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Testing the safety-net role of hedgerow tree roots by ^{15}N placement at different soil depths

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Abstract. Trees which root below crops may have a beneficial role in simultaneous agroforestry systems by intercepting and recycling nutrients which leach below the crop rooting zone. They may also compete less strongly for nutrients than trees which root mainly within the same zone as crops. To test these hypotheses we placed highly enriched ^{15}N-labelled ammonium sulphate at three depths in the soil between mixed hedgerows of the shallow-rooting *Gliricidia sepium* and the deep rooting *Peltophorum dasyrrhachis*. A year after the isotope application most of the residual ^{15}N in the soil remained close to the injection points due to the joint application with a carbon source which promoted ^{15}N immobilization. Temporal ^{15}N uptake patterns (two-weekly leaf sub-sampling) as well as total ^{15}N recovery measurements suggested that *Peltophorum* obtained more N from the subsoil than *Gliricidia*. Despite this *Gliricidia* appeared to compete weakly with the crop for N as it recovered little ^{15}N from any depth but obtained an estimated 44–58% of its N from atmospheric N_2-fixation. *Gliricidia* took up an estimated 21 kg N ha^{-1} and Peltophorum an estimated 42 kg N ha^{-1} from beneath the main crop rooting zone. The results demonstrate that direct placement of ^{15}N can be used to identify N sourcing by trees and crops in simultaneous agroforestry systems, although the heterogeneity of tree root distributions needs to be taken into account when designing experiments.

Introduction

Where crop roots are restricted, as at early crop growth stages or in soils which have chemical or physical barriers to root growth at depth, nutrients are easily leached beyond the reach of crop roots. This is particularly true of mineral nitrogen, which is poorly retained in soils. The presence of trees in fields will improve overall nutrient use efficiency if these trees actively take up nutrients which would otherwise have been lost by leaching (Young, 1997). The idea that recycling by trees of nutrients which have leached beyond the range of crop roots is of benefit to the nutrient balance of a field has become known as the safety – net hypothesis (van Noordwijk et al., 1996; van Noordwijk et al., 1992). This may be contrasted with a 'nutrient pump' role, where trees are taking up nutrients from deep soil layers or groundwater which have not recently passed through the crop rooting zone (Cannell et al., 1996).

N dynamics in mixed cropping systems are complex. Trees may compete with crops for N in the surface soil layers. Spatial and temporal patterns of N release and uptake will be affected by such factors as the timing of N additions, the quality of pruning materials, and the degree of synchrony of crop and tree demand (Handayanto et al., 1997; Xu et al., 1993). In assessing the overall effect of incorporation of trees into cropping systems, the benefit of improved N use efficiency must be set against competition for and uptake of N which would otherwise have been used by the crop (Cannell et al., 1996). In general, good intercropping trees are likely to be those whose spatio-temporal pattern of N uptake overlaps little with that of the crop.

Prediction of yield from a mixed cropping system also requires estimation of other interactions, such as shading effects, and competition for water. The design of productive, locally adapted agroforestry systems will remain largely a process of trial and error unless a mechanistic understanding of these processes is reached. The development of complex models is helping to facilitate understanding of the overall effects of tree – crop interactions, but must be accompanied by field validation (Cadisch et al., 1997; van Noordwijk, 1996). This study was designed in part to provide data suitable for comparison with simulated data produced using the WaNuLCAS model (van Noordwijk and Lusiana, 1997). This model incorporates a detailed treatment of soil N processes and plant uptake from up to 12 soil compartments.

Hedgerow intercropping trials in North Lampung showed that *Peltophorum dasyrrhachis*, a relatively slow growing, non-nodulating leguminous tree, had a stronger positive effect on sustained crop yields than *Gliricidia sepium*, a tree which fixes nitrogen and produces abundant high quality prunings (van Noordwijk et al., 1997a). *Peltophorum* has a sparse root system which extends deeply into the soil. In contrast, *Gliricidia* has a dense, shallow root system largely coincident with that of annual crop species (Akiefnawati 1995; Hairiah et al., 1992). The present study was designed to test the specific hypotheses that the more deeply rooted *Peltophorum* takes up more N from the subsoil, and competes with the crop less strongly for topsoil N, than *Gliricidia*.

