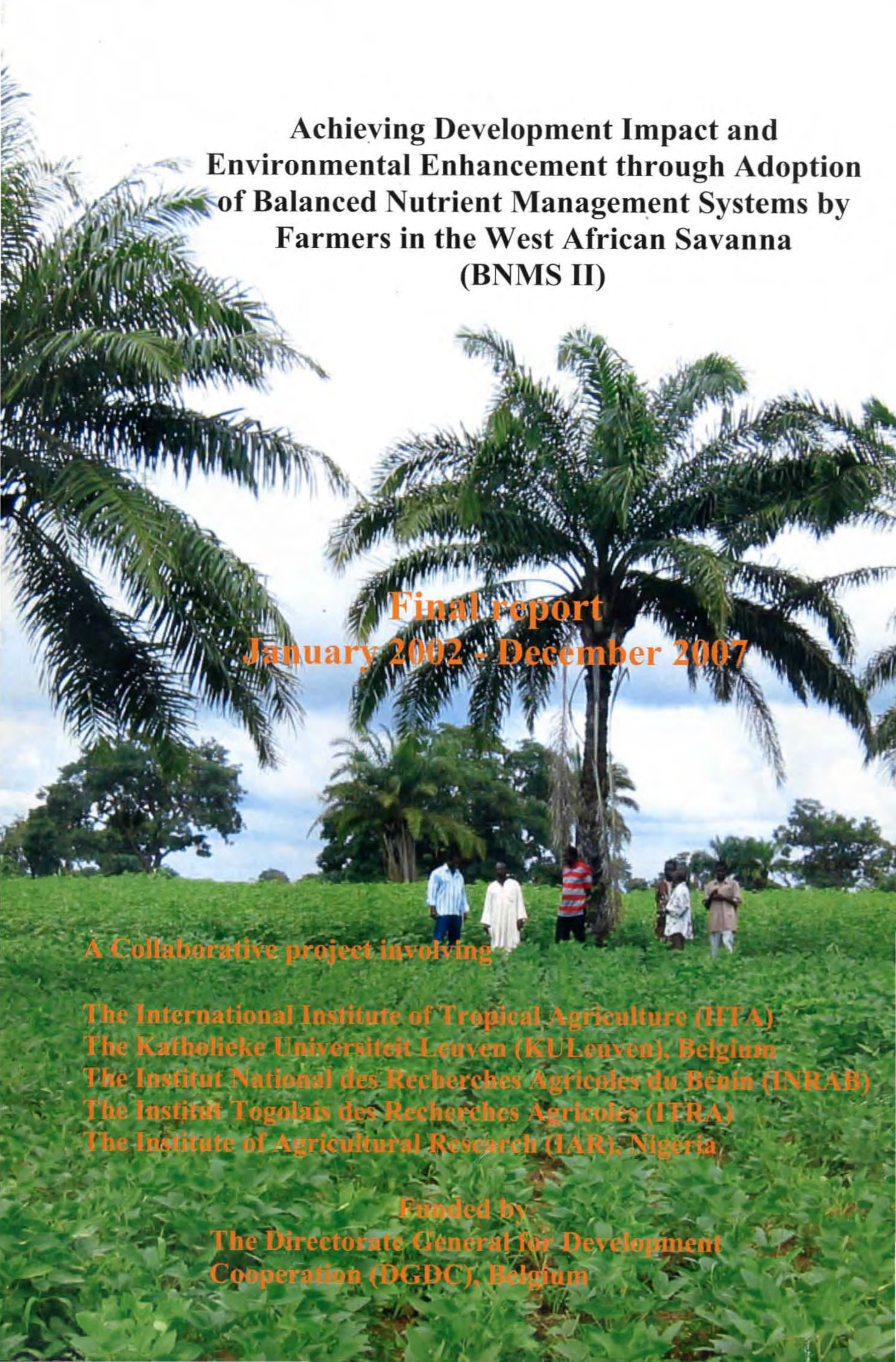

Achieving Development Impact and Environmental Enhancement through Adoption of Balanced Nutrient Management Systems by Farmers in the West African Savanna (BNMS II)

