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Estimates of the residual nitrogen benefit of groundnut to maize in Northeast Thailand

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Abstract

Four cultivars of groundnut were grown in upland soil in Northeast Thailand to study the residual benefit of the stover to a subsequent maize crop. An N-balance estimate of the total residual N in the maize supplied by the groundnut was made. In addition three independent estimates were made of the residual benefits to maize when the groundnut stover was returned to the land and incorporated. The first estimate (Estimate 1) was an N-balance estimate. A dual labelling approach was used where ^{15}N-labelled stover was added to unlabelled microplots (Estimate 2) or unlabelled stover was added to ^{15}N-labelled soil microplots (Estimate 3). The nodulating groundnut cultivars fixed between 59–64% of their nitrogen (as estimated by the ^{15}N isotope dilution method using non-nodulating groundnut as a non-fixing reference) producing between 100 and 130 kg N ha^{-1} in their stover. Although the following maize crop suffered from drought stress, maize grain N and dry weights were up to 80% and 65% greater respectively in the plots where the stover was returned as compared with the plots where the stover was removed. These benefits were comparable with applications of 75 kg N ha^{-1} nitrogen in the form of urea. The total residual N estimates of the contribution of the nodulated groundnut to the maize ranged from 16.4–27.5 kg N ha^{-1}. Estimates of the residual N supplied by the stover and fallen leaves ranged from 11.9–21.3 kg N ha^{-1} using the N-balance method (Estimate 1), from 6.3–9.6 kg N ha^{-1} with the labelled stover method (Estimate 2) and from 0–11.4 kg N ha^{-1} with the labelled soil method. There was closest agreement between the two ^{15}N based estimates suggesting that 'apparent added nitrogen interactions' in these soils may not be important and that N balance estimates can overestimate the residual N in crops following legumes, even in very poor soils. This work also indicates the considerable ability of local groundnut cultivars to fix atmospheric nitrogen and the potential benefits from returning and incorporating legume residues to the soil in the upland cropping systems of Northeast Thailand. The applicability of the ^{15}N methodology used here and possible reasons for the discrepancies between estimates 1, 2 and 3 are discussed.

Introduction

Groundnut (*Arachis hypogaea* L.) is known to fix substantial quantities of nitrogen from the atmosphere under favourable conditions in the tropics – between 80 and 150 kg N ha^{-1} in 90 days (e.g. Giller et al., 1987; Toomsan, 1990). Estimates of the residual N supplied to subsequent crops by groundnut and other legumes when their residues are incorporated are variable and frequently around 20% of the N applied (e.g. Sisworo et al., 1990). In this study we compared the amounts of nitrogen fixed by four groundnut cultivars using the ^{15}N-isotope dilution method (Witty, 1983). Three independent estimates were then made of the residual nitrogen taken up by a following crop of maize. The first estimate was obtained by constructing an N balance sheet for the two crops, i.e. by attributing increased yield and N uptake in the maize crop to the legume. In addition a dual approach was used where ^{15}N-labelled stover was added to unlabelled microplots to give a direct ^{15}N-based estimate or unlabelled stover was added to ^{15}N-labelled soil microplots to give an indirect ^{15}N-based estimate.

Methods

Experimental design

The experimental work was carried out at an upland field site in Khon Kaen province in Northeast Thailand. The soil on the site was an Oxic Paleustult, a loamy sand with pH 4.9, organic carbon 0.4% and total N 0.08% (based on analysis of samples from a depth of 0–15 cm). The proportions of sand, silt and clay in the soil were 88%, 3% and 9% respectively. Available P was 27 mg kg^{-1} (Bray II method). The climate is tropical with mean monthly temperatures from 26–32 °C. There are distinct seasons; the rainy season usually lasts from May till September and the dry season from October till April. The average annual rainfall is 1200 mm. Five groundnut cultivars were grown: Tainan 9 (currently the most widely-grown cultivar in the North-East of Thailand), KK 60-1, KK 60-2, KK 60-3 (recently released cultivars) and a non-nodulating reference cultivar (referred to as nonnod) obtained from ICRISAT, Hyderabad, India. The cultivars were the main plots and these were randomised in latin squares. The main plot was divided into two subplots each of which had a microplot. The two subplots were treated identically for the first groundnut season. The main plots were 13 m × 10 m, the two sub-plots were 6 m × 10 m and the microplots were 4.5 m × 1 m. The experiment was laid out in a split-plot design with five replicates.

