. Adding an intermediate pool NDF + ADF improved the prediction of C and N dynamics for CHR but not for GM. Therefore, successful prediction of N dynamics required the search of N partitioning among pools by NCSOIL, as long as no chemical analysis of N was suitable for this purpose.

Keywords: C and N mineralisation, decomposition rate, NCSOIL model, near-infrared spectroscopy, N immobilisation

Introduction

In Africa, few farmers use adequate inorganic fertilisers because of their limited availability and high cost (Kelly 2006). The use of fallow legume cover crops such as chickpea (*Cicer arietinum* L) and dolichos (*Lablab purpureus* L.) as sources of nitrogen (N) has been advocated as a feasible alternative to the use of expensive inorganic fertilisers in the Kenyan wheat belt (Danga et al. 2010). Fallow legumes contribute significant quantities of N after their residues decay following incorporation into the soil (López-Bellido et al. 2004, Walley et al. 2007). However, to develop effective legume fallowing techniques, it is necessary to know their residue decomposition and nutrient-release dynamics. With such knowledge, it is easy to synchronise the period of maximum supply with the period of maximum demand (Delin and Engström 2010) by the succeeding wheat crop. Legume residues decay rapidly under both field (Njunie et al. 2004) and laboratory (Odhiambo 2010) conditions, which make them useful as short-term fallow cover crops in cereal rotations. However, both residue and soil properties affect the decomposition of plant residues. Decay rates are site-specific, being controlled by such factors as soil water, aeration, temperature (Cabrera et al. 2005) and soil pH (Leifeld et al. 2008). For example, low pH inhibits microbial activity and decomposition of organic matter (Leifeld et al. 2008).

The dynamic model NCSOIL (Molina et al. 1983) has been used by Hadas et al. (2004) and Beraud et al. (2005) to derive kinetic properties of residues and composts added to the soil in order to characterise their ability to release N. They found that the rates of decomposition of organic materials added to soil could be described more precisely if they were assumed to comprise two or three components, each decomposing at a specific rate. Gabrielle et al. (2004) employed two pools partitioning in NCSOIL simulations of various organic amendments and obtained good predictions for stable amendments, but for less stable ones the CO_2 release was underestimated. It is often difficult to identify specific pools of mineralisable N by laboratory analysis (Cabrera et al. 2005), which, in turn, makes it difficult to decide when to use two or more pools in the model. Thus, there is a need to gain insight into the significance of each component in relation to its concentration and biochemical stability. If measured biochemical properties of residues were used as input data in carbon (C) and N models, the optimisation of the unknown kinetic variables and the prediction of decomposition rates and the C and N release could improve and be more meaningful (Trinsoutrot et al. 2000a, Nicolardot et al. 2001, Thuries et al. 2005). Successful use of near-infrared spectroscopy (NIRS) to quantify the organic residues quality and prediction of its decomposition has been reported (Trinsoutrot et al. 2000a,

Nicolardot et al. 2001, Bruun et al. 2005, Thuries et al. 2005, Peltre et al. 2011, Kabore et al. 2012). The present study hypothesised that the biochemical indices determined by NIRS could be used as the required residue pools of the NCSOIL model. The objectives of this study were: (1) to determine the decomposition rates of two chickpea residues differing in maturity on four acid soils and (2) to predict their decomposition and N dynamics using the NCSOIL model in combination with NIRS analysis of the residue components.

Materials and methods

Soils and residues

Four acid soils from a depth of 0–200 mm obtained from four major wheat-growing locations in Kenya were studied. The locations and soils were: Njoro (clay loam, Haplustepts), Molo (clay, Haplustalf), Eldoret (clay, Petroferric haplustox) and Rongai (clay loam, Eutrandepts). For the main experiment, the soils had to be sterilised, according to the regulations of the Israeli Governmental Agency for Plant Protection, by autoclaving the samples at 121 ºC and 0.12 MPa pressure for 40 min. Later, an additional experiment was done using non-sterilised Eldoret soil in an authorised quarantine room to test the validity of N transformations in the main experiment. The soil texture was determined by the hydrometer method (Gee and Or 2002), the water-holding capacity (WHC) of the soils was determined by equilibrating wet soil samples on a sand box, the soil pH was measured in a 1:2.5 suspension, and total N and C contents of the soils and of the chickpea residues were determined with an NC Element Analyzer (Flash EA 1112 Series, Thermo Finnigan Italia, Milan, Italy).

The two chickpea residues studied were green manure (GM) harvested at blooming and mature residue (CHR) collected after grain harvest. Neutral detergent fibre (NDF), acid detergent fibre (ADF) and protein contents were determined by scanning oven-dried (60 °C for 48 h), ground (0.5 mm sieve) chickpea residue samples on a NIRS Systems 6500 (Foss Tecator) reflectance spectrometer (Bruun et al. 2005).