A direct test of root activity was made, by placement of ^{15}N at different soil depths in the hedgerow intercropping system and measurement of relative recovery by trees and crops. In studies of root activity distributions, ^{32}P has been more generally used than ^{15}N (IAEA, 1975). Phosphorus is likely to remain within a relatively restricted soil location, in contrast to N which is highly mobile in soils. Both ionic forms of N have low adsorption coefficients (defined as the ratio of adsorbed ions to ions in solution) and are therefore subject to rapid leaching (Wong et al., 1990). The mobility of N may be limited by the addition of a carbon source to stimulate immobilization and gradual re-release of labelled nitrogen (Witty and Ritz, 1984), and this was the method used here.

Materials and methods

Study site

The experiment was set up on a farmer's field near the field station of Universitas Brawijaya/ICRAF in North Lampung, Sumatera, Indonesia (4°31′ S, 104°55′ E). Rainfall is 2000–2500 mm annually, with a wet season extending from November to May. Temperatures fluctuate little throughout the year, generally remaining in the range 25–35 °C (Van der Heide et al., 1992). The experiment was carried out during the second cropping cycle of the wet season.

The soils in the study area are Typic Kandiudults with pH (H_2O) around 5.2 in the topsoil and 4.8 in the subsoil. Aluminium in the subsoil solution reaches 106 μmol l^{-1} (Van der Heide et al., 1992). Total N varies from around 0.15% in the topsoil to 0.05% in the subsoil. Low pH and high concentrations of aluminium in the subsoil, associated with the presence of a plinthitic layer, severely restrict rooting depth of many species (Hairiah et al., 1991).

Hedgerows of *Gliricidia* and *Peltophorum* were established in the field four years previously. *Gliricidia* was established by planting stakes, *Peltophorum* by transplanting wildings (spontaneous seedlings). Alternating hedgerows of *Peltophorum* and *Gliricidia* were spaced 4 m apart, with a distance of 0.5 m between trees in the hedgerow. Van Noordwijk et al. (1997b) gave details of the establishment phase of this trial. Groundnut was sown on 15th April 1995. Seven rows were sown per alley, at a spacing of 0.5 × 0.25 m. Hedgerows were pruned before sowing, either at ground level or at 0.75 m stem height, and the prunings spread on the crop alley.

^{15}N recovery experiment

Placements of ^{15}N were made in the centre of the crop alley (between alternating *Gliricidia* and *Peltophorum* hedgerows), on 12th May 1995, 27 days after sowing the groundnut. Three placements were made at 5 cm and 35 cm soil depths, and two at 55 cm depth. Placements at the same soil depth were separated by a minimum of 4 m, and were made within the same alley. The separation between placements at different depths was at least 30 m. This compromise on the randomness of the design was considered essential to reduce the risk of contamination between treatments, particularly the chance that large recoveries would be attributed to deep placements because of horizontal foraging from shallow placements. Limitations of space, and the need for sufficient separation between placements, restricted the number of replications possible. For this reason the effects of hedgerow pruning height have been disregarded in this study.

Ammonium sulphate (20 atom % ^{15}N) was applied to the soil through plastic tubes installed in holes pre-augered to the required depth, ensuring a tight fit with the surrounding soil. Five tubes were installed per application site, 25 cm apart, in a 1 m strip along the centre of the crop alley. A 25 ml solution of 0.4 g N, mixed with sucrose to give a C:N ratio of 8:1, was applied through each tube. The carbon source was intended to stimulate microbial immobilization of the ^{15}N, maintaining it within a limited soil volume. Total N applied per site was thus 2 g, equivalent to approximately 20 kg ha^{-1}. Plastic tubes were capped after application.