Final report
January 2002 - December 2007

A Collaborative project involving

The International Institute of Tropical Agriculture (IITA)
The Katholieke Universiteit Leuven (KULeuven), Belgium
The Institut National des Recherches Agricoles du Bénin (INRAB)
The Institut Togolais des Recherches Agricoles (ITRA)
The Institute of Agricultural Research (IAR), Nigeria

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I. Preface

The collaborative project between the *International Institute of Tropical Agriculture* (IITA) and the *Katholieke Universiteit Leuven* (KULeuven) on "Achieving Development Impact and Environmental Enhancement through Adoption of Balanced Nutrient Management Systems by Farmers in the West African Savanna (BNMS II)" started in 2002 and was funded for 5+1 years, until the end of 2007, the last year benefiting from a no-cost extension. The overall purpose of the project was to develop, test and promulgate balanced nutrient management system technologies specifically adapted to the local biophysical and socio-economic environments of the savanna, which enable a sustainable increase in farm productivity and profitability whilst improving overall soil fertility in maize-based farming systems. This work has been carried out in close partnership with farmers, NARS, NGOs, IITA, and KULeuven scientists.

The BNMSII project was built on a previous phase of the project (BNMSI), in turn building on several subsequent projects between IITA and KULeuven. From a purely basic research project on soil organic matter dynamics in 1987, the partners and the activities moved towards a much more impact-oriented set of interventions, fostering the continuum between process-oriented research and directly impact oriented work at farm level. One of the most important features of this collaboration is undeniably the long-term perspective that was created through the various phases since 1987. This allowed forging strong partnerships, capitalizing on the many trained local and Belgian staff and building on the foundations of a continuously growing expertise. It is no doubt unique in the development sector that donors appreciate the long-term perspective; specifically in natural resource management studies such a prerequisite. Therefore we express our sincere thanks to DGCD for this unique opportunity and the thrust they gave us.

The work in BNMSII was divided in the original proposal in several project outputs, which determined the layout of this final report. In the final year, during the no-cost extension, all the activities under the respective outputs were finalized and consolidated. We refer to the different annual reports that have been submitted annually for more details.

This report summarizes and highlights the activities conducted over the entire project period. Hence it summarizes the main achievements in Section II. Training and capacity building is summarized in section III, a list of scientific papers is to be found in section IV.

II. Research activity reports

As indicated above, only the highlights of the main activities are revived here. For more detailed information, we refer to the different annual reports and theses or publications that are all available on simple request.

Output 1: Biomass production increased to increase soil organic matter

Objectives

- To document existing quantitative information on biomass production, nutrient balances and soil fertility practices currently employed by farmers (both men and women) in the Derived Savanna and Northern Guinea savanna benchmark villages in Bénin and Nigeria respectively;
- To develop ways to grow adequate amounts of biomass on farm to provide for the necessary inputs to sustain yields and to optimize fertilizer use efficiency; to develop simple and non-labour intensive conservation/storage technologies for organic amendments (manure storage, appropriate mixtures of organic resources);
- To develop simulation models that predict biomass production and its effects on SOM build-up for a wide range of plants and soil types.

Several experiments conducted in phase I of the BNMS project indicated the benefits of combined applications of organic matter and fertilizer to crops, but the key question is always how this organic matter can be produced, and preserved over the dry season to be available at the time the cereal crop is planted.
While documenting existing information on biomass production and soil fertility practices, it came out that 2 zones of the savanna differed very much in the type of resources that can be explored for organic matter production and their management. In the Derived Savanna (DS) the dry season lasts from mid-November to mid-April whereas in the northern Guinea Savanna the dry season last longer. Options for organic matter production would therefore differ in the 2 areas.

Activity 1. Screen and select legume species and accessions through on-farm evaluation over a range of soils to identify potential soil-related constraints to production

(Details in the annual Reports 2002 and 2003, and in the PhD thesis of Mr K. Aihou)