Incubation experiment

The chickpea residues (GM and CHR) were applied to the four acid soils. The treatments were soil + green manure (GM), soil + mature residue (CHR), and unamended soil (control). The incubation experiment was laid out in a completely randomised design with factorial arrangement and replicated three times. Prior to incubation, the chickpea residues were oven-dried at 40 °C to a constant weight and finely ground to pass through a 1 mm mesh. Twenty grams of air-dry soil (2 mm mesh size) was amended with 100 mg chickpea residues in 300 ml bottles. The residue application rate was 0.5%, equivalent to 2 250 mg C kg^{-1} soil (based on an average C content of 0.45 g g^{-1} residue). The soils and mixtures were incubated for periods of 0, 1, 3, 7, 14, 21, 28, 42, 56, 70, 84, 112, 140, 196 and 280 d. Separate samples were prepared for each incubation period. The combinations of three residues (including the no-residue controls) × four soil types × three replicates × 15 sampling times resulted in 540 observations. The samples were inoculated with 1.0 ml of garden soil extract of an Israeli soil (Bet Dagan, pH 7.5) to provide microorganisms and then wetted with distilled water to reach 80% WHC. The bottles were covered with thin plastic cling film perforated with needle holes to ensure gas exchange. The bottles were then placed in trays and watered to maintain humidity in an incubation chamber at a controlled temperature of 30 °C. The water content of the samples was readjusted according to weight after they had lost not more than 10% of their initial moisture. During the last 24 h of each incubation period, the samples were uncovered and transferred to 2 l airtight jars, which had a 20 ml vial containing 2–4 ml 1M NaOH to absorb CO_2. The actual amount of NaOH depended on the expected respiratory activity. The period for trapping CO_2 in NaOH was increased from 24 h to 72 and 120 h as the rate of evolution declined. Excess NaOH was titrated with 0.2 M HCl after the carbonate had been precipitated with $BaCl_2$. The rate of CO_2 emission from the soil was calculated from the difference between the sample and a blank sample without soil. Cumulative CO_2 emission was calculated as the sum of the daily rates and linear interpolation of values for rates in between measured dates. Ammonium and nitrate N were determined by extracting the entire 20 g soil sample with 100 ml of 1 M KCl by shaking for 1 h. The supernatant was filtered and analysed for NH_4^+ and NO_3^- with a Lachat autoanalyzer (Lachat Instruments, Milwaukee, WI, USA).

The complementary incubation experiment that was carried out later with the most acidic Eldoret soil only comprised three treatments, namely non-sterilised soil as the control, sterilised soil inoculated with garden extract of Bet Dagan soil (pH 7.5), and sterilised soil inoculated with extract of non-sterilised Eldoret soil. The incubation procedure was the same as in the main experiment and lasted 84 d during which samples were discarded periodically and extracted for analysis of NH_4^+ and NO_3^-.

Model description

The model NCSOIL comprises several organic pools that differ in their function (Molina et al. 1983, Antil et al. 2011). The organic residues comprise two or three pools that decompose at different rates. The mineralisable soil organic matter (SOM) comprises three pools, namely non-microbial mineralisable SOM (Pool II), the soil autochthonous microbial population (Pool I) that feeds on Pool II and on decayed microbial biomass, and a zymogenous microbial population (Pool 0) that feeds on the added residue pools. All soil organic pools are divided into labile and recalcitrant components. Each component decomposes by first-order kinetics ($-dC/dt = kC$) and is defined by its C content, first-order decomposition rate constant (k), microbial use efficiency factor (EFFAC) and C:N ratio. The rate of C flow from one pool to another depends on the above first three properties of the decomposing pool, whereas N flow is determined by the C flow, in accordance with the C:N ratios of both the decomposing and the produced organic pools.

Optimisation of the model and derivation of unknown variables

The measured data of CO_2 and inorganic N at each sampling date in the various treatments of the incubation

experiment were compared with similar data simulated with NCSOIL by means of the Marquardt algorithm (Barak et al. 1990) while searching optimal values of unknown properties or organic pools. The criterion for the best fit of simulated results to measured data was based on the weighted least sum of squares of residuals given by a χ^2 value as follows:

$$\chi^2 = \sum_j \sum_m \sum_n \left\{ \left[Y_{jmn} - Y_j(m,n,A) \right] / \mathrm{SD}_j \right\}^2 / \mathrm{DF}$$

where j is the index of the measured variable (CO_2 and inorganic N in this study), m is the sampling index (number of sampling times, 15 in the present study), n is the index of experimental treatments (four soils, used simultaneously to optimise properties of one residue), Y_{jmn} are measured values, $Y_j(m,n,A)$ are the simulated values with the set of NCSOIL parameters A, SD_j is the standard deviation of the Y_j measurements, and DF is the number of degrees of freedom.

Several properties of the soil organic pools (k, EFFAC and C:N) do not differ among soils and have been previously reported and used (Molina et al. 1983, Hadas et al. 2004, Beraud et al. 2005). Differences between soils are mainly the C content and C:N ratio of Pool II, and the initial size of soil microbial biomass Pool I, which is proportional to Pool II. These unknown properties were optimised by using the measured inorganic N contents and cumulative CO_2-C evolution in the untreated control soils. The properties of the soils were further used as four treatments in the optimisation of the properties of each residue.

The simulation of chickpea residues tested two alternatives: (1) two pools, a labile and a recalcitrant pool; and (2) three pools, a labile, an intermediate and a recalcitrant pool. In the two-pool option the insoluble NDF component was the recalcitrant and the remaining soluble organic component was the labile pool. The decomposition rate constants were then optimised as well as the C:N ratios. The three kinetically different residue pools were the labile pool as the soluble non-NDF component, the intermediate pool as the hemicellulose (NDF − ADF) component, and the recalcitrant pool as the ADF component. The decomposition rate constant of the intermediate pool and partitioning of the non-soluble N between the intermediate and resistant pools were optimised, assuming that the properties of the soluble pool were the same as those in the two-pools optimisation and that the decay of the recalcitrant pool during 280 d of the experiment would be insignificant (Beraud et al. 2005).

Results

Soil properties and composition of chickpea residues

The soil properties are shown in Table 1. Eldoret soil contained the least amount of organic C and N as well as the lowest pH of all soils studied.

The mature chickpea residue (CHR) contained less N than the green manure (GM) (Table 2). The total C content was almost the same in the two chickpea residues. Consequently, the C:N ratio in CHR was approximately five-times larger than in GM. The NDF, hemicellulose (NDF − ADF) and ADF components were larger in CHR than in GM. Obviously, the soluble non-NDF organic matter was smaller in CHR than in GM.