Sample collection

Leaf samples were taken from trees and groundnut plants before ^{15}N placement and approximately every two weeks thereafter. Samples were taken from the first fully formed leaves on each shoot.

In each replicate, trees and crop plants from zones at different distances from ^{15}N placements were sampled separately. Hedgerows on each side of a placement were either of *Gliricidia* or *Peltophorum*. Hedgerow trees were sampled in two zones; the three trees perpendicular to a placement site ('centre') and three trees either side of these ('border': six trees). The six crop plants in the centre row adjacent to placement tubes were sampled ('centre'), six plants in rows on either side of these ('border': 12 plants), and two plants at either end of each of the 'centre' and 'border' rows (Zone 3: 12 plants) (Figure 1).

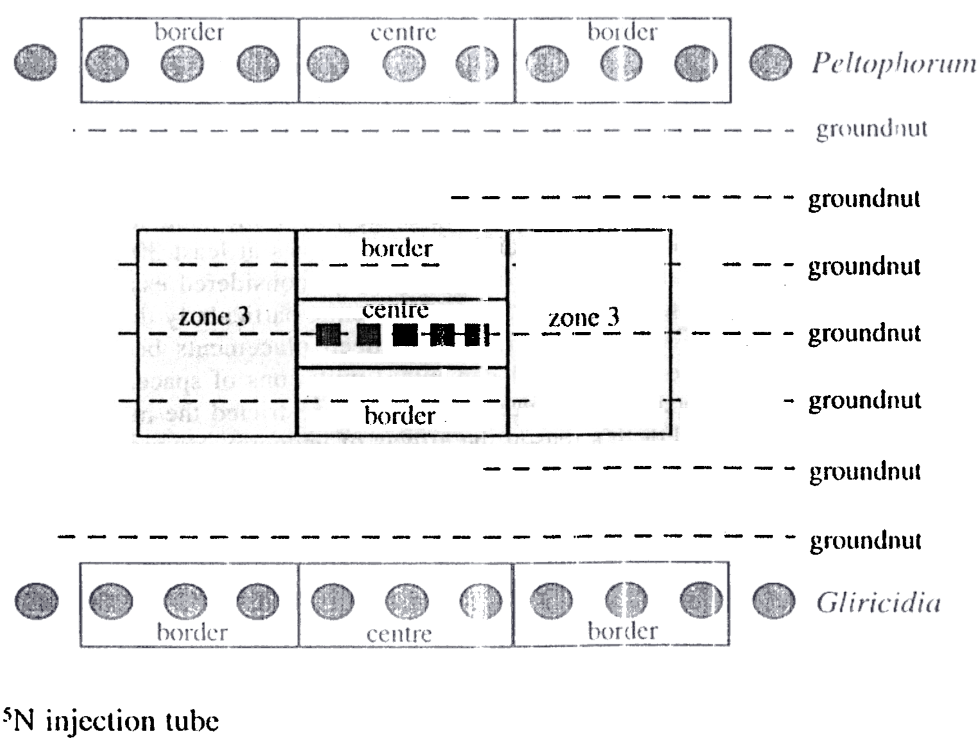

Figure 1. Layout of ^{15}N application plots in a hedgerow intercropping system at Brawijaya University in North Lampung, Sumatera, Indonesia.

Soil from the ^{15}N application points was sampled by augering 406 days after application. Samples were taken from beneath the five application tubes, and mixed to make composite samples for each depth interval. Samples were air dried and analysed for ^{15}N.

The ^{15}N enrichment of plant and soil samples was determined using a Europa 20/20 mass spectrometer (Europa Scientific, Crewe, UK) coupled to an automated C/N analyzer. ^{15}N enrichment is expressed as $\delta\ ^{15}N$ where $\delta\ ^{15}N$ (‰) was calculated as $1000 \times (\text{atom } \%_{sample} - \text{atom } \%_{reference}) / \text{atom } \%_{reference}$ and where atom $\%_{reference}$ is 0.3663%.