The soil in the microplots was labelled using a solution of $(^{15}NH_4)_2SO_4$ with an enrichment of 10% atom ^{15}N excess. The N was applied at a rate of 10 kg N ha^{-1} with glucose added as a carbon source at a rate which gave the solution a C:N ratio of 10:1. The field was left for 8 days to allow for the immobilization of the applied nitrogen by the soil microorganisms so reducing the rate of release of labelled N (Giller and Witty, 1987). A commercial peat-based inoculum of *Bradyrhizobium* (Dept. of Agriculture, Ministry of Agriculture and Cooperatives, Bangkok, Thailand) was applied with the seed at sowing. The following fertilizers were also applied: 24.5 kg P ha^{-1} as triple super phosphate, 20 kg K ha^{-1} as KCl, 0.5 kg B ha^{-1} as borax and 310 kg ha^{-1} gypsum. Plants were thinned to leave 2 plants hill^{-1}. Weeds, pests and diseases were adequately controlled.

Harvest

The groundnut cultivars matured at between 90 and 110 days after planting (DAP). The grain was taken away and the remaining stover was then cut into lengths of approximately 10 cm. With groundnut the stover includes a large proportion of the roots which are pulled out of the ground when the pods are being harvested. Leaves which fell due to disease in the ten days before harvest were collected, weighed and treated as stover. The microplot was harvested separately and the border rows discarded. The plants were chopped up, thoroughly mixed and a sub-sample of 10% was taken, dried and ground for total N and ^{15}N analysis.

Stover incorporation

Stover was incorporated into one subplot: (+) stover, and removed from the other: (−) stover. Incorporation was carried out during land preparation 28 days before maize planting. This delay was longer than expected being caused by a labour shortage at the time of land preparation. The labelled stover derived from the original microplots was applied to a second microplot within the (+) stover subplot. This new microplot, the soil of which had received no ^{15}N label, was used for a direct ^{15}N based estimate of the residual N in the following crop of maize. ^{15}N released by the stover was taken up directly by the maize and the proportion of ^{15}N in the maize was converted into a residual N estimate using equation 5 below. The previously ^{15}N-labelled soil microplots were used as a basis for an indirect ^{15}N based residual N estimate. Unlabelled stover was incorporated into the (+) stover microplot whereas nothing was incorporated into the (−) stover microplot. Maize was then grown on the two microplots and differences in their ^{15}N contents reflected the release and uptake of unlabelled N from the groundnut residues in the (+) stover microplot, i.e. the unlabelled N released from the residue diluted the ^{15}N label coming from the soil and this dilution was converted into a residual N estimate as explained in equation 6 below. The amount of stover applied to the microplot was equal in weight to the amount produced by the yield area (per unit area) and was taken randomly from the yield plot. An additional treatment was included adjacent to the main experimental area where the land had been left fallow during the wet season. Five plots of maize were planted each split into two subplots with or without applications of 75 kg N ha^{-1} as urea (the recommended N application rate for Northeast Thailand).

The stover was incorporated during ploughing (mechanically done). Where stover was added to the microplot it was incorporated using a hand hoe. Maize was planted 3 plants $hill^{-1}$ and later thinned to one plant $hill^{-1}$. Disease, weeds and insect pests were adequately controlled and recommended levels of fertilizer were applied: 21 kg P ha^{-1} as triple super phosphate, 22.2 kg K ha^{-1} as KCl. The crop was irrigated when necessary and harvested after 120 days. When sampling the plants in the microplots for ^{15}N analysis, the border rows were discarded. The plants were separated into grain heads and stover, dried and ground for analysis.

Chemical analysis

The oven-dried material was ground using a hammer mill, and sub-samples ground further into a fine powder using a roller mill. 5 mg samples were weighed into small tin capsules which were then closed and rolled into a ball. These samples were then analyzed for ^{15}N and total N using a Micromass 622 mass spectrometer linked to a Europa Scientific Roboprep automatic C/N analyzer.