Carbon and N mineralisation from the control soils

Rates of CO_2 evolution from non-amended control soils (Figure 1) rapidly increased from day 1 to the maximum at day 3 for all soils, except in Njoro soil where the peak was at day 1 and then declined with time.

The cumulative C mineralisation varied among soils and ranged from 2 630 mg kg^{-1} for the Eldoret soil to 3 482 mg kg^{-1} for the Molo soil after 280 d incubation (Figure 2).

In all soils the mineralised C was approximately 15% of their initial total organic C contents, except for the Njoro soil (11.6%), which suggests that C mineralisation was controlled by soil C content and availability. Inorganic N accumulation in the Molo soil was 312 mg kg^{-1} after 280 d incubation, twice as much as that in the Eldoret soil (158 mg kg^{-1}) in which the least amount of inorganic N had accumulated (Figure 2) and the organic N content was the smallest as well. The N mineralisation relative to total N content was smallest in the Njoro soil, particularly when considering its large initial NH_4^+-N content, similar to its relative C mineralisation. Nitrification was delayed in all soils and nitrate accumulation was first observed on day 84 (data not shown).

Table 2: Chemical properties (all expressed as g kg^{-1} of dry matter) of the chickpea residues used in the incubation experiments. TOC = total organic carbon, TN = total nitrogen, OM = organic matter, NDF = neutral detergent fibre, ADF = acid detergent fibre, CHR = mature chickpea, GM = green manure, DM = dry matter

Residue	TOC	TN	Soluble OM[a]	NDF	ADF	Ash	Protein
CHR	440	7.8	219	782	581	1.3	40
GM	450	39.8	454	452	358	93.8	240

[a] Calculated as (DM − Ash) − NDF

Table 1: Physical and chemical properties of the soils used in the incubation experiment. WHC = water-holding capacity, CEC = cation exchange capacity, OC = organic matter

Soil	Taxonomy (USDA)	Particle size distribution (g kg^{-1})			WHC (g g^{-1})	CEC (cmol(+) kg^{-1})	pH	Total OC (g kg^{-1})	Total N (g kg^{-1})	Inorganic N (mg kg^{-1})	
		Sand	Silt	Clay						NO_3	NH_4
Njoro	Haplustepts	319	340	341	23	25.6	6.35	25.3	2.0	2.0	59
Molo	Haplustalf	260	300	440	27	35.7	5.10	23.4	2.1	0.4	27
Eldoret	Petroferric haplustox	260	140	600	21	12.3	4.78	16.9	1.4	1.1	20
Rongai	Eutrandepts	300	280	420	23	16.6	5.86	18.9	1.7	0.6	23

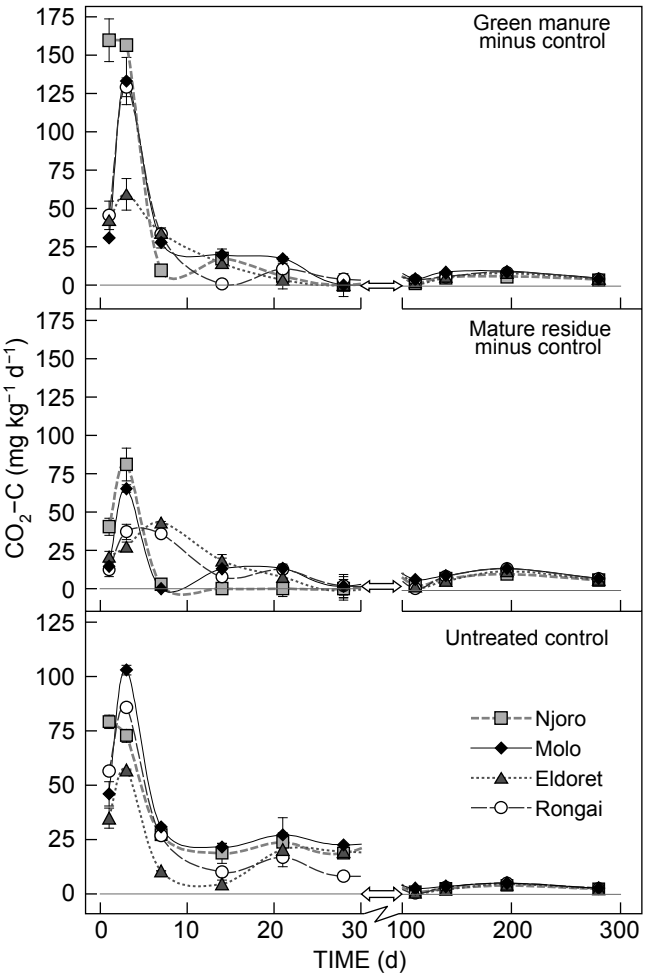

Figure 1: Rates of CO_2 evolution from residues added to soils (amended soils minus control) and from the control soils. Bars represent the SE