Groundnut plants were harvested on 14th July 1995, and divided into above – ground biomass, pods and roots. Trees were pruned on 19th May 1995 (*Gliricidia* trees only), and on 2nd November 1995 (all trees), and divided into leaf and stem. For harvest and pruning events the fresh weight of each sub-component was recorded, and subsamples were dried. Groundnut biomass subsamples were further divided after drying into stem and leaf, and pod subsamples were divided into husk and grain. Total dry weights were estimated for each component by multiplying total fresh weight by the subsample dry weight ratio. Each sub-component was analysed separately for ^{15}N and % N. Plant samples were ground in increasing order of predicted ^{15}N enrichment to reduce the effects of cross-contamination. Removal of ^{15}N in plants was calculated for pruning events and at groundnut harvest. ^{15}N removed in bi-weekly leaf samples was also quantified and included in the recovery calculation. Total ^{15}N uptake was calculated as the sum of excess ^{15}N removed in all plant parts. Natural ^{15}N levels of each species were used as background levels for calculation of ^{15}N excess. Proportional recovery of ^{15}N was calculated as the total recovery of ^{15}N excess in all plant parts divided by the excess ^{15}N applied.

% N recovery

$$100 \times \left(\frac{\sum_{i}^{n} \text{Dry weight} \times \%\,N / 100 \times (\delta\ ^{15}N_{sample} - \delta\ ^{15}N_{background})}{N_{fertilizer} \times (\delta\ ^{15}N_{fertilizer} - \delta\ ^{15}N_{background})} \right)$$

^{15}N in litterfall (which was negligible), and in tree roots and stumps, was not included. No ^{15}N enrichment was detected in groundnut samples from Zone 3 so these were not included in the analysis.

Biological nitrogen fixation

The proportions of N in groundnut and Gliricidia derived from atmospheric fixation were estimated from leaf samples taken the day before placement of ^{15}N, using the natural abundance method (Shearer and Kohl, 1986).

$$\%\ N \text{ from fixation} = 100 \times \frac{\delta\ ^{15}N_{reference\ plant} - \delta\ ^{15}N_{fixing\ plant}}{\delta\ ^{15}N_{reference\ plant} - B}$$

Where reference plants were *Peltophorum* samples taken the day before ^{15}N application and maize and rice samples collected in unlabelled control plots in the following season. B is the δ ^{15}N value for the fixing plant when grown on N – free medium. B values of –2.6 for groundnut shoots (G. Cadisch, 1997 unpublished) and –1.45 for *Gliricidia* prunings (Ladha et al., 1993) were used.

Statistical analysis

Analysis of variance was carried out on log or arc sin (% values) transformed values using Genstat (Payne et al., 1987) for species comparison within the same ^{15}N application depth. Due to the limited experimental design no statistical analysis was performed on data between ^{15}N application depths.

Results

The vertical pattern of recovery of ^{15}N in soil samples taken 406 days after ^{15}N application (Figure 2) showed, at least for the upper two positions, that

