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# GRAIN LEGUMES IN PEARL MILLET SYSTEMS IN NORTHERN NAMIBIA: AN ASSESSMENT OF POTENTIAL NITROGEN CONTRIBUTIONS

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## SUMMARY

A nutrient-balance model was used to investigate the nitrogen contributions of cowpea (*Vigna unguiculata*) to pearl millet (*Pennisetum glaucum*) intercropping systems in semi-arid northern Namibia. Data on nitrogen fixation, production, crop nitrogen off-take and competition effects came from two seasons of fieldwork. Supplementary data were taken from secondary sources. The model was used as a tool to attempt to identify grain legume management options with the potential to make significant contributions to soil fertility. The crop parameters pearl millet grain yield, nitrogen fixation rates, nitrogen harvest index and biomass production were found to be critical in determining system nitrogen inputs and outputs as was the form of residue management. The model indicated that it is extremely difficult to manage grain legumes in dryland environments in ways that lead to consistent increases in pearl millet grain yields, measurable against season-to-season variation due to other factors. Several of the options for improved legume management conflict strongly with farmers' risk-avoidance strategies and their tendency to invest preferentially in off-farm activities in an environment where livelihoods have diversified considerably away from agriculture. Potential routes for increasing grain legume contributions to soil fertility in dryland areas are discussed.

## INTRODUCTION

Expectations remain high that legumes have considerable potential to contribute to soil fertility and sustainable yield increases in semi-arid African farming systems (Palm *et al.*, 1997). Though grain legumes, particularly cowpea (*Vigna unguiculata*), occur widely in traditional cropping systems (e.g. Mortimore *et al.*, 1997) there are few signs of deliberate use of legumes for soil fertility management (SFM) by African farmers anywhere on the continent. The examples that exist are usually in relatively intensive production systems with a significant market orientation and, thus, are not typical of the smallholder, subsistence-based majority.

If legumes are to supply the nitrogen (N) required for increased cereal grain yields – pearl millet (*Pennisetum glaucum*) in this research – the N off-take by the cereal should be matched by $N_2$-fixation inputs from the legume. This is a crude assumption but nonetheless valid when looking for improvements in cereal production when soil nutrient stocks are low and legume N is the main input into the system.

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Table 1. Topsoil (0–0.3 m) characteristics in farmers' fields in North Central Region (NCR) and Kavango Region (from analysis of 33 samples from randomly chosen fields). Standard deviations in brackets.

| Region | pH ($H_2O$) | OM (%) | Olsen-P (mg $kg^{-1}$) | Sand (%) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|
| Mean for fields in: | | | | | | |
| NCR (n = 16) | 7.23 (0.62) | 0.51 (0.43) | 2.7 (1.2) | 87 (2.2) | 6 (1.8) | 7 (2.2) |
| Kavango (n = 17) | 7.17 (0.63) | 0.42 (0.19) | 1.9 (1.47) | 93 (3.6) | 3 (1.0) | 4 (2.0) |
| Overall mean | 7.19 (0.61) | 0.45 (0.31) | 4.1 (1.3) | 91 (3.7) | 4 (2.3) | 5 (2.2) |

A nitrogen-balance model developed using quantitative data from farmers' fields was combined with information on farmers' livelihood strategies to provide answers to a number of questions relating to legumes and soil fertility in semi-arid Africa through work undertaken in northern Namibia. These questions are:

1. Do grain legumes have the potential to make noticeable contributions of nitrogen to cereal-based cropping systems in semi-arid environments?
2. Are the changes in management practice required to realize the potential contributions of legumes to smallholder cereal production systems realistic?
3. What conditions stimulate or inhibit the inclination and ability of farmers to invest in soil fertility management in semi-arid areas?

## MATERIALS AND METHODS

The field research was conducted over two seasons (1998 and 1999) and data from the field provided the main parameters for the modelling activities in 2000. Measurements of legume density and grain and residue production were made in 30–52 farmers fields, across three study villages, during the two seasons of the field research.

### *Study area*

The research was conducted in two regions of northern Namibia, namely, North Central Region (NCR) and Kavango Region. The former has a long history of agriculture and though it has only 6.3 % of the total land area, it is home to 45 % of Namibia's population. There is a high settlement density throughout the region. Kavango Region neighbours NCR to the west. More recently settled, it is much more sparsely populated and extensively utilized than NCR, with most settlements clustered around watercourses and the few deep wells. Rainfall is a serious constraint across northern Namibia with annual totals of only 360 mm in western NCR, rising to approximately 600 mm in the east of Kavango Region.