Calculations and data analysis

The proportion of nitrogen in the groundnut derived from fixation was calculated by comparing the ^{15}N enrichments in the fixing cultivars with that of the nonnod groundnut, i.e.

$$\%\text{ N from } N_2\text{-fixation} = \left[1 - \left(\frac{R_{\text{nodulated legume}}}{R_{\text{reference plant}}}\right)\right] \times 100\% \qquad (1)$$

(where R = atom % ^{15}N excess)

$$\text{N from } N_2\text{-fixation (kg ha}^{-1}) = \frac{\%\text{ N from } N_2\text{-fixation}}{100} \times \text{total N} \qquad (2)$$

Nitrogen fixation amounts were also calculated by difference (i.e. a calculation based on the assumption that the fixing cultivars took up the same amount of soil N as the non-fixing cultivar and the remainder was fixed).

The total residual N in the maize (in kg ha^{-1}) including contributions from the groundnut below ground or from leaf-fall before harvest

$$= \text{maize}_{(+)\text{stover}}\text{ N} - \text{maize after nonnod}_{(-)\text{stover}}\text{ N} \qquad (3)$$

The amount of nitrogen in the maize derived from the groundnut stover added to the (+) stover plots was calculated in three ways. The first was an N balance estimate, i.e.

$$\text{Estimate 1 (kg N ha}^{-1}) = \text{maize}_{(+)\text{stover}}\text{ N} - \text{maize}_{(-)\text{stover}}\text{ N} \qquad (4)$$

The second estimate was a direct ^{15}N-based estimate for which ^{15}N-labeled stover was added to microplots of unlabelled soil.

Estimate 2 (kg N ha^{-1})

$$= \left(\frac{R_{maize}}{R_{groundnut\ stover}}\right) \times \text{total maize N} \qquad (5)$$

The third was an indirect ^{15}N-based estimate for which unlabelled stover was added to microplots with ^{15}N-labelled soil previously used to measure N_2-fixation.

Estimate 3 (kg N ha^{-1})

$$= \left[1 - \left(\frac{R\ maize_{(+)stover}}{R\ maize_{(-)stover}}\right)\right] \times \text{total maize N} \qquad (6)$$

This is only valid if the amount of ^{15}N removed by the first crop did not differ between (+) stover and (−) stover treatments. For this reason the amounts of ^{15}N-removed by the groundnut were calculated for the (+) stover and (−) stover subplots of each main plot and tested for significant differences.

An estimate of contributions from the groundnut below ground or from leaf-fall before harvest was calculated (in kg N ha^{-1}) as:

$$maize_{(-)stover}\,N - \text{maize after}\ nonnod_{(-)stover}\,N \qquad (7)$$

An ANOVA was performed on the data using the split plot model in the GENSTAT 5 statistical package (Payne, 1987).

Results

Groundnut

All of the groundnut cultivars grew well in the field producing pod yields of 1730–2180 kg ha^{-1} (Table 1), which were large in comparison to average yields for the region. The nodulating groundnut cultivars fixed between 59–64% of their nitrogen as estimated by the ^{15}N isotope dilution method and fixed a total of between 101–130 kg N ha^{-1} (Table 2). Mean atom % ^{15}N excess values were in the range 0.137–0.164 for the stover of the fixing cultivars and 0.399 for the nonnod cultivar (Table 4). The nitrogen difference estimates of fixation were consistently slightly smaller than the isotope dilution estimates but generally they agreed well (Table 2) and showed the same differences between cultivars. The amount of nitrogen in the stover which was later incorporated into the (+) stover subplots varied in the fixing cultivars between 100 and 130 kg N ha^{-1} of which 61–86 kg N ha^{-1} was derived from fixation (Table 2). The amounts of nitrogen removed in the grain by the fixing cultivars varied from 59–75 kg N ha^{-1}, with 35–47 kg N ha^{-1} coming from nitrogen fixation and the difference, 22–32 kg N ha^{-1}, coming from the soil (Tables 2 and 3). The net inputs from fixation, calculated as the fixed nitrogen returned to the soil in the stover less the soil nitrogen removed in the grain, were 29–64 kg N ha^{-1} for the fixing cultivars with a net removal of 14 kg N ha^{-1} by the non-nodulating cultivar (Table 3).