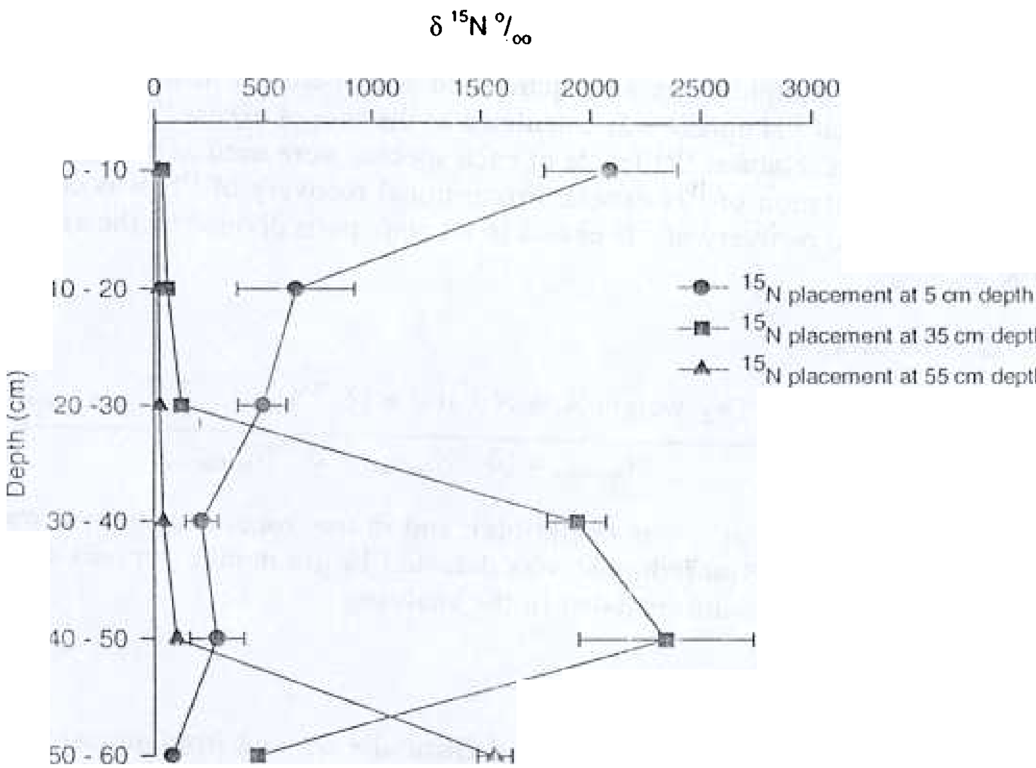

Figure 2. Residual δ ^{15}N ‰ in total soil N, 406 days after placement of $(^{15}NH_4)_2SO_4$ (20 atom % ^{15}N) in a hedgerow intercropping system in North Lampung, Indonesia, +/– the standard error of the means.

the location of ^{15}N was still clearly related to placement location. Differences in δ ^{15}N between sampling depths were significant ($P < 0.001$).

All species showed a consistent increase in ^{15}N enrichment in leaf samples taken during the first eight weeks after ^{15}N placement at 5 cm (Figure 3). Groundnut leaves had the highest isotope enrichment at all dates after ^{15}N placement, even from the deepest placement of 55 cm. *Gliricidia* leaves were only significantly enriched with ^{15}N placement at 5 cm depth, whereas placement depths of 35 and 55 cm gave only a small increase in ^{15}N above background levels. ^{15}N enrichment of *Peltophorum* leaves increased more markedly than *Gliricidia* at all placement depths, but particularly at lower depths.

The mean total ^{15}N recovery by 'centre' groundnut plants (0.125 m distance from the ^{15}N application site) from placements at 5 cm depth was 13.8% of the amount of ^{15}N applied (Table 1). Recovery declined with application depth, but even from 55 cm placements over 3% of ^{15}N applied was recovered. In groundnut, recovery by 'border' plants (0.5 m distance from the ^{15}N application site) was small in relation to that by 'centre' plants. In contrast, the trees recovered more similar amounts in 'border' and 'centre' zones. Recovery of ^{15}N by *Gliricidia* trees was similar at all depths and a small percentage (< 2.1%) of that applied. *Peltophorum* trees apparently recovered most ^{15}N from the lowest placement depth but the difference was not statistically significant due to the variability and low number of replicates.