In the Derived Savanna we focused our attention on *Cajanus cajan* as source of biomass because of its ability to stay green over the dry season and provide a sizable amount of organic matter at the time the next maize crop is planted in April (Figure 1). *Cajanus cajan* is one of the perennial shrub legumes known by farmers as a simultaneous fallow component in cropping systems. Being a shrubby grain legume, it is a source of protein (21%), as well as a source of N in maize-based cropping systems. But like other resource management technologies, the rate of adoption by farmers is very low, only 3%. *Cajanus cajan* has been tested as an agroforestry practice in alley cropping or in intercropping and it has been considered to be a resource management technology because of its dense biomass and also for its multipurpose uses. But due to low soil fertility, lack of adaptation of germplasm, vulnerability to pests and diseases, and large variability in *Cajanus cajan* yields, the rate of its adoption has been very low. *Cajanus cajan* could however diversify the cropping systems and serve as a source of protein, provided accessions can be introduced that can overcome the aforementioned constraints. The general objective of this trial was therefore to screen *Cajanus cajan* accessions for their ability to produce both an immediate return for the farmer (grains) and a sufficient quantity of OM. The organic matter needs to be preserved in-situ (as standing biomass or litter) over the dry season to provide half of the recommended N to a maize crop grown in the first season of the next year. We therefore conducted a screening study of cajanus accessions in on-farm conditions to identify varieties suited for organic matter production.

The screening was established in 2002 in a total of 9 farmers' fields, located in 3 villages situated around Allada, southern Bénin. In each field, 16 plots measuring 8 × 8 m were delineated, and the same 16 treatments established on each of the 9 fields. The treatments in 2002 involved maize-pigeon pea [*Cajanus cajan* (L.) Millsp.] intercropping and relay-cropping, to be followed by a maize test crop in the second year to quantify effects of the pigeon pea OM on a subsequent maize crop. The 16 treatments included 11 treatments with pigeon pea, 3 treatments with only maize in 2002 to allow the evaluation of N response in the second year's maize crop. The 11 pigeon pea treatments consisted of two long-duration (ICP 13555 and local variety) and 3 medium-duration (ICP 7184, ICP 7187, ICP 7898) varieties, planted as intercrop in maize during the first rainy season; and six short-duration varieties (ICP 85010, ICP 85063, ICP 8807, ICPL 161, ICPL 85010, ICPL 88039) planted in the second rainy season, after a crop of maize grown in the first rainy season.

Figure 1. Cajanus cajan at the beginning of the rainy season before being cut down to serve as organic matter for the next maize season

A visual observation, giving a score from 1 to 5, of the quantity of standing pigeon pea biomass and pigeon pea litter was made at the end of February 2003. In terms of standing

biomass and leaf litter present towards the end of the dry season, the local pigeon pea variety outperformed all the improved varieties, and consistently received a score of 4 and above in all fields. Among the improved varieties, the medium- and long-duration varieties, which were planted at the same time as the maize intercrop in May, had more biomass and litter than the short duration varieties, which were planted as a relay crop in the maize. Pigeon pea grain yield was low to negligible for all these varieties due to insect pest damage. Insect pest control by spraying proved difficult because of the indeterminate flowering characteristic of the longer-duration varieties.
The pigeon pea data indicate that the improved varieties were better first screened on-station together with a range of local accessions to identify a few possible 'winners' that can then be taken to on-farm testing. An integrated approach to avoid insect damage will be required. The data also indicate that short duration varieties that could be used as a second-season crop have less potential as a source of organic matter for the next year's cereal crop.

More than 96% of women and 90% of men recognize the role of *Cajanus cajan* in soil fertility improvement. The major driver of *Cajanus cajan* cropping appears to be food production although it is considered very useful for the treatment of common and dangerous diseases. Sustained cultivation of the crop in the study area is threatened by poor cropping techniques and pest/disease infestation.

An on-station screening was conducted comparing 10 varieties: 5 early and 5 medium *Cajanus cajan* maturing varieties. The observations of time to flowering and time to podding indicated that the classification of varieties into early or late maturing did not hold in the ecology where they were tested. There were significant difference in yield with ICP8863 giving the highest yields (2674 kg ha^{-1}) among the earlier maturing varieties, and ICP8807 the highest (1276 kg ha^{-1}) among the late maturing varieties.
Visual observed indicated that some varieties ICP8863 and ICP 7187 produced a large quantity of biomass in addition to having good grain yields.