Due to its complex drainage characteristics, NCR has a wider range of soil types than has Kavango, and some areas of quite fertile soil. In general, however, soils are sandy and infertile in both regions with marked deficiencies in nitrogen and phosphorus (P) (Table 1).

### *Livelihoods and farming systems*

Farmers' livelihoods are relatively diversified in northern Namibia. Keyler (1995) reports that, on average, only 20 % of household income is derived from agriculture, as compared with the average figure for Africa of 40 % (Ellis, 2000). Thus, as in many risky environments, farmers appear to have sought out off-farm income-generating options and these compete with agriculture for resources. This is a significant observation when considering farmers' ability to invest in soil management.

Pearl millet is the most common cereal crop in the area, accounting for 92 % and 84 % of the cereal grain harvested in NCR and Kavango respectively (Keyler, 1995). There are few measurements of pearl millet grain yields in farmers' fields, but they are thought to be mostly low (e.g. 200–400 kg $ha^{-1}$, Keyler, 1995). This average masks great variability but West African work in similar environments suggests that mean yields of 1200–1600 kg $ha^{-1}$ should be possible with improved management of soil fertility (e.g. Christianson *et al.*, 1990; Bationo *et al.*, 1993).

Farmers rate decline in soil fertility as the second most important farming-related problem in the study area, after unreliable rainfall, and this has pushed soil management up the development agenda in recent years. Clearly, both N and P requirements need to be met for moderate pearl millet yields (800–1000 kg $ha^{-1}$) and West African work indicates that modest N (20–30 kg $ha^{-1}$) and P (10–15 kg $ha^{-1}$) fertilizer application will dramatically improve yields in adequate rainfall years (Bationo *et al.*, 1992). Keyler (1995) looked at rainfall in northern Namibia over 23 seasons between 1969–1995 and concluded that the probability of rain (and crop) failure in northern Namibia is at least 50 % in any year. With such a high probability of crop failure, N fertilizer application to pearl millet cannot be recommended and, as in many similar environments, legume $N_2$-fixation has been proposed as one of the few alternatives to mineral fertilizers for improving N supply.

Local varieties of several grain legumes are widely known and cultivated. These include cowpea, groundnut (*Arachis hypogaea*) and Bambara groundnut (*Vigna subterranea*). With groundnut and Bambara, monocropping is common but usually restricted to small plots. Cowpea, however, is almost always intercropped with pearl millet. In the study area, erect or bushy indeterminate cowpea varieties are grown by most farmers. The importance of the pearl millet staple, lack of access to good seed, poor markets and high incidence of pests and diseases make legume monocropping in large plots difficult or unattractive.

'Improved' pearl millet/cowpea intercropping systems appear to offer potential for contributing legume N to the system. As 20–25 % of the residue N will become available to succeeding crops, incorporation of cowpea stover or other good quality residues before planting cereals has been shown to improve cereal yields (McDonagh *et al.*, 1993). However, legumes will only contribute directly to soil fertility if the residues are incorporated, and this conflicts with the use of legume residues as fodder.

### *$N_2$-fixation and production*

Nitrogen fixation was measured in 1998 (21 fields) and 1999 (52 fields) in legumes growing in farmers' fields across three study villages using the $^{15}N$ natural abundance technique (Shearer and Kohl, 1986). For each legume in each field, the aboveground parts of three hills were collected. The term hill is used to mean all the plants at a particular planting point in the field; it is common for an individual hill to consist of 2–3 individual plants. For each group of legumes sampled in a particular field, several non-fixing reference plants were also sampled in the same way and their mean $\delta^{15}$N signature was used in calculating the fixation estimates. In most cases it was possible to find three or all of the following reference species close to the legume: pearl millet, maize, sorghum, grass (unspecified species). Legume plants were sampled as far as possible at the time of maximum biomass, just before flowering. At the same time 10 $m^2$ samples of legume crop were taken (above-ground parts only) and air-dried, with a sub-sample oven-dried to give estimates of productivity. The nitrogen harvest index (NHI) of the legumes was calculated using N concentration (of grain and residues) and productivity data. Legume and reference samples for $N_2$-fixation analysis were air dried, chopped, mixed and sub-sampled. The sub-samples were then oven-dried, finely ground in a ball mill, weighed into tin capsules and analyzed for N and $\delta^{15}$N using an Europa Scientific 20–20 Isotope Ratio mass Spectrometer.

