R.A. Date et al. (eds.), Plant Soil Interactions at Low pH, 779–784, 199
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Nitrogen supply from rotational or spatially zoned inclusion of Leguminosae for sustainable maize production on an acid soil in Indonesia

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Key words: alley cropping, *Calliandra*, covercrops, *Gliricidia*, legumes, maize, nitrogen recovery, *Peltophorum* root distribution

Abstract

On acid upland soils in the humid tropics, the combination of high leaching rates and shallow rooted crops may lead to low efficiencies of N use. Sustainability of crop production in this zone depends on either large amounts of external inputs, or on maximising efficiency of the use of local as well as small amounts of external resources. Additional sources of soil organic matter can be obtained by including leguminous cover crops in a rotational system or by spatially zoned systems, with a permanent presence of trees. In view of the high leaching rates, spatially zoned systems with deep-rooted trees may be more effective.

Long term soil fertility experiments were started on an Ultisol in Lampung, Sumatera, Indonesia. Data are discussed here for cropping systems based on rotations of maize and leguminous cover crops and for hedgerow intercropping systems (spatially zoned). Maize production in rotations with leguminous cover crops was highest when *Mucuna pruriens, Calopogonium mucunoides* or *C. caeruleum* were used. Compared to a grass-weed fallow control, an additional grain yield of 0.5–1 t ha^{-1} could be obtained. The efficiency of using biomass N was about 0.8 times that of using urea in two split applications. The best results for hedgerow intercropping, a maize yield increase of 1 t ha^{-1} over a control, were obtained with the local tree species *Peltophorum dasyrachis*.

Introduction

A large number of reasons may cause the non-sustainability of agricultural systems, sustainable systems being defined as those which meet a number of criteria at the *local* (farm/village), the *regional* (district/watershed), as well as at the *national* and *global* scale (Van der Heide et al., 1992). The mechanisms for responding to and correcting non-sustainable systems, depend on the scale. At the local scale the main problem to be considered is the trade-off between short term productivity and long term conservation of the resource base for future production.

The combination of high rainfall and shallow-rooted crops, due to Al toxicity of the subsoil, leads to severe problems in nutrient supply in the humid tropics on the acid soils (Oxisols and Ultisols) which are typical for this zone (Van Noordwijk et al., 1991a). N and P deficiency probably are the most severe constraints (Nye and Greenland, 1960). Due to its high mobility, N is of special interest in the humid tropics. For a site in southern Sumatera with an annual rainfall of 2.2 m, Van Noordwijk et al. (1992a) estimated, on the basis of a simple, one- dimensional leaching model, that the annual infiltration depth of nitrate (no adsorption) or ammonium (assumed adsorption or retardation constant 3) would, in the absence of surface runoff, be 3.0 or 0.8 m, respectively As the rooting depth of the major food crops maize, rice and soybean on this soil is only about 0.2, 0.5 and 0.4 m, the timing and placement of N supply by mineralisation and fertilisation is of crucial importance for increasing the efficiency of N use by improving synchrony and synlocation of N supply and demand (Van Noordwijk et al., 1992a).

Supplying N in organic sources might be more efficient than inorganic sources. Organic inputs are also needed to maintain soil organic matter levels. According to Young (1989) annual aboveground inputs of about 8.5 t ha^{-1} are required in order to maintain a soil carbon content of 2% (w/w) in an 11 cm top layer of a soil with a bulk density of 1.4 g cm^{-3}. According to Sitompul and Listyarini (1992), this target can not be met by only retaining crop residues in the field in cassava monocultures or cassava intercropped with maize or soybean and cowpea (estimated dry weight input 4.3, 5.1 and 5.2 t ha^{-1} yr^{-1}, respectively), but for cassava intercropped with upland rice the target can be met. In many farming systems part of the crop residues is used as fodder or fuel, so that the target is rarely met in practice.