Table 1. Pod, stover and total dry matter yields (kg ha^{-1}) for five groundnut cultivars grown at Khon Kaen

Groundnut cultivar	Pod	Stover	Total
Tainan 9	2180	4400	6580
KK 60-1	2020	5070	7100
KK 60-2	1730	5190	6920
KK 60-3	1780	5650	7430
Nonnod	660	4280	4940
SED	113	277	355

SED = Standard error of the differences between means.

Due to an attack of groundnut leaf spot late in season there were varying amounts of leaf fall with the groundnut cultivars before harvest, up to 50% with KK 60-3, less with KK 60-1 and KK 60-2 and almost none with the cultivar Tainan 9 (leaf-fall data not presented). When harvesting the stover as many of the fallen leaves as possible were collected and treated as stover because normally there would not be large leaf losses just before harvest. Inevitably, however, some were left behind and those that were collected would have lost much of their nitrogen to the soil. This introduced a complicating (though interesting) factor into the experiment which must be considered when interpreting the results.

Table 2. Total N yield, % N from N_2-fixation and fixed N values for five cultivars of groundnut grown at Khon Kaen

Groundnut cultivar	Nitrogen (kg ha^{-1})			% N from N_2-fixation		Fixed N (kg ha^{-1})[a]		
	Grain	Stover	Total	^{15}N dilution	Difference[b]	Grain	Stover	Total
Tainan 9	75	100	180	60	56	43	61	108
KK 60-1	73	110	192	64	58	47	72	123
KK 60-2	59	110	172	59	53	35	63	101
KK 60-3	60	130	201	64	60	38	86	130
Nonnod	14	60	77	–	–	–	–	–
SED	4.3	9.4	6.0	3.3	2.3	4.1	6.0	8.5

[a] Using the ^{15}N dilution method.
[b] Using the difference method, i.e. assuming the difference between N content of the fixing and nonnod varieties was fixed.
SED = standard error of the differences between means.

Table 3. Calculations of the net inputs to the system from nitrogen fixation (kg N ha^{-1}) for five cultivars of groundnut grown at Khon Kaen

Groundnut cultivar	Soil N in grain	Fixed N in stover	Net inputs (from fixation[a])
Tainan 9	32	61	29
KK 60-1	26	72	46
KK 60-2	24	63	39
KK 60-3	22	86	64
Nonnod[b]	14	–	−14
SED	4.3	6.0	7.8

[a] The net inputs to the system from nitrogen fixation have been calculated as the fixed nitrogen returned to the soil in the stover minus the soil nitrogen removed in the grain.
[b] Nonnod not included in ANOVA for fixed N.
SED = standard error of the difference between means.

Maize

Although the following maize crop suffered from drought stress towards the end of its growth, treatment dry weight and total N differences were pronounced (Tables 5 and 6 respectively). Maize grain and total dry matter yields from treatments where the residues of the fixing groundnut cultivars were returned to the land ranged from 2615–3009 kg ha^{-1} and 6064–7303 kg ha^{-1} respectively and were comparable with the fallow treatment to which 75 kg N ha^{-1} nitrogen in the form of urea was added (Table 5). Where the groundnut residues had been removed the maize grain and dry matter yields

Table 4. Mean atom % excess ^{15}N values for groundnut and maize grown at Khon Kaen

Groundnut cultivar	Mean atom % ^{15}N excess			
	Groundnut		Maize stover	
	Stover	Grain	Estimate 2[a]	Estimate 3[b]
Tainan 9	0.144	0.124	0.012	0.087
KK 60-1	0.139	0.128	0.013	0.091
KK 60-2	0.164	0.145	0.012	0.092
KK 60-3	0.137	0.126	0.010	0.088
Nonnod	0.399	0.343	0.011	0.112
SED	0.0206	0.0121	0.0020	0.0072

[a] Maize grown on unlabelled soil to which ^{15}N-labelled groundnut stover had been added.
[b] Maize grown on ^{15}N-labelled soil to which unlabelled groundnut stover had been added.
SED = standard error of the differences between means.