### *N-utilization efficiency*

Losses of N in legume residues can be high, particularly where large amounts are applied to sandy soils in the tropics (McDonagh *et al.*, 1993). Of the residue N 20–40 % is likely to become available to crops the year after incorporation, with additional increments in subsequent years. In the model, a total N-use efficiency (i.e. over several years) of 80 % has been assumed.

### *Modelling*

A spreadsheet model (using Microsoft Excel 97) was developed to quantify potential contributions from grain legumes to the N balance in the pearl millet intercropping system. Inputs and outputs and the main N transformations were quantified using standard methodology (Pieri, 1983; Stoorvogel *et al.*, 1993). Secondary data on N flows and transformations in semi-arid cereal systems were integrated with data collected in the field from the three study villages. There are many uncertainties with this type of modelling (e.g. Scoones and Toulmin, 1998) and in this work, whenever there was doubt over a numerical value a *best-case* approach was taken. For example, high N utilization use efficiencies (80 %) and low leaching/volatilization losses were assumed. This strategy ensured that the model was much more likely to over-estimate the potential size of the legume contribution to soil fertility than underestimate it.

The seasonal N balance (BAL) for a number of individual fields was calculated as follows:

$$\begin{aligned}\mathrm{BAL} &= \mathrm{Input} - \mathrm{Output}\\ \mathrm{Input} &= \mathrm{F} + \mathrm{Mf} + \mathrm{Mc} + \mathrm{Nfix} + \mathrm{Adep} + \mathrm{Hhw}\\ \mathrm{Output} &= \mathrm{Hg} + \mathrm{Rb} + \mathrm{Rg} + \mathrm{E} + \mathrm{L} + \mathrm{Dnit}\end{aligned}$$

Table 2. Provenance of data used in the nitrogen balance model.

| Model variables | Notation (NUTMON equivalent) | Description and assumptions |
|---|---|---|
| INPUTS | | |
| Fertilizers | F (IN1) | Estimated from farmer information on type and quantity. |
| Fresh manure | Mf (IN2c) | Assumed: 50 % of nitrogen taken in by grazing returned to same field as fresh manure; 60 % gaseous loss of residue derived N (Cadish *et al.*, 1994). |
| Kraal manure | Mc (IN2a) | Assumed: nitrogen concentration of 0.8 %, Based on analysis and secondary data (Bayer and Pietrowicz, 1986; Kasembe *et al.*, 1983; Kyomo and Chagula, 1983; Semoka *et al.*, 1992). |
| Pig manure | Mc (IN2b) | Assumed: nitrogen concentration of 0.4 %, (Kasembe *et al.*, 1983). |
| Nitrogen fixation | Nfix (IN4) | Field measurements used (see Table 3). |
| Atmospheric deposition | Adep (IN3) | NUTMON transfer functions used (Smaling and Fresco, 1993). |
| Compost and household waste | Hhw (IN2d) | Estimated from farmer information.<br>Assumed: nitrogen concentration of 1.1 % (Wortmann and Kaizzi, 1998). |
| Sedimentation | (IN5) | No estimates made. |
| OUTPUTS | | |
| Crop yields | Hg (OUT1) | Farmer estimates or set depending on objective of modelling scenario. Grain nitrogen concentrations taken from secondary sources e.g. 2.4 % N for pearl millet (Bationo, 1993; Rebafka *et al.*, 1994), 4.5 % N for cowpea (Bationo, 1993; Rebafka *et al.*, 1994). |
| Crop residues | Rb + Rg (OUT 2)[†] | Residue : grain ratios calculated from field data and applied for pearl millet (3.5 : 1) and cowpea (5 : 1). |
| Leaching | L (OUT3) | No estimates made but likely to be low in most fields. |
| Denitrification | Dnit (OUT4) | Assumed to be 30 % of applied mineral fertilizer N where applicable. |
| Erosion | E (OUT5) | No estimates made. |

[†] Rb = losses from burning residues, Rg = losses from grazing residues.

with variables as defined in Table 2. The equation is approximately equivalent to that used in the NUTMON model (Stoorvogel *et al.*, 1993), which is also detailed in Table 2.

Initially the model was run with ‘typical’ management and productivity data for an ‘average’ field, i.e. using mean values calculated from the field data for inputs and outputs. These consisted of a pearl millet grain yield of 300 kg $\text{ha}^{-1}$, a cowpea grain yield of 80 kg $\text{ha}^{-1}$ with pearl millet residues grazed and burnt, and cowpea residues neither grazed nor burnt. From this starting point, a number of changes were made to investigate the sensitivity of the model to productivity management, for example cowpea density changes, different residue management regimes (+/− grazing or burning) and different amounts of inputs.