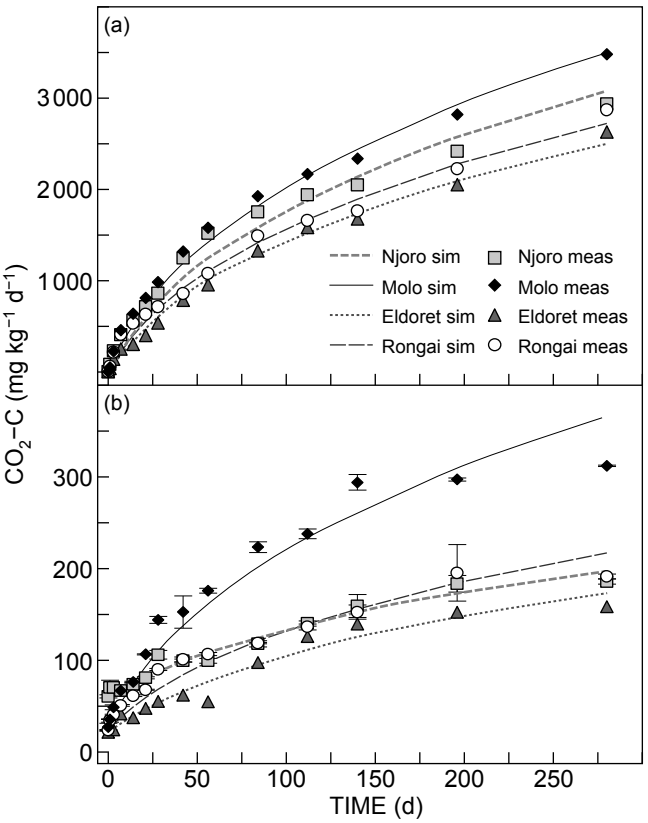

Figure 2: Mineralisation in the control soils: measured and simulated cumulative CO_2 evolution (top) and inorganic N concentrations (bottom). sim = simulated, meas = measured. Bars represent SE

In the complementary experiment, nitrate accumulation was delayed in the sterilised soils and first observed on day 87 with no difference between the sources of inoculation (Figure 3). Sterilisation increased the initial NH_4^+-N content and total inorganic N accumulation in Eldoret soil, which caused some mineralisation of soil organic matter and increased its decomposability as compared with the non- sterilised soil. The amount of inorganic N accumulation in the sterilised soil was not affected by the source of the garden extract after 87 d of incubation (Figure 3). This trend was similar to the inorganic N content on day 84 in the Eldoret soil in the main experiment (Figure 2).

Chickpea residue decomposition: C and N dynamics in soils

Peak evolution of CO_2 from residues was attained on day 3 in all soils, except in GM in the Njoro soil, where peak evolution was observed on day 1 (Figure 1). The CO_2 evolution decreased rapidly with time until day 14, after which the rates declined slowly and gradually approached a constant value after 28 d. At peak evolution (day 3), the amounts of CO_2-C released by decomposition of GM in Eldoret, Rongai, Molo and Njoro soils were 59, 129, 133 and 157 mg kg^{-1} d^{-1}, respectively (Figure 1). At the same stage, decomposition of CHR in Eldoret, Rongai, Molo and Njoro soils released 28, 37, 65 and 81 mg CO_2-C kg^{-1} d^{-1}, respectively. By the end of the incubation, GM had mineralised approximately 50% of the added C in all soils, except for Molo soil, in which it mineralised 69% of the added C (Figure 4). On average, the CHR mineralised 47% of the added C in 280 d, whereas the GM mineralised 55%.

The recovery of N from the GM was approximately 50% (Eldoret 42%) after 42 d and after 84 d it ranged from 52% (Molo) to 58% (Njoro) (Figure 4). Beyond 112 d, there was only a small increase in N release from GM across sites, while in Rongai soil the recovery of N even decreased. By 280 d the average release of N from GM was approximately 64% of the added N. However, the cumulative N recovery from the CHR was always negative, indicating that mature chickpea straw immobilised N throughout the incubation period. Maximum immobilisation occurred on day 28, when approximately 41 mg N kg^{-1} soil was immobilised and averaged for all soils. On average, after 280 d, CHR immobilised 27.9 mg N kg^{-1} soil, which was equivalent to 12.7 mg N g^{-1} of added C.

Soil pool characteristics

The optimised C and N contents of Pool II and Pool I of each soil are shown in Table 3 and the simulated mineralisation curves are shown in Figure 2. The potentially

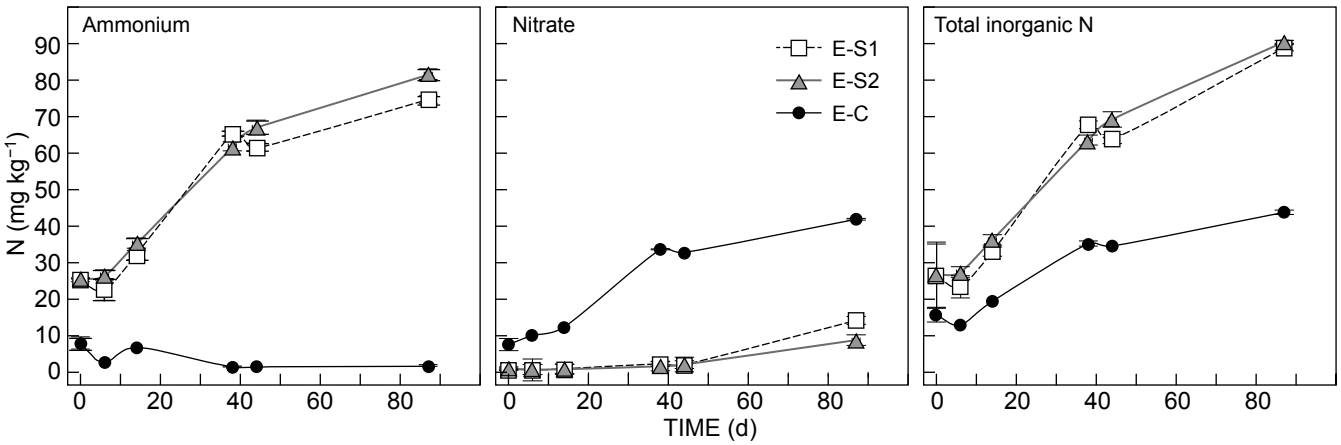

Figure 3: Ammonium-, nitrate- and total inorganic N accumulation in Eldoret soil in the complementary experiment: non-sterilised control (E-C), and sterilised-inoculated with garden extract from either Eldoret (E-S1) or Bet Dagan (E-S2) soils