Table 5. Grain and total dry matter yields of maize grown after five groundnut cultivars or after fallow plots with stover removed from (− stover) or returned to (+ stover) the soil

Previous groundnut cultivar	Maize grain yield ($kg\ ha^{-1}$)		% difference	Maize total dry matter ($kg\ ha^{-1}$)		% difference
	− stover	+ stover		− stover	+ stover	
Tainan 9	1652	2731	65	3940	6416	63
KK 60-1	1982	2955	50	4698	6689	42
KK 60-2	1965	2615	33	4613	6064	32
KK 60-3	2128	3009	41	5238	7303	39
Nonnod	1744	2221	27	4067	5323	31
	−N	+N[b]		−N	+N[b]	
Fallow[a]	1912	2723	42	4546	6394	41
SED cultivar	217			407		
Stover	137			257		
Interaction	307			575		

[a] Fallow treatment not included in the analysis of variance.
[b] Nitrogen applied in the form of urea at the rate of $75\ kg\ N\ ha^{-1}$.
SED = standard error of the differences between means.

Table 6. Nitrogen in a crop of maize grown after five groundnut cultivars under two stover management practises or after fallow plots with stover removed from (− stover) or returned to (+ stover) the soil

Previous groundnut cultivar	Maize grain N ($kg\ ha^{-1}$)		% difference	Maize total N ($kg\ ha^{-1}$)		% difference
	− stover	+ stover		− stover	+ stover	
Tainan 9	19.3	34.8	80	29	50	72
KK 60-1	25.5	32.1	26	37	52	41
KK 60-2	22.9	40.0	75	34	46	35
KK 60-3	24.9	37.4	50	39	57	46
Nonnod	19.1	24.3	27	30	37	23
	−N	+N[b]		−N	+N[b]	
Fallow[a]	15.1	39.5	162	22	56	155
SED cultivar	2.9			3.7		
Stover	1.9			2.3		
Interaction	4.2			5.2		

[a] Fallow treatment not included in the analysis of variance.
[b] Nitrogen applied in the form of urea at the rate of $75\ kg\ N\ ha^{-1}$.
SED = standard error of the differences between means.

were 1652–2128 $kg\ ha^{-1}$ and 3940–5238 $kg\ ha^{-1}$ (Table 5). Dry weights were up to 65% greater in the plots where the stover was returned as compared with the plots where the stover was removed and total N values were up to 72% greater in the (+) stover plots (Table 6).

Residual N

Four values for residual N in maize have been calculated; the first is an N balance estimate of the total residual N. This includes all the contributions from the legume above and below ground and has been calculated as the difference between maize N from the (+) stover plots of the fixing cultivars and (−) stover plots of the nonnod cultivar (Equation 3). The remaining three estimates are of the residual N supplied in the stover and rely on the differences between the (+) stover and (−) stover plots for each cultivar (Equations 4–6).

The total residual estimates range from 16.4–27.5 kg N ha^{-1} (Table 7). The highest estimate, 27.5 kg N ha^{-1} was in maize grown after groundnut cultivar KK60-3. The residual N estimates after the other cultivars did not differ greatly (16.4–22.8 kg N ha^{-1}). The residual N contributed from below ground or from natural leaf-fall before the groundnut harvest has been calculated as the difference between maize N from the (−) stover plots between the fixing cultivars and the nonnod cultivar and ranged from 0.1–9.6 kg N ha^{-1} (Table 7, Equation 7).