A number of scenarios were tested with the pearl millet/cowpea intercropping system with the objective of identifying management options with the most potential to improve legume contributions to soil fertility.

Table 3. Mean millet and cowpea production based on measurements made in for 53 farmers fields in northern Namibia, 1999 (standard deviations in brackets).

| Crop | Grain ($kg\ ha^{-1}$) | Residue ($kg\ ha^{-1}$) | Mean hill weights ($g\ hill^{-1}$) | Mean residue : grain ratios | N harvest index |
|---|---|---|---|---|---|
| Pearl millet | 300 (115) | 1050 (432) | – | 3.5:1 | – |
| Cowpea | 80 (28) | 400 (188) | 60 (15.7) | 5.0:1 | 0.34 |

Table 4. Summary of nitrogen fixation data by species measured in farmers' fields in northern Namibia using the $^{15}N$ isotope dilution method.

| Species measured in 1998 | Nitrogen fixation ( %) | *s.d.* (n) | Species measured in 1999 | Nitrogen fixation ( %) | *s.d.* (n) |
|---|---|---|---|---|---|
| Cowpea | 33 | 26 (28) | Cowpea | 57 | 26 (84) |
| Bambara | 60 | 32 (8) | Bambara | 48 | 26 (2) |
| Groundnut | 32 | 18 (9) | Groundnut | 64 | 23 (10) |
| | | | Lablab | 50 | 25 (4) |
| | | | Mungbean | 29 | 30 (5) |
| | | | Pigeonpea | 45 | 31 (5) |

## RESULTS

### *Production*

Pearl millet and legume production data are given in Table 3. The pearl millet and cowpea yields provided by this data set were used to model the 'average' field described above. In this research, even in the small areas where legumes were monocropped, the average grain yield in farmers' fields was under 1 t $ha^{-1}$ (Hillyer and McDonagh, 1999). For comparison, 2 t $ha^{-1}$ would appear to be close to the maximum attainable by cowpea when intercropped with pearl millet in a rain-fed semi-arid environment; (Christianson *et al.*, 1990; Bationo *et al.*, 1993).

### *$N_2$-fixation*

In the first season, $N_2$-fixation estimates were found to be variable but low for cowpea and groundnut (32–33 %) and higher for Bambara (60 %, Table 4). The low figures for cowpea and groundnut were surprising as these legumes are considered to be relatively effective N fixers (Giller, 2001). In the second season, the corresponding estimates for cowpea were 57 % on average. Cowpea $N_2$-fixation was set at 30 % for initial scenarios and subsequently at 60 % (to represent 'best-case').

The NHI of the cowpea, a measure of the proportion of the accumulated N removed from the field, was 34 %. This is lower than many values reported for cowpea and other grain legumes (Giller *et al.*, 1993).

### *Nitrogen balance and legume contributions in an 'average' field*

The N balance for the 'average' field under 'typical' management was −8.3 kg $ha^{-1}$. The component fluxes are detailed in Table 5. Cowpea is cultivated at a density

Table 5. Nitrogen balance from an 'average' field (pearl millet and cowpea grain yields of 300 and 80 kg ha$^{-1}$ respectively with millet residues grazed and burnt cowpea residues neither grazed nor burnt). Component fluxes are derived from field measurements and secondary data as detailed in Table 2 and text.

| | Flux | Definition | N (kg ha$^{-1}$) |
|---|---|---|---|
| IN | F | Mineral fertilizer | 0.0 |
| | Mf | Manure | 0.3 |
| | Atdep | Atmospheric deposition | 3.4 |
| | $N_{fix}$ | Biological $N_2$-fixation | 6.4 |
| | Total in | | 10.1 |
| OUT | Hg | Harvest | 10.8 |
| | Rb + Rg | Residue burning and grazing losses | 7.6 |
| | Total out | | 18.4 |
| | NBAL | inputs – outputs | −8.3 |

of 6700 hills ha$^{-1}$ yielding 80 kg ha$^{-1}$ grain and 400 kg ha$^{-1}$ residue. The total $N_2$-fixation is 6.4 kg N ha$^{-1}$, 3.6 kg of which is removed in the grain. As the model assumes that the residue use efficiency (over several seasons) is 80 %, 20 % of the cowpea residue N is subtracted from the remaining 2.8 kg N to give a net N contribution of 1.4 kg ha$^{-1}$.