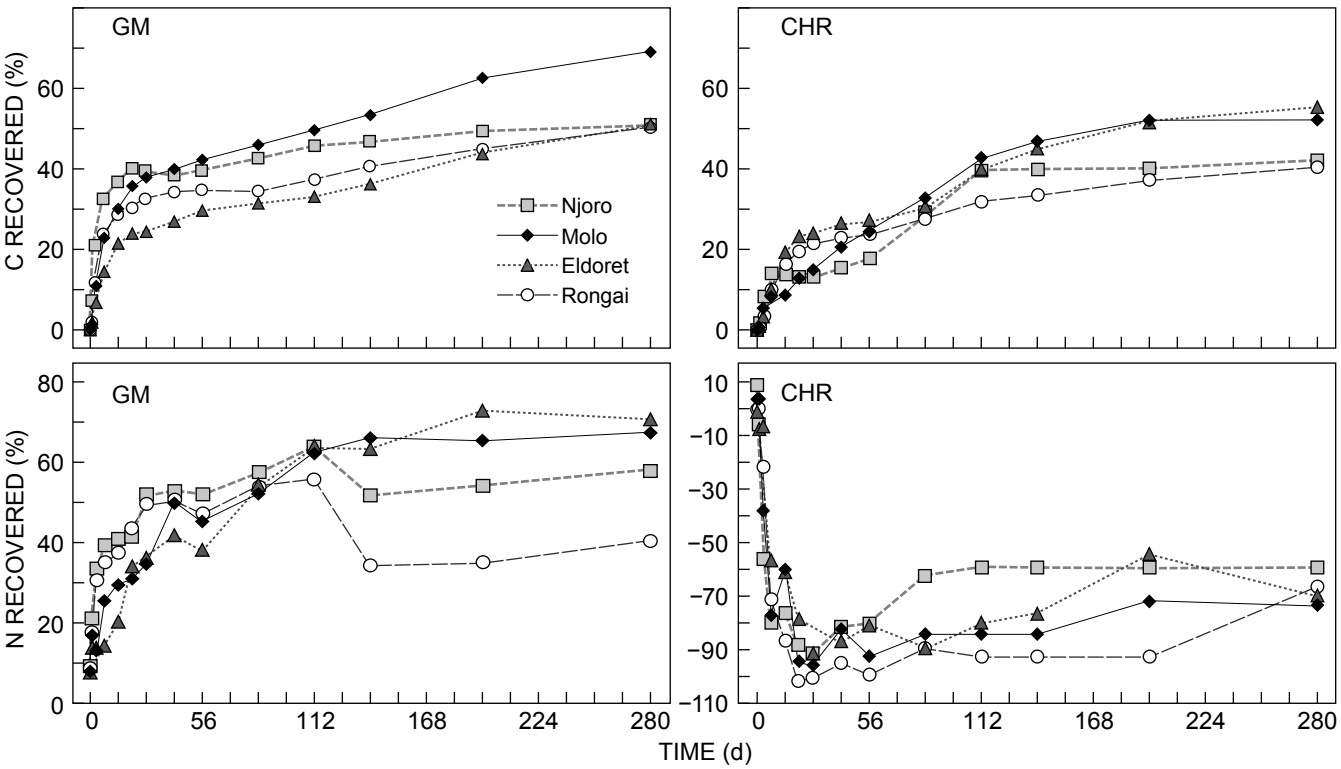

Figure 4: Recovery of added C and N from chickpea green manure (left) and mature chickpea residue (right) in four soils: cumulative CO_2 evolution (top) and inorganic N accumulation (bottom) as a percentage of total residue C and N

mineralisable N (PMN) was 9.9%, 22.5%, 15.5% and 16.1% of the total soil N in the Njoro, Molo, Eldoret and Rongai soils, respectively. The χ^2 values were small, indicating a good fit of the simulated to measured mineralisation, which can also be observed in Figure 2.

Simulation of chickpea mineralisation with a two-pool optimisation

A value of 44.2% was assigned to the C content of the NDF fraction according to Ruffo and Bolero (2003) and the remainder was the soluble C. The partitioning of N between the two pools was optimised along with the two rate constants. The optimised decomposition rate constant of the insoluble component of GM was insignificantly very small, i.e. therefore it was fixed at a value of 0.0001 d^{-1} so as to obtain stable results for the other two optimised variables (Table 4). In the mature chickpea residue, the optimised C:N ratio of the labile pool resulted in very high values of over 106, therefore 1% of total N was assigned to the labile pool.

The NIRS-measured concentrations in the two pools resulted in satisfactory predictions of inorganic N and CO_2 that was released from both chickpea GM and mature

Table 3: Optimised soil properties used for model simulation of soil carbon (C) and nitrogen (N) mineralisation

Optimised data	Njoro	Molo	Eldoret	Rongai
Pool I				
C (mg kg^{-1})	59	141	64	82
N (mg kg^{-1})	9.9	23.6	10.8	13.7
Pool II				
C (mg kg^{-1})	4 482	4 995	3 631	3 930
N (mg kg^{-1})	198	472	216	273
C:N	22.7	10.6	16.8	14.4
$\chi^{2\,a}$	0.031	0.029	0.024	0.034

[a] The least weighted sum of squares of residuals

Table 4: Carbon (C) and nitrogen (N) in two pools of the chickpea residues. The optimisation was against C and N mineralisation data of all soils simultaneously. GM = green manure, CHR = mature chickpea

Residue pools		C and N components (mg kg^{-1} soil)			Rate constant (d^{-1})
		C	N	C:N	
GM	Soluble	1 251	130	9.65	0.47
	Insoluble	999	52	19.2	0.0001
	χ^2				0.0412
CHR	Soluble	472	0.04	1 210	0.169
	Insoluble	1 728	38.96	44.4	0.0034
	χ^2				0.0497