The N balance estimate ranged from 11.9–21.3 kg N ha^{-1}. The highest estimate (21.3 kg N^{-1}) was after the cultivar Tainan 9. The direct ^{15}N estimate (Estimate 2) was about half of the N balance estimate for all of the fixing cultivars ranging from 6.3–9.6 kg N ha^{-1} (Table 7) with a low estimate of 2.2 kg N ha^{-1} for the nonnod cultivar. The indirect ^{15}N estimate (Estimate 3) gave residual N estimates of 0–11.4 kg N ha^{-1} (Table 7) though with high variability. The main assumption with Estimate 3 is that the ^{15}N-enrichment of the labile soil N pool was identical in the paired subplots. Variation in the ^{15}N enrichment of this labile pool may have been the cause of the high variability found with this estimate though we did not measure the enrichment of the N remaining in the soil at the time of maize planting. Such variability could have been caused by non-uniform application of the ^{15}N fertilizer or by differences in initial soil characteristics such as amounts of organic matter. Mean enrichments in the maize stover were from 0.010–0.013 atom % excess ^{15}N for Estimate 2 and from 0.087–0.112 atom % excess ^{15}N for Estimate 3 (Table 4). It was not possible to correlate the negative residual estimate values with ^{15}N enrichment in the groundnut residues or the amounts of ^{15}N removed from each plot.

Discussion

Groundnut

All the fixing cultivars provided a net input of nitrogen into the soil and this can be attributed to the relatively high rates of fixation. The good agreement between the ^{15}N isotope dilution and the N difference estimates of fixation give us confidence that the non-nodulating cultivar was a good non-fixing reference and that the technique worked well. Other workers have estimated similar rates of fixation by groundnut in Thailand (e.g. Suwanarit et al., 1986). Our values for net

Table 7. Estimates of residual N (kg N ha^{-1}) in maize grown after five groundnut cultivars in Khon Kaen and some additional calculations

Previous groundnut cultivar	Total residual N estimate[a]	Residual N from fallen leaves or below ground[b]	Residual N from added stover: Estimate 1[c]	Residual N from added stover: Estimate 2[d]	Residual N from added stover: Estimate 3[e]
Tainan 9	21.4	0.1	21.3	9.6	11.4
KK 60-1	22.8	8.6	14.2	8.7	8.7
KK 60-2	16.4	4.5	11.9	6.3	0
KK 60-3	27.5	9.6	17.9	9.6	4.4
Nonnod	7.8	0	7.8	2.2	4.7

[a] Calculated as the N from (+) stover plots − N from nonnod (−) stover plot (Equation 3).
[b] Calculated as the difference between the nonnod (−) stover treatment and the fixing cultivars (−) stover treatments (Equation 7).
[c] N balance estimate, calculated as the difference between (+) stover and (−) stover plots for each cultivar (Equation 4).
[d] Direct ^{15}N estimate, see text for explanation (Equation 5).
[e] ^{15}N estimate, see text for explanation (Equation 6).

inputs (29–64 kg N ha^{-1}) also compare well with the findings of other workers with groundnut in the tropics e.g. 42 and 38 kg N ha^{-1} (calculated from Suwanarit et al., 1986; Dakora et al., 1987) respectively. It has been demonstrated that for there to be a net input of nitrogen to the system the % N from N_2-fixation must be greater than the % of total N removed in the harvest (Giller et al., 1993; Myers and Wood, 1986). In this experiment, 30–47% of the groundnut N was removed in the grain which was well below the amounts fixed and so the net benefits of N to the system from N_2-fixation were reasonably high. Where N_2-fixation rates are low or where the N harvest index is very high the legume crop will cause a net drain of soil N (e.g. Sisworo et al., 1990). This drain is usually considerably less than that caused by cereal crops, however, which can easily remove 60–100 kg N ha^{-1} per year or more depending on the crop (Giller et al., 1993).

In a separate field study using litter bags to measure the rate of weight loss from groundnut residues more than 50% of the N and C was lost from the bags in the first two weeks after incorporation of the residues (McDonagh, unpublished results). This suggests the decomposition of the groundnut residues in these soils is very rapid under favourable conditions with a danger of large losses through leaching before the N demand of the following maize matches the supply. However, although there was an unexpectedly long delay between residue incorporation and maize planting (28 days), the maize still derived a high proportion of its N from the groundnut residue. It is apparent that although studies with litterbags are useful for indicating the speed of the initial breakdown processes, they tell us little about the timing of availability of the resulting nutrients to plants or about the potential for likely leaching losses from the soil.