It has been shown that the competition between cowpea and pearl millet is strong if cowpea densities exceed 20 000 hills ha$^{-1}$ (Reddy *et al.*, 1992; Grema and Hess, 1994). In the model, setting the cowpea density to 20 000 hills ha$^{-1}$ gave a three-fold increase in cowpea grain yield. The associated rise in net legume N contributions increased the pearl millet grain yield by only 60 kg ha$^{-1}$. The calculations made by the model to arrive at this result are detailed in Table 6.

Using the model to look at the consequences of increased pearl millet yields, it is seen that if the cowpea-derived N is to drive pearl millet grain yields up to a more attractive level of 600 kg ha$^{-1}$ the cowpea net N input should be 13 kg N ha$^{-1}$. The model indicates that a cowpea residue production of over 10.5 t ha$^{-1}$ would be required to effect this, equivalent to an unrealistic cowpea density of 176 500 hills ha$^{-1}$ using mean measured cowpea hill weights. This is assuming a linear density/productivity relationship with cowpea, which would clearly not hold at these high densities, but the underlying result is that implausibly large increases in cowpea density would be required to provide a substantial N input.

### *Sensitivity analysis*

Figure 1 illustrates the effect of changes in particular model inputs or parameters on the N balance. The gradients of the linear relationships are given in Table 7 for the 'average' field (cowpea grain yield: 80 kg ha$^{-1}$) and the same field with a higher than average cowpea grain yield (200 kg ha$^{-1}$). The N balance is more sensitive to the size of the pearl millet harvest (gradient = −7.1) than anything else. However, even when the grain legume is a very small part of the system, $N_2$-fixation rate in the cowpea is almost as influential (gradient = 6.4). In cases of high cowpea grain production

Table 6. Detail of model calculations when estimating potential pearl millet grain yield increases associated with increasing cowpea densities from typical (6700 hills ha$^{-1}$) to maximum (20 000 hills ha$^{-1}$).

| Parameter/output | Legume density | | | | Assumptions |
|---|---|---|---|---|---|
| | 6700 hills ha$^{-1}$ | | 20 000 hills ha$^{-1}$ | | |
| | Grain (kg ha$^{-1}$) | Residue (kg ha$^{-1}$) | Grain (kg ha$^{-1}$) | Residue (kg ha$^{-1}$) | |
| 1. Legume production | 80 | 400 | 240 | 1200 | Cowpea hill dry weight = 60g[†]<br>Production increases linearly with density at these densities |
| 2. Legume nitrogen content | 3.6 | 7.0 | 10.8 | 21.0 | Grain: 4.5 % N<br>Residue: 1.75 % N |
| 3. Fixed legume N | 2.2 | 4.2 | 6.5 | 12.6 | $N_2$-fixation = 60 % (from field measurements) |
| 4. Soil derived N | 1.4 | 2.8 | 4.3 | 8.4 | Calculated: 2–3 |
| 5. Net legume N contribution to soil[‡] | 2.8 | | 8.3 | | NHI = 33 % (this is low: best case scenario) |
| 6. Amount of net legume N contribution taken up by pearl millet crop | 1.4 | | 4.1 | | 80 % N use efficiency by millet[¶] |
| 7. Maximum pearl millet grain yield response | 31 | 109 | 91 | 319 | Grain: 2.4 % N<br>Residue: 0.6 %<br>NHI: 22 % |

[†] Mean value from field measurements in 1999.

[‡] Net legume contribution to soil = fixed N in residues − soil derived N removed in grain.

[¶] The 80 % N use efficiency must be applied to the total residue N so 20 % of the total residue N is subtracted from the net $N_2$-fixation value to arrive at this figure.

(e.g. 200 kg ha$^{-1}$) the $N_2$-fixation rate is more than twice as influential than any other process or flow in determining the final N balance (gradient: 15.9, Table 7).

### *Legume residue management*

The N balance is also very sensitive to residue management (Table 8), particularly for cowpea. Grazing or burning the residues of this crop increases the system N deficit several fold and transforms the legume crop into a net N miner. The only residue management option that allows legumes to contribute N to the system is for the residues to be left in the field and protected from both grazing and burning.