When leguminous plants are to be included in the cropping system as source of nitrogen and additional source of organic matter, they should produce more biomass (and/or a higher fraction of this should be returned to the soil) than the crops or weeds which they replace. Two main options are: *rotational* systems, where an 'improved fallow' leads to accelerated soil fertility recovery, or *spatially zoned* systems where a zone is permanently reserved for this function. Under conditions of serious leaching, the second option may be more promising. For the first option, leguminous trees can be used if a number of years is available, or cover crops if only part of a cropping season is to be used; legume cover crops can yield 3–5 t ha^{-1} in 6 months (Hairiah et al., 1992a). For the second option hedgerows of regularly pruned trees have become a research interest in the past decade (Kang et al., 1989); regularly pruned hedgerow trees at a 4 m spacing can yield 4–12 t ha^{-1} (Hairiah et al., 1992b). Neither option has found wide farmer acceptance, but this may be partly due to technical reasons, such as the lack of suitable species for the local soil conditions. On acid soils a few successes with hedgerow intercropping have been obtained on research stations (Benites, 1990; Gichuru and Kang, 1989), but negative conclusions on the scope for including trees are common as well (Arya, 1990).

Data of five-year soil fertility experiments are reported here for a rotational system with various leguminous cover crops and for a hedgerow intercropping trial with a number of tree species, including the local tree species *Peltophorum dasyrachis*.

The main hypotheses addressed are: 1) under a high rainfall regime the efficiency of N transfer from organic inputs to crops is at least equal to that for inorganic fertiliser and 2) spatially zoned systems based on a deep-rooted tree are better for maintaining soil productivity for shallow rooted food crops than rotational systems.

Table 1. Urea fertiliser equivalent (UFE), total N content of cover crop biomass (TNC_c) minus that of the fallow grasses (TNC_g) and available nitrogen fraction (ANF) of five cover crops in rotation with maize; data for, on average, 6 months growth of cover crops; UFE = 60 × yield increase by preceding cover crop divided by yield increase by applying 60 kg ha^{-1} of N as urea; ANF = UFE/(TNC_c - TNC_g); TNC_g = 44 kg ha^{-1}

	UFE (kg ha^{-1})	TNC_c-TNC_g (kg ha^{-1})	ANF (%)
Mucuna pruriens utilis	57	69	83
Calopogonium caeruleum[a]	67	72	93
Calopogonium mucunoides	67	86	78
Centrosema pubescens	49	87	56
Crotalaria juncea	6	65	9

[a] In preceding years *Pueraria phaseoloides* and *Flemingia congesta* were used on these plots.

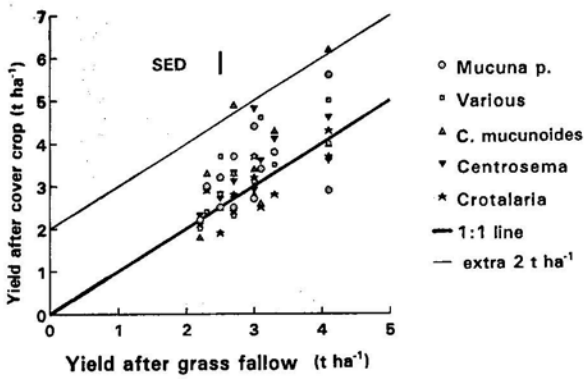

Fig. 1. Maize grain yield following cover crops (either for 6 months or for 3 months, flowed by a soybean crop) in relation to the yields after a grass/weed fallow; data for 4 years and two fertiliser N levels (0 and 60 kg ha^{-1}) are included; the 1:1 line and a line representing a yield benefit of 2 t ha^{-1} are indicated. SED indicates the standard error of differences within one year (after Utomo et al., 1992).

Material and methods

Experiments were carried out at Karta (4° 31'S, 104° 55'E) in N.Lampung (Sumatera, Indonesia), on a Grossarenic Kandiudult. The shallow topsoil layer of about 15 cm and the subsoil had pH(H_2O) of 4.5–5.0 and 4.5, organic C content of 1.5–2 and 0.5%, Bray

II extractable P content of 20 and 5 mg g^{-1} and Al saturation of the exchange complex of about 20 and 60%, respectively. Further description of the soil profile, field site and climate were given by Hairiah et al. (1991), Van der Heide et al. (1992), Van Noordwijk et al. (1992a). In view of the large spatial variability (Nugroho et al., 1992), yield data were obtained from relatively large plots and data for a number of years were jointly analysed.