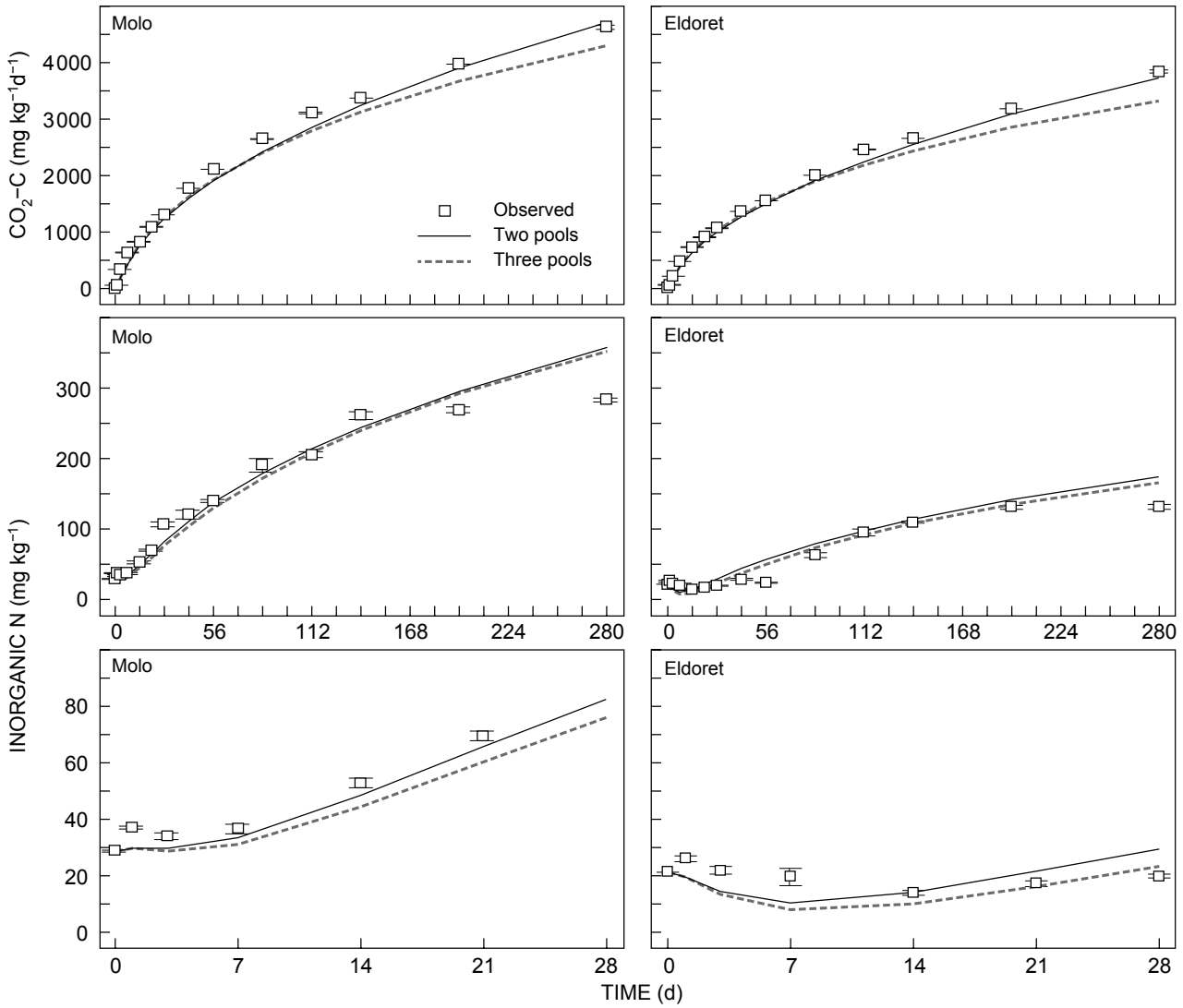

Figure 5: Mineralisation of C (top) and N (bottom) in four soils amended with chickpea green manure: measured (symbols) and simulated (lines) using two options of residue pools definitions: NIR-two and NIR-three pools. Bars represent the SE

residue, as indicated by the χ^2 values (Table 4) and as observed in Figures 5 and 6 (only results for the Molo and Eldoret soils are shown; results for Njoro soil were similar to those for Molo soil, and the Rongai soil results were similar to those for Eldoret soil).

Simulation of chickpea mineralisation using a three-pool optimisation

The insoluble components (NDF) of the residues NDF − ADF and ADF represented the intermediately decaying and recalcitrant pools, respectively. Their C content was