Samples from border *Peltophorum* trees from two of the 35 cm placement depth plots showed very high enrichments, in one case resulting in calculated ^{15}N recovery greater than the amount applied. This suggests either that the subsamples analysed for ^{15}N content were not representative of the material from these trees, or that biomass estimates were inappropriate. Cross conta-

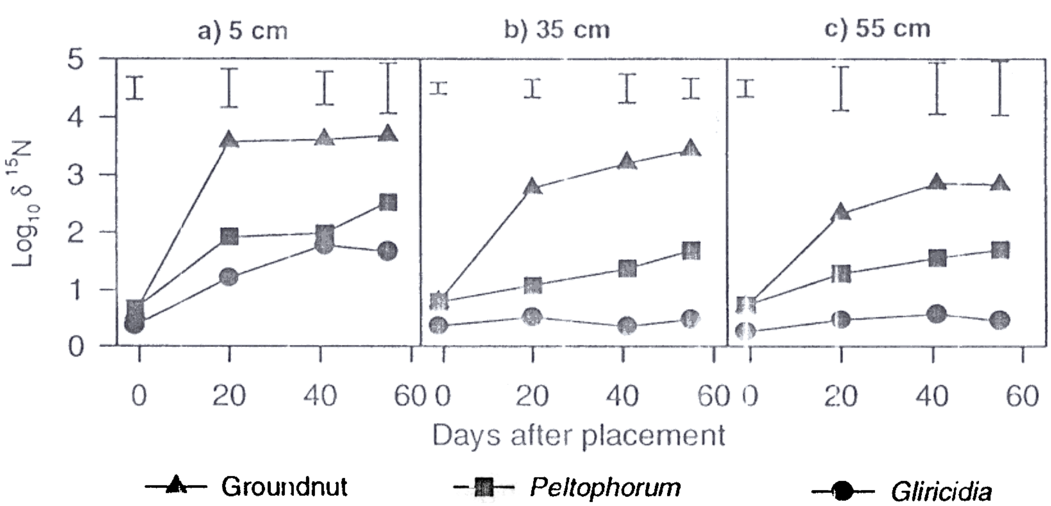

Figure 3. Changes in Log_{10} δ ^{15}N (‰) in leaves of groundnut, *Gliricidia* and *Peltophorum* after placements of ^{15}N at depths of 5 cm, 35 cm and 55 cm in a hedgerow intercropping system in North Lampung, Indonesia. Standard errors of the difference between means are shown.

Table 1. Measured total recovery of ^{15}N applied (per cent) by 'centre' and 'border' plants (relative to application site) at three soil depths by groundnut and hedgerow trees *Gliricidia* and *Peltophorum* in a hedgerow intercropping system in North Lampung, Indonesia. SE = Standard error of the mean.

Crop/Tree		^{15}N recovery (% of applied) ^{15}N placement depth					
		5 cm		35 cm		55 cm	
		Mean	SE	Mean	SE	Mean	SE
Groundnut	Centre	13.8	3.1	8.9	3.0	3.5	0.6
	Border	1.1	0.3	1.0	0.5	0.2	0.02
Gliricidia	Centre	0.3	0.1	0.2	0.1	0.2	0.1
	Border	2.1	0.9	0.2	0.1	0.7	0.1
Peltophorum	Centre	5.0	2.2	5.6	4.5	7.8	7.8
	Border	4.5	3.8	76.7	44.6	2.0	1.7
Total		26.7		* 92.6 * 15.9		14.5	

SE = Standard error of the mean.
* Including; ** Not including *Peltophorum* border recov

mination of samples during sample processing is unlikely since leaf and stem samples had similar high enrichments.

The non-fixing *Peltophorum*, maize and rice plant had higher $\delta\ ^{15}N$ signatures than the fixing legumes and were used as reference plants for the estimation of N_2 fixation by groundnut and *Gliricidia*. *Peltophorum* may have a deeper rooting profile than the fixing legume species (Hairiah et al., 1992) and thus may obtain N from different pools. This would make it unsuitable as a reference plant if isotopic enrichment changes with soil depth (Shearer and Kohl, 1986). However, natural abundance ($\delta\ ^{15}N$) of *Peltophorum* did not differ significantly from that in the more shallowly rooting maize and rice. Because it is not certain which is the best reference plant we expressed % N_2 fixation as the range obtained by using the different reference plants. The percentage of N in (26 day old) groundnut derived from atmospheric fixation was low (6–28%, Table 2), although this may have increased as the crop matured. *Gliricidia* derived approximately half of its N requirement from fixation.