Maize

Dakora et al. (1987) reported maize grain yield increases of 89% when grown after groundnut as compared with a non fertilized fallow which was equivalent to the response from additions of 60 kg ha^{-1} of inorganic N. This agrees well with our data where increases of up to 65% (Table 5) were observed where groundnut residues were returned, approximately equivalent to the response from addition of 75 kg N ha^{-1} as urea to a fallow treatment. The increases in maize yield and total N in plots where groundnut stover was returned indicate that the residue was of benefit to the following crop and, as there was a similar response from the inorganic N application, much of this benefit can be attributed to the N in the residue. Improvements in soil water holding capacity and cation exchange capacity may have contributed to the observed benefit, but were probably of minor importance in comparison with the nitrogen effect.

Total residual N and residual N from below ground

The actual benefits of residual N in the maize crop supplied by the groundnut residue can be calculated in many ways. Estimates of total residual N include any below ground or fallen leaf contributions which would not show up in the comparison between (+) stover and (−) stover plots and these fit approximately with the amounts of N in the residues for each cultivar. The largest estimate (27.5 kg N ha^{-1}) was in maize grown after groundnut cultivar KK 60-3 which was the cultivar with the highest stover N content (130 kg N ha^{-1}) and the highest calculated net input from fixation (64 kg N ha^{-1}, Table 3) whereas the other cultivars all had similar stover N contents (around 100 kg N ha^{-1}) and similar total residual N estimates in the following maize (Table 2).

It is important to know if there can be a residual N contribution from the groundnut even when the stover is removed, which it usually is in farmers' fields in Northeast Thailand. This could come from below ground, e.g. nodule senescence, root exudation, decay of old roots and those left in the ground at harvest, or from natural leaf fall above ground before harvest. This estimate has been calculated as the difference in maize N from the (−) stover plots between the fixing cultivars and the nonnod cultivar (Table 7) and ranged from 0–9.6 kg N ha^{-1}. Cultivar Tainan 9, which had negligible leaf loss before harvest, apparently contributed nothing from below ground when the stover was removed. Conversely, the greatest contribution came from KK 60-3, the cultivar which lost most of its leaves just before harvest. This suggests that there was little significant contribution to soil N from below ground and that the apparent effect has been caused by N contributed from fallen leaves which would not have fallen in the absence of disease attack. This observation has important implications as it indicates that the contribution of groundnut to soil fertility is likely to be very small if the residues are removed from the land. Other legumes (e.g. soyabean) can be completely different in this respect where substantial leaf-fall before pod maturity is usual.

Residual N estimates from returned stover

The two ^{15}N based estimates and the N balance estimate all quantify the residual N in the maize from the groundnut stover returned to the (+) stover plots but removed from the (−) stover plots. These estimates do not include any below ground benefits associated with the groundnut crop (see above) or any residual benefit from natural leaf fall before harvest as both of these contributions would have been equal in the (+) stover and (−) stover plots. These three estimates, however should be directly comparable as they are all measuring the same effect.

i) Estimate 1

It is surprising that the highest residual N balance estimate was for the cultivar Tainan 9 which had the lowest residue N input and not after cultivar KK 60-3, which had the highest. This is probably related to residue quality. As mentioned above there was very little leaf fall in Tainan 9 so the stover contained a greater proportion of fresh leaves. With the other cultivars up to 50% of the stover nitrogen returned to the (+) stover plots was in leaves which had fallen due to disease in the week prior to harvest. The rapid loss of material from the little bags in the mineralization study suggest that much of the most easily released N from the residues would have been lost from these leaves before they were recovered and their remaining N would have been more resistant to decomposition. This argument also implies that the true total N production of the groundnut was probably much higher than was measured in the cultivars where leaf fall was significant. Few studies have been reported where fallen leaves are collected throughout the growth of the crop and, although it is often impractical or very difficult to do this, if leaf fall is not considered, legume N production may be greatly underestimated.