Activity 2. Farmer-participatory testing of integrated crop-livestock systems including the preservation of organic amendments over the dry season in the northern Guinea savanna

(Details in the annual reports 2002-2006, and in the MSc hesis of Ms. I. Vandeplas)

In the northern Guinea savanna (NGS) keeping organic matter in the field as green or dead biomass until the start of the rainy season is impossible because of the longer dry season and the presence of livestock on the fields during the dry season.
Integrating crops with livestock production in intensified zero-grazing systems in West Africa creates opportunities to recycle nutrients and reduce fertilizer demands, preserve organic matter over the long dry season of the Guinea savanna and fulfil the increasing demand for livestock. Farmer-participatory testing and adaptation of integrated cereal-legume-livestock production systems is an important process contributing to the development of new technologies that facilitate the intensification of crop-livestock production and can be widely adopted by farmers.

Since 2002, 12 farmers in 3 villages (Hayin Dogo, Danayamaka and Ikuzeh in Kaduna State, northern Nigeria) in the dry Guinea savanna have been involved in testing best-bet (BB) options including: an improved continuous maize system with an option of relaying cowpea at the end of the season; residues of both crops were fed to goats and the manure produced was returned to the field along with a modest dose of fertilizer (BB1), a two-year maize-legume rotation; residues were exported and an increased dose of fertilizer was applied to maize (BB2), a two-year maize-legume rotation on two plots; residues of both crops were recycled as in BB1 and manure was returned to the maize plot only along with a modest dose of fertilizer (BB3). Legumes in BB2 and BB3 included either a long-duration soybean or groundnut. A cereal-based farmer's practice (FP) was included as well.

Maize yields were enhanced when rotated with legumes such as soybean or groundnut (BB2 and BB3), relative to continuous maize treatments in BB1 and in the FP treatment, highlighting the beneficial effect of incorporating legumes into maize-based systems of the Guinea savannas. Among the legume-maize rotations, no beneficial effect of the use of manure on maize yield was observed, relative to treatments where synthetic fertilizer only was used. Maize yields after legumes in the treatment without manure (BB2) were as good as, or better than, maize yields in treatments with the use of manure (BB3). Groundnut stover and grain yields were higher than soybean yields. In particularly, groundnut stover yields were relatively high, stressing the potential of groundnut to provide large quantities of fodder for animal feeding.
Within BB 2 and 3, maize in rotation with groundnut achieved a higher grain yield than maize in rotation with soybean in most years. The difference in maize yield between Gn/Sb-Mz rotations with and without the integration of livestock was small, though yield was slightly increased in BB2 without livestock. So, the combined application of manure and synthetic fertiliser to maize resulted in similar or slightly lower maize yield compared to the application of a higher dose of synthetic fertiliser only.

Between 1.7 and 4.4 t maize stover ha^{-1} were annually produced in the BB options with livestock and fed to goats over the dry season. Groundnut produced considerably higher quantities of stover than soybean. Also, stover production of maize after groundnut was higher than that of maize after soybean.
While the annual manure DM production in BB 1 was highest, the nutrient concentration in the manure was low. Also a large part of the goat feed was not produced in-situ in BB1, and consequently, the manure nutrient content of in-situ origin was low. In the Sb-Mz rotation (BB 3), the DM and nutrient contents of manure were also relatively low, primarily as a result of a low stover production in previous years. The Gn-Mz rotation, on the other hand, had the highest manure nutrient content of in-situ origin, because of a good stover production in previous years.

It may be feasible to further reduce DM and nutrient losses during stover and manure handling and storage and enhance the carry-over rate of DM and nutrients. However, covering approximately one-third of the nutrient demand of maize with in-situ produced manure may be regarded as a current upper limit of what can be achieved in zero-grazing cereal-legume-livestock systems in the dry savanna under on-farm, farmer-managed conditions.

Activity 3. Soil survey in the research villages Affem and Sessaro/Laoudè in Central Togo

(Details in annual reports 2005 and 2006)

Smallholder farmers effectively deal with soil variation by location-specific field management based on the crop performance and crop responses they observed in their fields over past years. On-farm research that aims to improve soil fertility management and productivity of small-scale farmers has to reckon with that soil variation, and has to come up with flexible recommendations rather than blanket recommendations. Blanket recommendations may raise the 'average' productivity in an area, but yield negative responses on part of the fields and farms, and therefore discredit extension messages. Flexible recommendations could be based on soil quality indicators that can be observed by farmers rather than indicators that require formal laboratory analysis. Some of the soil characteristics that affect productivity and yield responses are to a large extent controlled by past field management (e.g., past P fertilizer applications) and hence may require indicators that are based on crop performance, deficiency symptoms, and/or weed composition. Other soil factors such as soil depth, stoniness, slope, risk of water logging, soil texture, organic carbon content and the soil's capacity to retain water and retain or fix nutrients are more stable in time. Their spatial variation is often related to the position in the landscape, and they can to some extent be directly observed by the farmers.