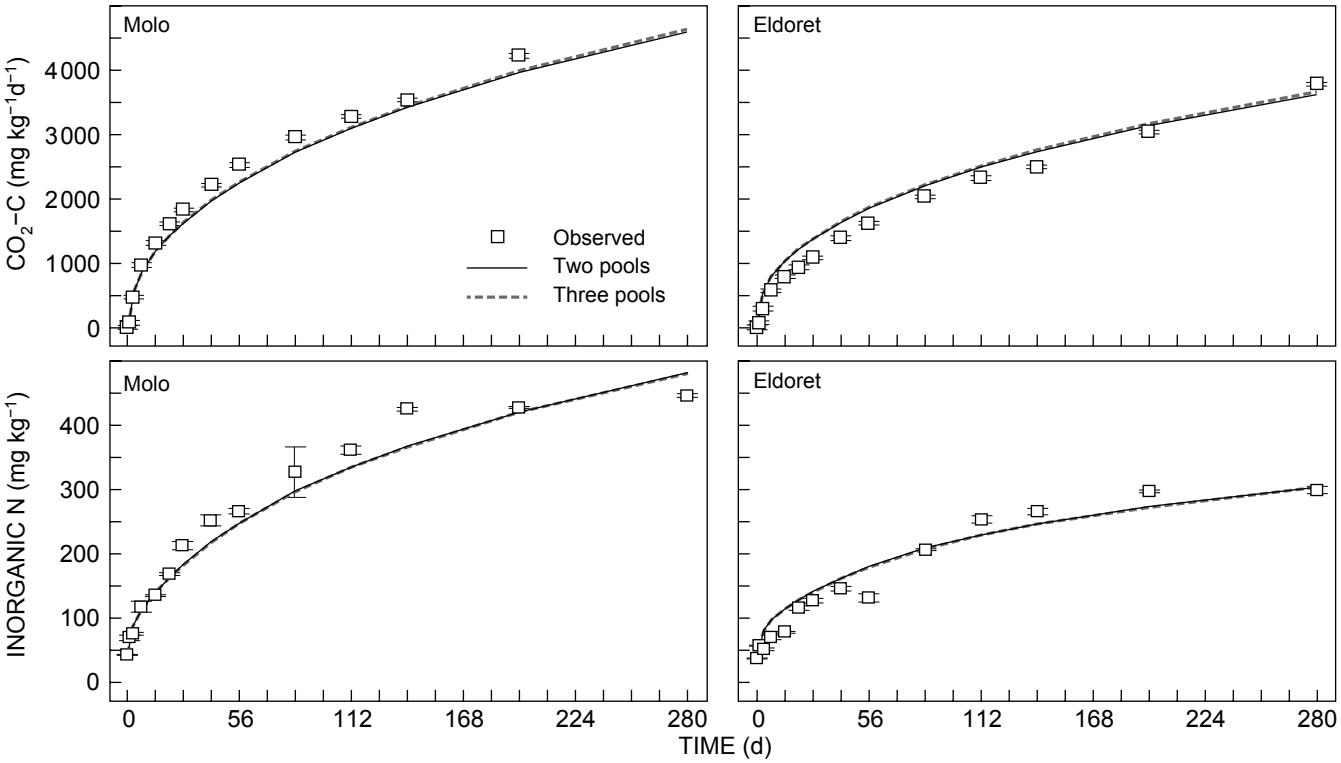

Figure 6: Mineralisation of C (top) and N (middle, and bottom– expended short-term) in four soils amended with mature chickpea residue: measured (symbols) and simulated (lines) using two options of residue pools definitions: NIR-two and NIR-three pools. Bars represent the SE

set at 44.2% as in the two-pool optimisation. The distribution of insoluble N between the two insoluble pools and the decomposition rate constant of the intermediate (NDF − ADF) pool for both residues, which were optimised are as shown in Table 5. The C:N ratio of the intermediate pool was extremely large in both residues, meaning that insoluble N was entirely in the ADF pool. The intermediate pool in GM was relatively very small and so was its optimised decomposition rate constant. Consequently, this pool contributed very little to C and N mineralisation and the improvement of their prediction compared with the two-pool assumption (Table 4) was insignificant, as shown by the similar χ^2 value and the similar simulated lines (Figure 5). In CHR, the amount of C in the intermediate pool was similar to that of the soluble pool, twice as much as in GM, and its optimised decomposition rate constant was over 10-times larger (Table 5). This means that its overall contribution to C and N turnover was considerable, as shown by the improvement (decrease) of the χ^2 value compared with the two-pool assumption. The simulation results of the CHR chickpea with three pools underestimated CO_2 from 170 d onwards, whereas the N immobilisation in the first weeks of incubation in the Eldoret and Rongai soils was better simulated by the three-pools than the two-pools simulation (Figure 5).

Table 5: Carbon (C) and nitrogen (N) in three pools of chickpea residues. The previously optimised soluble N and labile rate constants were used as input, and the partitioning of insoluble N and decomposition rate constants of the intermediate pool were optimised with NCSOIL for all soils simultaneously in a three-pool optimisation. GM = green manure, CHR = mature chickpea, ND = neutral detergent, NDF = neutral detergent fibre, ADF = acid detergent fibre

Residue pools		C and N components (mg kg^{-1} soil)			Rate constant all soils (d^{-1})
		C	N	C:N	
GM	ND soluble	1 251	130	9.65	0.47
	NDF − ADF	212	0.0	>10 000	0.0015
	ADF	787	52	15.1	0.0001
	χ^2				0.0408
CHR	ND soluble	472	0.039	1210	0.169
	NDF − ADF	448	0.0	>10 000	0.023
	ADF	1 280	38.96	33.2	0.0001
	χ^2				0.0418

Discussion

Properties of residues and soils

The residues tested in this work represented two growth stages of chickpea at which they could be incorporated in soil in a wheat–chickpea rotation in Kenya and tropical regions (Danga et al. 2009, 2010). They differed greatly in their soluble component and in their N content (Table 2), which seemed to control the rate of their decomposition and the consequent net N mineralisation.

The mineralisation of soil organic matter in the four studied soils was generally proportional to their organic C and N content, with the largest values obtained for Molo soil and the smallest for Eldoret soil (Table 1, Figure 2). Nevertheless, while the total C:N ratio of all soils was within a narrow range (11.1–12.6), the potentially mineralisable C:N

ratio (of Pool II) ranged from 10.6 to 22.7 (Table 3), though in both cases the largest value was for Njoro soil. The mineralisable C ranged from 17.7% of total C in Njoro soil to 21.4% in Molo soil, comparable to the range of 15–35% reported by Nicolardot and Molina (1994) and 11.9–30.9% reported by Charoulis et al. (2005) for soils from locations of various climates. The average percentage of mineralisable N was 16% of total N, within the range of 3.84–55.57% of total N reported by Charoulis et al. (2005). The Eldoret soil mineralised less C and N than the other soils because of its low soil organic C and N content. The complementary experiment with Eldoret soil proved that sterilisation and inoculation of the most acidic soil from Kenya with garden extract of the local Bet Dagan soil (pH 7.5) did not reduce the mineralisation capability of the soils, even though nitrification was delayed for several weeks (Figure 3).