An experiment with maize-soybean-cover crop rotations was carried out from 1986–1990. *Mucuna pruriens* var. *utilis*, *Calopogonium mucunoides*, *Centrosema pubescens* and *Crotalaria juncea* were grown each year for a period of 3 or 6 months. On one plot *Calopogonium caeruleum* was used in the last two years, preceded by *Pueraria phaseoloides* and *Flemingia congesta*. The cover crops were alternated by a single maize (cv Arjuna) crop or, when 3 months of cover crops were used, by a soybean (cv Wilis) - maize sequence. A grass/weed fallow was used as a control for the effects of leguminous cover crops. Nitrogen fertilisation (0 or 60 kg N ha^{-1} as urea, applied in two splits) was applied to the maize. The experiment was laid out as a completely randomised block design with three replicates and a plot size of 6 × 8 m. All crops of maize received a basal dressing of P, K and Zn. No soil tillage was used and all (cover) crop residues were left at the surface. Only maize grain yields are discussed here; further details were given by Hairiah et al. (1992a) and Utomo et al. (1992).

On the same field, a hedgerow intercropping experiment was carried out from 1987–1991. A maize-soybean-*Mucuna* rotation was intercropped in 4 m wide alleys between hedgerows of *Leucaena leucocephala*, *Erythrina orientalis*, *Gliricidia sepium*, *Calliandra calothyrsus*, the local tree *Peltophorum dasyrachis* or alternating hedgerows of *Gliricidia* and *Peltophorum*. Tree spacing in the hedgerows was 0.5 m. Five rows of maize (cv Arjuna) were planted at 0.75 × 0.4 m in the alleys. Control plots had the same maize population per ha, but spaced at 0.8 × 0.4 m. The experiment had two blocks and large plots: 24 × 16 m (3 alleys plus border strips). Further details were given by Hairiah et al. (1992b) and Sitompul and Listyarini (1992).

Previous reports have used the name *Peltophorum pterocarpa*. The correct name, however, is *P. dasyrachis* Kurz.

Results

Maize N response

Fertiliser N at 60 kg ha^{-1} increased maize grain yield by about 1 t ha^{-1} (Utomo et al., 1992). As the harvest index (grain yield divided by total biomass) was about 0.43, the average tissue N concentration in the vegetative parts 0.6% and in the grain 1.3%, this yield increase corresponds to an apparent N recovery of 35%.

Maize in rotations with cover crops

In a 3-month period, *Mucuna pruriens* var. *utilis* had the highest biomass production (about 2 t ha^{-1}) and N contribution (about 70 kg ha^{-1}) of the leguminous cover crops tested. In a 6-month growth period, the *Calopogonium* species and *Centrosema* performed best, with a biomass of about 5 t ha^{-1} and an N content of 100–200 kg ha^{-1} (Hairiah et al., 1992a). Figure 1 shows maize yields (for six growing seasons and two N fertiliser levels) following cover crops versus that of corresponding control plots with a grass/weed fallow of the same duration and N rate. Under the null-hypothesis of no treatment effects all points should be scattered around the 1:1 line. Most data are around or slightly above the 1:1 line. For *Crotalaria juncea* no overall positive effects were noted. In some cases a grain yield increase of 2 t ha^{-1} was obtained after a cover crop, but yield increases of 0.5–1 t ha^{-1} were more common. For an average cover crop growth period of 6 months, the maize response to cover crops is compared to that of urea fertiliser in Table 1. As a first step, the 'Urea Fertiliser Equivalent' (UFE) is calculated as the amount of urea fertiliser which would give the same yield increase as the cover crops. Next, the difference in N content was calculated between the leguminous cover crop and the grass/weed fallow which was used for deriving the fertiliser response. Finally, the 'Available Nitrogen Fraction', (ANF), was calculated as the ratio of these two parameters. For the two *Calopogonium* species and *Mucuna* the N supply from cover crop biomass was 80–90% as effective as that from urea, so the apparent N recovery (g/g) was around 30%. For *Centrosema* a relative efficiency of 50% was found (apparent N recovery 17%) and *Crotalaria* hardly led to any yield response, despite its high N content.