A detailed soil survey was conducted in the research villages of Affem and Sessaro/Laoudè in Central Togo to provide the necessary baseline information for on-farm trials in these villages. In these on-farm trials, field plots were laid out at many locations across the landscape to establish the relation between crop performance and treatment responses on the one hand and soil factors on the other hand. The soil survey was conducted to establish the nature and range of soil variation present at the landscape scale, and to identify the characteristics and typical landscape position of the major soils in the village. Special attention was also given to the relation with present land use and with the perception the farmers had about the soils in their village. Once the baseline soil data from the survey are available, morphological soil characteristics observed with the auger in experimental fields can be linked to a soil type for which a full soil profile characterization has been done during the soil survey, and for which we know the spatial extent across the landscape

The soil maps produced for the two villages distinguish 3 map units. These are essentially land facets containing an association of soil types. The first unit, labeled S1, represents the crests and upper slopes in the landscape. It covers 3% of the area of both Affem and Sessaro/Laoudè. The second map unit, labeled S2, represents the middle slope, and covers a large area of the two villages (90% of Affem; 43% of Sessaro/Laoudè). The soils in this unit are similar in nature to those in S1, but are generally more brownish and often limited in depth by the presence of a petroplinthic horizon often occurring at a depth between 40 and 100cm. The S1 and S2 units are currently used for the same crops: mainly maize, sorghum, soybean, cowpea, pigeon pea, cassava, yam, and cotton. Part of the land is under recent fallows, forest, or planted with fruit trees (mango, papaya, cashew nut). The soils in unit 2 were found to be chemically poor, but physically good except for the poor water holding capacity for the shallow and very gravelly soils which are more prevalent in the S2 unit than in the S1 unit. Based on the observed variation in texture, organic matter and gravel content and soil depth among the soil profiles in units S1 and S2, a considerable variation in the moisture supply capacity is expected for these soils.
The third map unit (S3) are located on the lower slope and valley bottom, but at times present also in the middle slope section, contains the hydromorphic soils developed mainly in colluvial or alluvial deposits. This unit only covers 8% of Affem, but 43% of Sessaro/Laoudè. Some of these soils are limited in depth by the presence of saprolite at shallow depth (profile SL6).
The maps provide valuable information which is referred to for field management while designing on-farm trials. It is expected that the national agriculture institutions and farmers will be the main users of the maps.

Activity 4. Assessment of nutrient deficiencies in maize in nutrient omission trials

(Details in annual reports 2004 and 2006, and in the MSC. thesis of Mr. S. Van Houdt)

In many parts of Africa, land use intensification has accelerated nutrient removal from the soils and increased deficiencies in plants. This depletion is increasingly being addressed by applying fertilizers containing primarily N, P, and K, though still at inadequate amounts. The application of NPK fertilizer increases crop yields, but accelerates depletion of other nutrients causing deficiencies or imbalances. In addition to the major nutrients considered in current fertilizer formulations, the response of maize to S and Zn has been reported in parts of sub-Saharan Africa. However, insufficient information is available to define the scale of deficiency and no strategies are defined to address the deficiencies. Besides crop yield, nutrient deficiencies may affect the nutritional quality of the harvested products. The objective of the study was to identify nutrients limiting maize production in the savanna, taking into consideration a wide range of nutrients.

Nutrient omission trials were conducted in 15 farmers' fields in the villages; Kasuwan Magani, Ankwa and Ngorot situated in the northern Guinea savanna of Nigeria, and in 38 farmers' fields in the villages Affem and Sessaro in the central region of Togo. Every farmer constituted a replication (block) in the trial design. Roughly half the plots were situated close to the farmer's compound, the remaining plots were far away from the compound. The experimental field size for each farmer was 28.5×10 m, consisting of 8 parallel experimental plots containing four 10 m rows of maize.