## DISCUSSION

Even the poorest soil is likely to be able to bear the ‘average’ net N losses predicted by the model (−8.3 kg N ha$^{-1}$) for a long time. When cultivated, all soils mineralize a few per cent of their total N each season and, in this way, 25–30 kg N ha$^{-1}$ will be made available annually in most soils in northern Namibia. Thus, in a strictly biophysical sense these systems are able to operate ‘sustainably’ with consistent but small N deficits. This is providing farmers are able to plant early enough to catch the

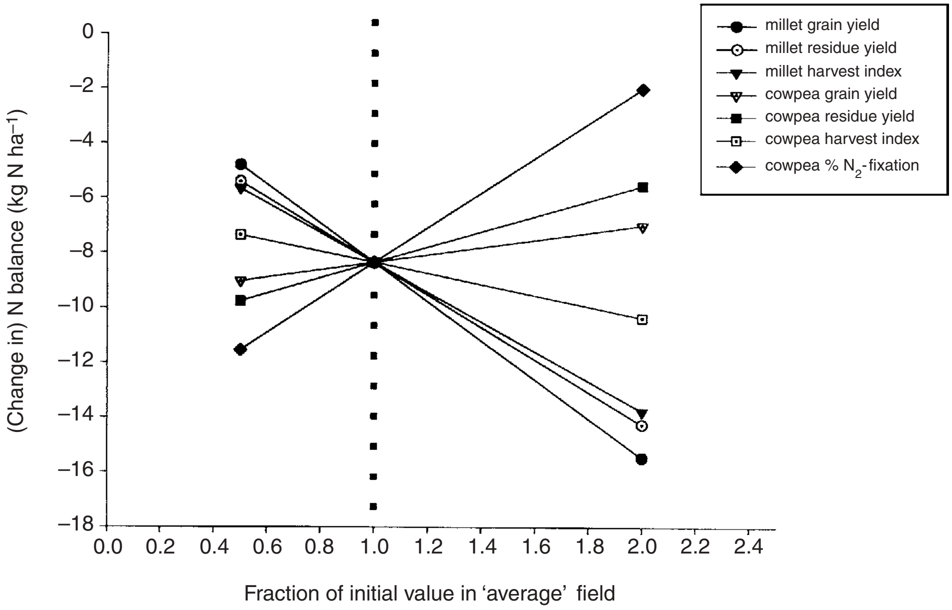

Figure 1. Sensitivity of the nitrogen balance for the 'average' field to changes in key model parameters. The effect of multiplying the original value by a factor of 0.5–2.0 is represented for each parameter.

Table 7. Gradients of linear relationships in Figure 1 indicating sensitivity of N balance to model parameters (i.e. the greater the value, the more sensitive the balance to the parameter).

| Cowpea grain yield (kg ha$^{-1}$) | Pearl millet | | | Cowpea | | | |
|---|---|---|---|---|---|---|---|
| | Grain | Residue | Harvest index | Gain | Residue | Harvest index | $N_2$-fixation |
| 80 | −7.1[†] | −5.9 | −5.4 | 1.4 | 2.8 | −2.0 | 6.4 |
| 200 | −7.1 | −5.9 | −5.4 | 3.4 | 7.0 | −5.0 | 15.9 |

[†] Units are effectively the change in N balance (in kg N ha$^{-1}$) cause by doubling the magnitude of the parameter in question.

Table 8. Sensitivity of model to residue management.

| | Nitrogen balance (kg ha$^{-1}$) | | | |
|---|---|---|---|---|
| | Residue grazed | | Residue not grazed | |
| Crop | Burnt[†] | Not burnt | Burnt | Not burnt |
| Pearl millet[‡] | −8.3 | −7.6 | −8.1 | −2.5 |
| Cowpea[¶] | −7.9 | −6.7 | −7.5 | −2.5 |

[†] The most likely situation (against which other scenarios are compared) is for pearl millet residues to be grazed and burnt and cowpea residues to be neither grazed nor burnt.

[‡] Assuming cowpea residues not grazed or burnt.

[¶] Assuming pearl millet residues not grazed or burnt.

first flush of nutrient mineralization with the onset of the rains. However, the pearl millet productivity (grain yield) is low, below potential (judging by what can be realized in similar environments) and frequently insufficient for farmer needs. Hence the potential value of legume-derived N to boost pearl millet yields.