Table 2. Dry weight (t ha^{-1} yr^{-1}) and N concentration (% of dry weight) of prunings of leaves (incl. fine twigs) and stems (diameter less than 2 cm) obtained from hedgerow trees

	Leaf			Stems		% N	
Species	'88-'89	'90	'91	'90	'91	Leaf	Stem
Erythrina	4.5	2.4	6.4	2.1	4.0	3.6	1.6
Leucaena	8.0	6.9	2.8	6.9	1.7	4.5	1.2
Gliricidia	8.5	8.4	4.9	6.6	1.3	4.0	1.3
Peltophorum	8.0	6.0	12.2	2.3	3.6	2.9	0.8
Glir./Pelt.	8.0	8.5	9.2	3.3	2.8	3.9	1.5
Calliandra	12.5	10.4	4.0	6.3	2.0	4.0	1.5

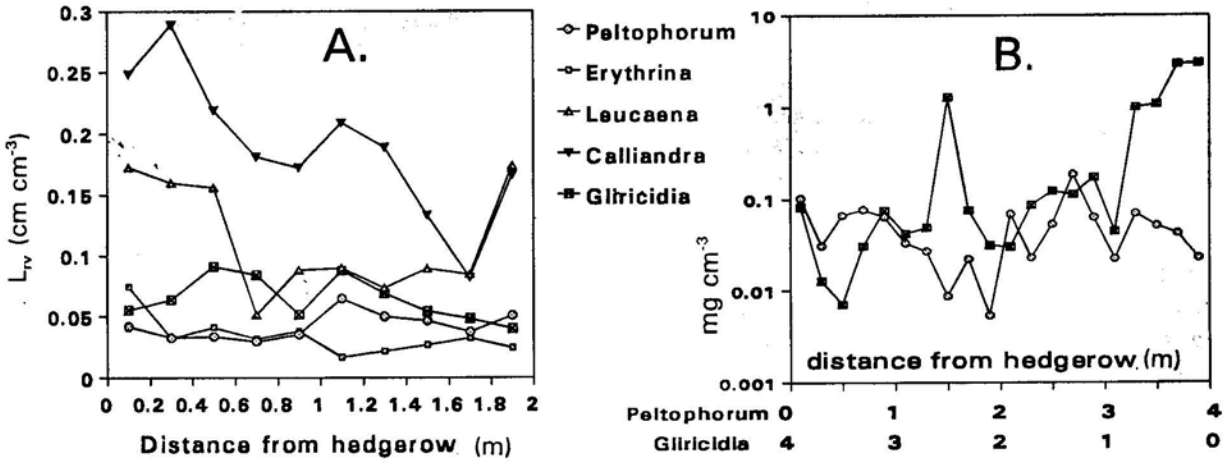

Fig. 2. **A.** Root length density, Lrv of five hedgerow trees in the (about 15 cm) as a function of distance to the nearest hedgerow, **B.** Root dry weight density of *Peltophorum* and *Gliricidia* grown in a alternating hedgerows (after Hairiah, 1992b).

Performance of hedgerow trees

Figure 2 shows the root distribution of the different hedgerow trees in the topsoil. *Calliandra* had the highest root length density in the topsoil, but this was still at least a factor 4 lower than the root length density recorded for maize on this soil (Van Noordwijk et al., 1992a). The data for the alternating hedgerows of *Gliricidia* and *Peltophorum* show that roots of both species (which can be easily distinguished by colour) extended over at least 4 m, until the next hedgerow. A nearly uniform tree root density was found in the alleys.

Table 2 summarises the pruned biomass production for the various trees. In the initial 3 years, *Calliandra* had the highest biomass production, *Erythrina* the lowest, and the other species all had a biomass production of about 8 t ha^{-1} $year^{-1}$ (Hairiah et al., 1992b). The biomass production by *Peltophorum* increased with time, while that of *Calliandra*, *Leucaena* and *Gliricidia* decreased. Many of the *Erythrina* trees died after a heavy pruning (cutting back to the original level) in 1991. *Peltophorum* had the lowest N concentration in its leaves. Total input of N from pruned leaves and twigs per year (data for 1990 and 1991) was 160, 220, 270, 260, 345 and 290 kg ha^{-1} for *Erythrina*, it Leucaena, *Gliricidia*, *Peltophorum*, the mixed plot and *Calliandra*, respectively.