The nutrient omission trial compared 8 treatments which were randomly allocated to 8 plots in each field. The 8 treatments encompassed (i) a farmer's practice control plot (referred to as 'FP'), (ii) a full-nutrition control treatment (referred to as 'P40'), (iii) a treatment 'P20' with full nutrition but only half of the P fertilizer of 'P40', and (iv) five treatments that received the full nutrition as in 'P40' except for one nutrient that was omitted (one at a time). The treatment labels of these 5 'omission' treatments ('P0', 'S0', 'K0', 'Zn0', and 'B0') refer to the nutrient that was omitted. In the FP treatment, the farmer was free to decide on type, quantity, and timing of the fertilizer application. The P40 treatment received 120 kg N ha^{-1} (23 kg N as $(NH_4)_2SO_4$ used for S application and 97 kg N as urea), 40 kg P ha^{-1} as Triple Super Phosphate (TSP), 80 kg K ha^{-1} as muriate of potash, 26 kg S ha^{-1} as $(NH_4)_2SO_4$, 5 kg Zn ha^{-1} as ZnO, and 1 kg B ha^{-1} as boric acid. The S0 treatment received NH_4Cl (at a rate of 23 kg N ha^{-1}) instead of $(NH_4)_2SO_4$.

Figure 2. Indication of sulfur limitation to maize growth in a farmer's field in central Togo.

Responses to omission of nutrients varied between the villages. Omission of P resulted in the largest reduction in yields in Sessaro village whereas the omission of S caused the largest reduction in Affem (Figure 2). There was a reduction in yield by omission of Zn in Sessaro but the magnitude varied among farmers and the overall reduction compared to complete nutrient treatment was not significant. However the reduction indicates the need to supply that nutrient as well. Omission of B tends to reduce the yield in Affem but the reduction was not significant. The overall response to the 2 micronutrients tested in this study was not significant, but the reduction in yield can serve as a warning for supply of those nutrients particularly since the role of those micronutrients for quality nutrition is known. There was no significant yield difference between the application of 20 kg P and 40 kg P ha^{-1}, particularly in Affem, suggesting that rate of 20 kg P ha^{-1} was sufficient. However yields were low, less than 3.5 Mg ha^{-1}. If higher yields are to be achieved, the rate of P may need to be increased to over 20 kg P ha^{-1}. However DRIS Indicated that the reduction of P rate induced negative P indices in a number of fields.

Output 2. Soil Processes. Recommendations published of new knowledge of soil processes (recapitalization of depleted soils and improving nutrient use efficiency) for efficient design of management practices that redress and increase soil productivity

Objectives

- To clarify the most relevant mechanisms governing interactions between organic and inorganic N inputs, and determine the necessary biophysical conditions which trigger these mechanisms.
- To elucidate the environmental (soil and climate) and plant-specific processes governing P-release and P-utilization from rock P when combined with P-efficient legume species.
- Evaluate the sustainability of BNMS recommended technologies.

- To understand and quantify the mechanisms regulating N and P availability and uptake in cropping systems or its components with the final aim being to enable extrapolation of recommendations to other cropping systems and environmental conditions.

Activity 1. Quantification of the mechanisms (direct nutritional or indirect mulch effects) leading to improvement in nutrient use in maize-based cropping systems after combining organic and inorganic inputs

1. On-station evaluation of poultry and pig manure in combination with fertilizer in Davié and Kasuwan Magani

(Details in the annual report 2002)

Combining both animal manure and fertilizer when fertilizing cereals often leads to yield increases. Yet it is difficult to identify the reason for the positive interaction between manure and fertilizer. The manure could provide one or more nutrients that are in short supply and not supplied with the fertilizer, or other benefits (priming effects, or the occurrence of benefits related to the buildup of soil organic matter on the longer term). Moreover, the difficulty in estimating the nutrient supply from the manure to the first year's and subsequent crops makes it difficult to optimize manure and fertilizer application rates. Therefore, we set out this trial to establish and test a method to estimate the N and P supply from manure to a maize crop, and to detect possible other benefits other than the supply of N and P. We established these on-station trials in 2002 at Davié (DS, southern Togo) and Kasuwan Magani (NGS, Kaduna State, Nigeria). At each site, the same 15 treatments, consisting of different combinations of urea, TSP, and poultry or pig manure, were tested in a randomized complete block design with 4 replications. A hybrid maize variety (Oba super 2) was used as the test crop, being the most common cereal in the mandate area.