Mineralisation of C and N from the two chickpea residues

At the initial stage of decomposition, maximal CO_2 evolution rates from GM were approximately twice as large as those from CHR (Figure 1). Yet, after 280 d the difference between C-recovery from both materials was much smaller with 55% for GM vs 47% for CHR (Figure 3). The large difference between the materials at the initial stage could be attributed to the difference in soluble C contents (CHR was half that of GM) and possibly also to the much smaller N content of CHR (Table 2). This was in agreement with Xu et al. (2006) who showed that cumulative respiration correlated positively with the concentrations of N and soluble C, and negatively with the C:N ratios of plant residues. The initial highest rates of CO_2 evolution from both materials were observed in Njoro soil (Figure 1). The greater C mineralisation in Njoro soil during the first three days of incubation could result from its much larger NH_4-N content (Table 1). Henriksen and Breland (1999) indicated that if concentrations of available N (added organic matter N + soil inorganic N) were less than 1.2% of added organic matter, the rate of C-mineralisation and growth of microbial biomass would be significantly reduced. Indeed, inorganic N in Njoro increased the percentage of 'available N' for CHR from 0.78% to 1.98%, whereas in the other soils the inorganic N barely increased to 1.2%. The percentage of C mineralisation from the residues (Figure 4) agreed reasonably well with values reported by others (Thuries et al. 2001).

The two residues greatly differed in their N dynamics in soil due to their different N contents or C:N ratios. These results concur with earlier findings reported by Trinsoutrot et al. (2000a) and Hadas et al. (2004). Green manure released N very rapidly to about 50–55% of its total N after 42–84 d (Figure 4), approximately the same as observed by Villegas-Pangga et al. (2000) for chickpea straw with a slightly larger C:N ratio than that of the GM in our study (13.3 vs 11.3). On the other hand, mature chickpea residue immobilised N very rapidly (Figure 5). The maximal N immobilisation on day 28 was approximately 40 mg N kg^{-1} soil equivalent to 8 g N kg^{-1} residue, slightly less than the commonly accepted practice of adding 10 g available N per 1 kg of cereal straw incorporated in soil. Indeed, the N content of CHR was slightly larger than that of cereal straw. Although part of the immobilised N was gradually released by the end of 280 d of incubation, inorganic N concentrations in the CHR-amended soils was still below that of the control soils (equivalent to 5.2 g kg^{-1} residue) (Figure 5). Similar results were reported by Pilbeam et al. (1998) for chickpea stems with a C:N ratio of 123.

Simulation of C and N dynamics related to residues' properties

The soluble C pools in CHR were relatively small, therefore the insoluble pools played a relatively greater role in C and N dynamics. The intermediate pool in GM was very small, less than 10% of total C (Table 5). The optimised N content and the decomposition rate constant of the intermediate pool were extremely small, resulting in a minor effect on C and N mineralisation (Figure 6). The insignificant decrease in χ^2 implied C and N dynamics in GM were largely controlled by the soluble pool, much the same as in the two-pools option. The C content of the intermediate pool in CHR was much larger than in GM, comparable to soluble C, while the optimised N content was zero and the rate constant was close to values found for cellulose and/or hemicellulose (Hadas et al. 2004, Nicolardot and Molina 1994, Probert et al. 2005, Trinsoutrot et al. 2000b). Therefore, C mineralisation from this pool was considerable, N dynamics prediction improved (Figure 5) and the χ^2 value improved slightly as well (Table 5). The mineralisation of organic C from various plant residues during incubation was accurately predicted using a decomposition model of a very labile, intermediary resistant and stable organic matter fractions, which were determined by NIRS (Peltre et al. 2011, Kabore et al. 2012), but the N mineralisation and dynamics was not included in this study. Even when the step-wise chemical digestion (SCD) fractions were analysed for their N content (Trinsoutrot et al. 2000b), the predicted net N immobilisation was consistently less than measured. Furthermore, Bruun et al. (2005) showed that NIRS predicted C mineralisation of plant materials slightly better than SCD, but prediction of N mineralisation was considerably worse than by SCD or by the C:N ratio of the materials.

Conclusions

Green manure residues enhanced inorganic N concentration in the soil relative to the control soils, which resulted in an average net N mineralisation of 64% of its total N in 280 d. In contrast, the application of mature chickpea residue decreased inorganic N concentration in the soil, which subsequently caused net N immobilisation throughout the incubation period. The mineralisation of the residues depended more on their quality and less on the soil substrate. Chickpea GM will contribute to the successive wheat crop available N of at least 40 kg N ha^{-1} and up to 80 kg N ha^{-1}. The NCSOIL model was a useful tool to explore the soil and chickpea residue properties that could not be measured analytically, yet controlled the net N mineralisation and C decomposition rates. The recalcitrant and labile C pools defined by the NIRS method (NDF and 1-NDF, respectively) predicted the dynamics of C mineralisation satisfactorily. Moreover, NIRS also enabled the definition of an additional intermediate C-pool, which improved the prediction of C and N mineralisation/

immobilisation particularly for the mature chickpea residue. However, a large disadvantage of the NIRS method is the lack of criteria for the determination of N content of the components that vary in their decomposability. Therefore, it had to be obtained by fitting the NCSOIL model to measured mineralisation data. Additional intermediate C-pool improved the prediction of C and N mineralisation/ immobilisation particularly for the mature chickpea residue. Knowing both C and N components of organic residues is essential for predicting their effect on crop available N dynamics following their incorporation in soil.

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