Mean total removal of N in prunings from border and centre zones was 140 kg ha^{-1} (*Gliricidia*) and 99 kg ha^{-1} (*Peltophorum*) (Table 3). N production was significantly higher in *Gliricidia* ($P < 0.01$), but taking into account the amount of atmospheric N_2 fixation (50% or 70 kg N ha^{-1}, average of three estimates), *Gliricidia* abstracted less N from the soil. Assuming that the proportion of ^{15}N uptake from 55 cm depth to the sum of ^{15}N uptake from all depths was the same ratio as total soil N uptake from this depth (30% and

Table 2. Natural ^{15}N abundance values and estimated nitrogen derived from atmospheric fixation in a hedgerow intercropping system in North Lampung, Indonesia. Standard errors are given in parentheses.

	δ ^{15}N ‰	B*	%N derived from N_2 fixation
Peltophorum (reference)	5.5 (0.4)		
Maize (reference)	6.0 (1.0)	–	–
Rice (reference)	7.9 (1.6)	–	–
Gliricidia	2.4 (0.4)	–1.45	44–58
Groundnut	5.0 (0.8)	–2.6	6–28

* B values (δ ^{15}N of plants grown in N free medium) obtained from Ladha et al. (1993) (*Gliricidia*) and Cadisch (unpublished data) (groundnut).

Table 3. Total removal of N in tree prunings, N fixation and N uptake from the soil over 203 days in a hedgerow intercropping system in North Lampung, Indonesia. Standard errors are given in parentheses.

	N in prunings (kg ha^{-1})	N fixation (kg ha^{-1})	N uptake from soil[a] (kg ha^{-1})	N uptake from safety-net zone[a] (kg ha^{-1})
Gliricidia	140 (8.9)	70	70	21
Peltophorum	99 (6.7)	0	99	42
SED	11.2**		8.1**	

[a] Total uptake of soil N was calculated assuming that *Gliricidia* obtains 50% of its N from fixation. Uptake from the safety-net zone was deduced from the proportion of ^{15}N recovery below 55 cm depth.

42% for *Gliricidia* and *Peltophorum* respectively), total soil N uptake from this safety-net zone (55 cm) was 21 kg ha^{-1} for *Gliricidia* and 40 kg ha^{-1} for *Peltophorum*.

Discussion

Atkinson et al. (1978) used ^{15}N placement in orchard tree based systems previously but their aim was to evaluate fertilizer N use efficiency (herbicide vs. grass cover) and the deepest application was 0.2 m. Our results suggest that direct ^{15}N placement has great potential for study of root activity in agroforestry systems as well as giving indications about the potential role of tree roots to act as a safety-net. The method of applying ^{15}N with a carbon source was successful in restricting its movement within the soil (Figure 2), which is essential to attribute root activity to defined rooting depths. ^{15}N enrichments obtained were sufficiently above background natural enrichments to quantify percentage recovery, particularly considering the ability of modern mass spectrometers to detect small differences in isotope enrichment. While treatment variation was acceptable in the groundnut crop, variation was large with the trees. This is likely to have resulted in part from heterogeneity in root distributions, and highlights the need for larger numbers of replicates for each treatment for future applications. This heterogeneity may be more pronounced in the centre of the crop alley, and ^{15}N application closer to the hedgerow may give higher and more consistent values for safety-net recovery.

The data set presented here is consistent with the hypothesis that *Peltophorum* takes up more N from deeper soil layers than *Gliricidia*. While ^{15}N recovery by groundnut decreased sharply with increasing depth of ^{15}N placement, recovery of ^{15}N by 'centre' trees (opposite ^{15}N placements) was similar at all depths. *Peltophorum* roots maintained their high activity at all depths and apparently took up more ^{15}N than *Gliricidia*. However, the high enrichment of some 'border' *Peltophorum* trees highlights the heterogeneity in root distributions. *Peltophorum* roots may extend 4 m or more from the stem (Rowe, pers. obs.) and individual trees may show a considerable variation in ^{15}N recovery according to the location of their roots. This heterogeneity in root distribution is likely to increase with distance from the tree, thus reduced variability in ^{15}N recovery may be obtained by applying the isotope closer to the tree base. Measuring recovery of ^{15}N by individual trees rather than as a mean of several trees may give a clearer indication of the heterogeneity of root systems.