The results from the modelling indicate that, in pearl millet/cowpea intercrops in northern Namibia, the technical constraints on grain legumes contributing to soil fertility are far more stringent than is often assumed by those promoting legume-based solutions to soil fertility. The $N_2$-fixation estimates for cowpea in 1998 were, at 33 %, approximately the same as its NHI. A crop fixing N at this rate, whatever its productivity and however the residues are managed, is unable to make a net N contribution to soil N. It is usually assumed that cowpea fixes a greater proportion of its N than this, particularly in poor soils, though published measurements from farmers' fields are few. The mean estimates of 60 % $N_2$-fixation for cowpea in the second season indicate a potential for net N contributions although it is clear that variability in the field is high.

If legume residues are grazed, much of the N will leave the field and that which is returned through manure is poorly conserved – subject to considerable losses through volatilization and denitrification (e.g. Cadish *et al.*, 1994). Similarly, most of the residue N is lost to the atmosphere if residues are burned. This imposes rather a strict residue management requirement on farmers, particularly for those with cattle: legume residues must not be grazed or burnt if the crop is to make a net N contribution to the system. The implications for grazing/burning pearl millet residues on the field N budget are fortunately, not so severe, as incorporation of pearl millet residues presents the farmer with potential problems related to land preparation and disease carry-over.

It is not solely the issue of residue management, however, that limits the utility of grain legumes in the system. Even when optimistic estimates are made of $N_2$-fixation, N-use efficiency, N losses and farmers' residue management, the model indicates that pearl millet grain yield increases as a result of inputs of legume N in residues are unlikely to exceed 100 kg ha$^{-1}$. Such an increase would be difficult to measure in farmers' fields against the 'noise' of yield variability caused by other influencing variables such as pest pressure and climate. If the effect is too small to see, it is unlikely that farmers would consider any significant management changes or investment to realize it. This also makes it difficult to convince farmers of the value of retaining legume residues in the field and so these resources are most likely to be used for fodder. This effectively converts the legume into a net miner of soil N.

These pessimistic modelling outputs suggest farmers may be reluctant to adopt new legume management measures that require even small amounts of investment (e.g. retaining residues in the field and increasing legume density) because they will not see improvements in cereal yield as a result of these changes. The benefits from using high quality residues to feed livestock are far more tangible and most farmers would be expected to use residues for this purpose. This does not, however, mean that legumes cannot contribute N to the system. The model demonstrates that some specific legume characteristics are vital in determining the size of the potential legume-N contribution. Examples of how these may be targeted are considered below:

*Identifying legumes with a low NHI.* Unfortunately, legume qualities useful for soil fertility (low NHI, large biomass production) often conflict with characteristics that make them suitable and attractive to crop breeders and farmers in marginal environments. Food production security is of primary concern in northern Namibia and short-duration grain legumes with high harvest indices (HI) are most likely to yield well. They are rarely able to deliver a net N input to the system, however. The 'fodder and grain' cowpea types produced at the International Institute of Tropical Agriculture (Singh *et al.*, 1997) do have a relatively low HI and show some promise with respect to soil fertility. If competition with pearl millet is to be avoided, however, the model suggests cowpea production and N inputs are unlikely to achieve levels that will impact measurably on soil fertility in the short term, even if farmers can be persuaded to protect the residues from grazing.

Legume green manures are a technically attractive option that effectively reduces the NHI to zero. However, this technology is notoriously *unattractive* to farmers when the legume does not provide a harvestable product. If a short-duration legume such as cowpea or mungbean (*Vigna radiata*) can be grown as a green manure before the main pearl millet crop, and yield edible green pods and/or leaves, this may appeal to farmers as a SFM strategy. The N-use efficiency of the legume N by the pearl millet can be high in such a system where the pearl millet crop is able to take up the legume residue N immediately. If farmers are to adopt a green manure it must grow prolifically, be easily managed and fit within the local farming system.

Pigeon pea (*Cajanus cajan*) is a grain legume with a very low HI and is of interest to farmers in northern Namibia. It may be difficult, however, to establish it in soils with low P and/or shallow soil pans. The crop competes very successfully for water with companion cereal crops when intercropped. This capacity to compete for moisture might make it unsuitable for wide-scale intercropping in environments as dry as northern Namibia, though work in Zimbabwe suggests this crop can be intercropped with maize without substantial cereal yield depression.

*Legumes better at fixing nitrogen.* Figure 1 illustrates the strong influence of mean $N_2$-fixation rate on the system N balance. Values for Bambara nut were double those measured in cowpea or groundnut in 1998, though cowpea fixation rates were higher in the second year. Bambara is indigenous to southern Africa and may, therefore, be better able to form effective symbiosis in these soils. However, although its fixation rates suggest this crop can contribute to soil fertility maintenance, it does not have the potential of cowpea in other respects. Bambara is less easily intercropped with cereals than cowpea and it does not have the remarkable adaptability and range of genotypes found with cowpea (Giller, 2001).