Residual N values of 11.9–21.3 kg N ha^{-1} may not appear very large when considering that the N in the stover ranged from 100–130 kg N ha^{-1}. This represents uptake of 12–26% of the N applied in the stover which is of a similar order to other reported uptake efficiencies from crop residues in the first crop after incorporation. Highly variable results have been reported however and the quality of the residue is clearly important. Sisworo et al. (1990) found recoveries in rice (^{15}N based) ranging from 11.4–27.5% of the N applied in cowpea residues with measurable recoveries in the sixth crop planted after residue incorporation and total recoveries of 44–73% after several cropping cycles. Where rice residues were incorporated only 2–4% of the N was taken up by the first crop with the second or third crop taking up more, presumably as immobilized N was released. In a pot study only 5% of the applied N in *Sesbania aculeata* was taken up by a crop of maize (Azam et al., 1985).

ii) Estimate 2

The residual N estimates made by the direct ^{15}N method were consistently about 50% of the N balance estimates. This may be because the addition of groundnut residue stimulated mineralization of native soil organic matter and release of N which was then taken up by the maize and contributed to the observed differences in maize N from (+) stover and (−) stover plots, i.e. there was a nitrogen priming effect or an added nitrogen interaction (ANI). However, as the soils were particularly infertile with very low amounts of N and organic matter it initially seems unlikely that these effects could have been so large. An alternative explanation is that the direct ^{15}N estimate was an underestimate of the residual N in the maize and that 'pool substitution' occurred to create an apparent ANI (cf. Jenkinson et al., 1985; Fox et al., 1990). This is when ^{15}N mineralized from the residue is taken up in the place of soil N by a process such as immobilization resulting in a dilution of the ^{15}N concentration of the residue N available for uptake by a subsequent crop. It is difficult to prove this occurred but the consistency and magnitude of the discrepancy between estimates 1 and 2 across treatments does initially suggest that apparent ANIs may have been a factor in this experiment.

iii) Estimate 3

The variation in the indirect ^{15}N estimates (Estimate 3) was disappointingly high and we cannot attach great significance to these data. However, the values for estimate 3 are closer to estimate 2 than estimate 1 and this does allow us to be more confident about the direct ^{15}N estimates, and more reluctant to use apparent ANIs to explain the observed differences between estimates 1 and 2.

One of the key conditions to be met for an apparent ANI to occur is for the processes which are depleting the soil derived mineral N, we assume immobilization is the main process in this case, not to be greatly stimulated by the addition of the substrate. This assumption may be valid when considering an addition of inorganic nitrogen to the soil where the microorganisms are limited by carbon and may therefore not respond to added nitrogen, but the addition of a high quality plant residue represents an addition of carbon and nitrogen both of which rapidly become available. Such additions are known to stimulate microbial activity and immobilization and where the additions are large these activity increases may also be large. Pool substitution processes will operate in this situation but their effects are likely to be small in comparison to real priming effects caused by the nitrogen and carbon released from the residues.

The plot to plot variation found in maize ^{15}N enrichment was not obviously correlated with the ^{15}N content of the groundnut, ^{15}N removal by the groundnut or amounts of leaf-fall in each plot so we must assume that soil heterogeneity or variation in application of ^{15}N was the cause. This result does, however, indicate the importance of confirming rather than assuming that the plant-available ^{15}N in adjacent plots of homogeneous soil labelled in the same way and with identical cropping histories will be the same. A soil incubation test (e.g. using the method of Waring and Bremner, 1964) to ascertain the ^{15}N content of the readily mineralizable N, or the ^{15}N uptake of a fast growing test plant would be more reliable methods of estimating the ^{15}N enrichment of available soil N shortly before incorporation of the residue. This also illustrates the importance of relative pool sizes when using ^{15}N as a tracer. The N content of the groundnut residue would have been small in comparison to the soil N pool and small variations from plot to plot in the latter would have masked any dilution in the (+) stover plots caused by unlabelled N additions.

This work demonstrates the considerable ability of local groundnut cultivars to fix atmospheric nitrogen and the benefits possible from returning and incorporating legume residues to the soil in the upland cropping systems of Northeast Thailand. Neither of the ^{15}N-based estimates agreed well with the N balance estimates of residual N in the maize and, although pool substitution probably contributed to this discrepancy we believe a nitrogen priming effect on mineralization of soil derived N was more significant. It is clear that ^{15}N labelled residues are extremely valuable tools for providing information on processes and interactions involving nitrogen in the soil.

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