The second hypothesis, that *Peltophorum* competes less strongly than *Gliricidia* for topsoil N, is not supported by the data. *Gliricidia* recovered very little ^{15}N from any placement depth. This indicates that it did not compete strongly with groundnut for N in this case. However, since N recovery by trees was calculated from a pruning nearly four months after groundnut harvest, the conclusions that can be drawn about competition within the growth phase of the crop are limited. The small ^{15}N recovery by *Gliricidia* suggests that it derived a high proportion of nitrogen from atmospheric fixation, and this is confirmed by the natural ^{15}N abundance estimate of 44–58% N_2 fixation (Table 2). *Gliricidia* apparently has taken up a smaller proportion of its soil derived N from labelled pools than *Peltophorum*, perhaps because it has a smaller proportion of roots in the centre of the alley where ^{15}N was placed (Table 3). To take into account variation in root activity with distance from the tree it would be best to inject ^{15}N at points across the alley to obtain an integrated N uptake activity measurement. The similar root distributions of crops and *Gliricidia* found on this site by Akiefnawati (1995), with proportionally high topsoil and low subsoil root length densities, suggests a niche overlap and consequent strong competition for N (Vandermeer, 1990). Schroth and Zech (1995) argued that *Gliricidia* tree root length densities were too low to cause strong competition with the crop for soil resources but their measured root length density was lower than those found in our study area. Total N uptake by *Gliricidia* in this system was substantial and would represent considerable competition if *Gliricidia* were not obtaining N from another source. Overlap of uptake distribution for other nutrients and for water is likely, however, and *Gliricidia* may be expected to compete strongly for these resources.

Uptake of ^{15}N by groundnut declined with the depth of ^{15}N placement, but 3% of applied ^{15}N was still recovered from 55 cm placement depth, showing that groundnut roots do penetrate the subsoil. This may be because decaying tree roots in this established system have provided channels where aluminium toxicity is less extreme (van Noordwijk et al., 1991). There is however substantially less uptake from this depth by 'border' plants, suggesting that deep roots extend horizontally less than shallow roots.

Conclusions

The study provides insights into the distribution of root activity in a hedgerow intercropping system, and its influence on the degree of complementarity in the system. The evidence from ^{15}N in soil after 406 days suggests that the placement method used successfully maintained labelled N within the target soil layer. Enrichment of plant materials can therefore be traced with some degree of certainty to uptake from this soil layer. The potential for *Peltophorum* to act as a safety – net has been shown, since it is actively taking up a substantial proportion (42%) of its N from deeper soil layers. The results also suggest that root distribution is not the sole factor explaining N uptake distribution. For example, no evidence was found that *Gliricidia* was in strong competition with the crop for topsoil N, despite its predominantly shallow root distribution. Indeed, *Gliricidia* recovered little ^{15}N from any depth. This is in part because of the large proportion of N obtained from atmospheric fixation, but *Gliricidia* must also have taken up a smaller proportion of its soil-derived N from labelled pools.

A more detailed measurement of ^{15}N uptake activity across the alley would be needed to calculate a reliable balance for N and assess the degree of competition with the crop for N by these two trees in the whole system. Management techniques, such as the additional pruning which was applied to *Gliricidia* trees, are likely to have a major effect on the root activity pattern in space and time. However, the method used will assist with developing a mechanistic understanding of nitrogen dynamics in mixed cropping systems, and combined with WaNuLCAS, allows the safety – net efficiency of contrasting trees to be evaluated (Cadisch et al., 1997).

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