Maize in hedgerow intercropping systems

Table 3 shows maize yields obtained in the alleys between hedgerow trees and maize yields in the control plots. Yields in the control plots were similar to those in the *Mucuna* rotation in the cover crop trial. For *Erythrina*, *Leucaena* or *Calliandra* no positive yield effect

Table 3. Maize grain yield (t ha^{-1}) in four cropping seasons in a hedgerow intercropping system. SED = standard error of differences. Fprob = probability of finding variance ratio as high as found under the null hypothesis of no treatment effects. For the overall average, seasons were treated as blocks

Treatment	Jan.'90 n = 2	Apr '90 n = 2	Jan.'91 n = 2	May '91 n = 2	Overall n=8
Control	1.50	1.73	3.60	2.26	2.30
Erythrina	2.08	2.28	2.80	2.28	2.35
Leucaena	1.40	2.50	2.94	2.02	2.21
Gliricidia	1.69	2.59	2.56	2.46	2.33
Peltophorum	2.99	2.68	4.56	3.04	3.32
Glir./Pelt.	2.31	2.00	3.13	2.73	2.55
Calliandra	1.08	2.70	2.99	2.42	2.30
Average	1.86	2.35	3.22	2.47	2.48
F-prob.	0.025	0.018	0.331	0.496	0.003
S.E.D.	0.38	0.21	0.79	0.47	0.27

of hedgerow intercropping was found. A statistically significant positive yield effect was found only for *Peltophorum*; on average the yield benefit was 1 t ha^{-1} of grain.

Discussion

Apparent N recovery of monocrop maize was about 35%, which agrees with model calculations for a similar climate and shallow-rooted maize crop by De Willigen and Van Noordwijk (1989). N use efficiency with the best cover crops (*Calopogonium* species and *Mucuna*) was slightly less than that with urea fertiliser, applied in two splits. The timing of N release from this biomass is apparently not optimal, so no improvement in recovery over inorganic fertiliser could be obtained. The lower available N fraction of *Centrosema* biomass (ANF, Table 1) corresponds with its slower N release under semi-controlled conditions (Handayanto et al., 1992). The very low ANF value for *Crotalaria juncea* is probably due to some form of allelopathic effect; maize germination was affected in these plots (Utomo et al., 1992).

Of the trees tested, the local species *Peltophorum dasyrachis* had the deepest root system (Hairiah et al., 1992b) and proved to be the only tree for which the positive effect on maize could compensate for the space reserved for the hedgerows, despite the fact that it was the only non-nodulated tree in the experiment. The N content of its prunings, 260 kg ha^{-1} yr^{-1} had been derived from either scavenging the topsoil or from its role as a 'safety-net' for leaching N, e.g. from the preceding *Mucuna* cover crop . Its N content was similar to that of other trees, which partly relied on N_2 fixation. The success of *Peltophorum* is probably not only due to its deep root distribution, however, a favourable, dense canopy shape and a high biomass per unit shade cast on the food crops may contributes to the success as well (Van Noordwijk et al., 1992b). If the yield increase of maize is compared with the amount of N in the prunings, a low ANF value is derived: 0.23 for *Peltophorum* and less than zero for other trees. This calculation does not take recycling of N into the hedgerow trees into account. Probably maize yield in the alleys is no longer limited by N supply, but by shade and a wider alley spacing might give better results.

Summarising, some supporting evidence was obtained for the hypothesis that spatially zoned systems based on a deep-rooted tree (safety-net) are better for maintaining soil productivity than rotational systems under a high rainfall regime. The choice of deep-rooted trees should, however, be made on the basis of local information. Negative effects of the pruning regime on the root distribution (Hairiah et al., 1992b; Van Noordwijk et al., 1991b) probably mean that a compromise must be found between pruning at a low stem height, which induces a shallow root system, and high pruning, which increases shading of the crop. An annual maize grain yield of 5 t ha^{-1}, obtained in two consecutive crops, can be considered adequate for the local conditions (Van der Heide et al., 1992). Based on a system with local hedgerow trees and a legume cover crop in the rotation, adequate productivity can be obtained for at least four years without the use of fertiliser N, but with some additional P supply.

Acknowledgements

The research reported here was carried out in cooperation between the DLO-Institute for Soil Fertility Research (IB-DLO, Haren, the Netherlands) and Brawijayah University (Malang, Indonesia) and financially supported by the EC (TS2–0069-NL) and the Dutch Ministry of Foreign Affairs (10/90/062). Thanks are due to Dr. K. Giller for critical comments on the manuscript.

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