*Monocropping rather than intercropping legumes.* If monocropping is to have a significant effect over the whole field it needs to be practised on a large scale. Currently it is rare to see large legume plots in northern Namibia. The high susceptibility of legumes to pests makes them (cowpea particularly) high risk crops for farmers when chemical pest control is not used. This risk can only increase if legume monocropping is more widely practised. If markets for the grain legumes are secured, then monocropping with chemical pest control becomes a possibility.

### *Improving markets and soil fertility*

It is useful to step back from the predominantly technical analysis above to consider some of the non-biophysical factors that appear to have a strong effect on farmers' soil management decisions. From this work it is clear that farmers need to grow larger amounts and a greater range of grain legumes than at present if these crops are to contribute to soil fertility. A strong incentive to increase legume production would come from improved markets. It is not clear when, how or if better markets might develop in northern Namibia given a) its remoteness from regions of high demand, and b) its proximity to other countries (notably S. Africa), with environments and infrastructure more conducive to commercial crop production. Pearl millet has some potential for development as a cash crop in Namibia but little internationally. Even in some parts of Namibia, it is being replaced by maize as the staple of choice. This limits its value as a cash crop and, presumably therefore, the incentive for farmers to increase production beyond household consumption requirements.

In addition to the well-known examples of Machakos and Kano (in Kenya and Nigeria respectively: Tiffen *et al.*, 1994; Mortimore, 1998) there are many reported studies, particularly from semi-arid West Africa where rural communities have increased their investments in soil management and are reaping the benefits (Wiggins, 2000). The explanations for the success are complex but a number indicate that, whatever else was important, the existence of a large, accessible market provides an unparalleled opportunity for agricultural development. The agricultural production environment for farmers who can competitively access substantial markets is not just better but qualitatively different from northern Namibia and the majority of dryland Africa. This should be borne in mind when considering the possible replication of these successes elsewhere. Studies on high value cash crops and improvements in market structure and development are well directed in these environments but in most cases, the challenge of providing smallholder farmers with reasonable access to markets is too great. The drier semi-arid environments, such as northern Namibia suffer the handicap of rain (and crop) failure one year in every two – an additional disincentive to agricultural intensification and investment, even with increased market opportunities.

The livelihoods of people in northern Namibia have increasingly diversified away from agriculture over the last decade, partly to fill the gap caused by growing population and declining agricultural productivity. This movement away from agriculture is an historical and global phenomenon. It may be that Namibian farmers have had to diversify away from agriculture in response to declining yields and that they will return if agricultural options, notably cash-cropping opportunities, are improved. Alternatively, it may be that off-farm options will multiply and continue to be less risky than agriculture and that new on-farm activities need to be very attractive indeed to persuade farmers to increase the investments they make on farm.

## CONCLUSIONS

There are, of course, other reasons for including grain legumes in the cropping system that explain the popularity of cowpea, for example labour complementarity and value as a fodder and food crop (Mortimore *et al*., 1997). However, indications from this research are that grain legumes cannot substantially improve soil fertility in northern Namibia or similar dryland environments. Even if it is technically possible, and the modelling work reported here has shown it to be difficult, the unreliable rainfall, poor market access and diversified livelihoods of rural people prevent investment in soil fertility being attractive. There are some small rays of hope. One is finding a grain legume with a low NHI or a green manure well adapted to the environment and the pearl millet intercropping system. This crop would consistently fix N at high rates and produce large quantities of biomass requiring very little management. However, such a legume may not exist for semi-arid areas, as plant breeders have not yet managed to break the tight relationship between biomass production and water demands. If such crops do exist they will only be found by screening new germplasm in a representative biophysical and management environment.

Alternatively it could be accepted that most farmers are unlikely ever to grow grain legumes primarily for soil fertility. There is still value in identifying legumes interesting to farmers for other reasons (e.g. short duration, food, fodder) and that fill biophysical/management niches within the pearl millet intercropping system. Each will contribute a small amount to soil fertility in some years and the combined effect of several grain legumes could be measurable cereal yield increases.

Both routes require improved and long-term access to new legume germplasm for farmers and researchers, with the latter prepared to do much of their work on-farm in partnership with farmers. The final conclusion of this research is, however, that grain legumes are unlikely to make a large contribution to soil N in many dryland environments.

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