The two sites had similar maximum yield levels (Ymax =3900 kg DM ha^{-1} in Davié and 3400 kg DM ha^{-1} in Kasuwan Magani). These yield levels remain well below the potential yields for hybrid maize in these agroecologies, indicating that resources other than N, P, and radiation were limiting yield. The soil at the Davié site has a relatively high supply of N and P (Nsoil = 163 kg N ha^{-1} and Psoil = 6.3 kg P ha^{-1}), allowing a grain yield of 1200 kg ha^{-1} when no N and no P is added, which is in line with the fact that the land had been fallow before the start of the experiment. In contrast, the soil at Kasuwan Magani, which was cropped until the start of the experiment, had a very low N and P supply (Nsoil = 28 kg N ha^{-1} and Psoil = 1.2 kg P ha^{-1}), and produced hardly any grain without the application of both N and P. The maximum N recovery fraction at both sites was quite low (0.40 at Davié and 0.42 at Kasuwan Magani). It should be noted that this is the maximum N recovery fraction when N is the only limiting factor. At higher levels of N supply, the response curve is approaching the maximum yield level of the site, and the recovery fraction decreases, even when adequate quantities of TSP are added. P recoveries were high; in particular at Davié (0.87 in Davié and 0.42 in Kasuwan Magani), possibly reflecting the fact that P is relatively immobile and P fixation in the top layers of these soils is low. Again, these are maximum P recoveries, and actual P recoveries at higher levels of P supply are much lower.

Plant availability of N in manure and in organic matter in general is lower than in soluble fertilizers (urea) because the N in organic form has to mineralize before plant uptake can occur. The fact that relative efficiencies above 1.0 were observed at the two sites, apparently suggesting a higher availability of the N in the manure compared to the N in urea, indicated that the two manures alleviated other limitations other than N and P. The relative efficiencies for P were below 1, except for poultry manure in Kasuwan Magani. Most P in animal manure is in inorganic form and comes in plant-available form after application, so the availability of manure-P could be close to that of TSP, but not higher. The relative efficiency above 1 for the poultry manure in Kasuwan Magani thus again indicated that the manure alleviated limitations other than N and P.

In short, the positive interaction between inorganic and organic sources of nitrogen or phosphorus was confirmed and can perhaps be ascribed to the alleviation of other limiting factors.

2. Development of tools to better understand water-nutrient interactions: Differential ^{13}C isotopic discrimination in maize at varying water stress and at low to high nitrogen availability

(Details in annual reports 2003, MSc. theses of Ms. E. Clymans and Mr. J. Unogwu, and in Dercon et al., 2006)

Results in the above trials, as well as in earlier ones conducted in the BNMS1 project revealed added benefits (positive interactions) when urea and organic matter (OM) are applied in combination to maize, but these added benefits occurred only on some but not all sites, or in some but not all years.
Different processes may lead to water-nutrient interactions, and explain why the interactions were observed in water-limited conditions. OM applied as mulch limits soil evaporation, thus increasing water availability for the crop, and enabling the crop to make better use of the N applied as urea (and OM). This might also be the case with subsurface-placed OM, if it limits soil evaporation by breaking the soils capillary continuity. Another possibility is that the OM addition results in better root development. The better root development could lead to higher N uptake efficiencies (of urea-N and OM-N), but could also increase water availability during dry spells, which would further increase N uptake (water-N interactions).

The general objective of this research was to investigate two hypotheses related to the mechanism responsible for positive urea – OM interactions:

1. Increased water availability resulting from OM application (as mulch but possibly also when sub-surface placed) increases the N uptake efficiency of the urea-N,
2. Increased root development resulting from the application of OM increases the N uptake efficiency directly and/or indirectly (indirectly by increased access to soil water reducing water stress during dry spells).

As one of the highlights of the BNMSII project and before focusing on the question of evidence of increased water availability and/or increased root development, we developed tools to screen and to better understand water-nutrient interactions. In this, we have relied on the ^{13}C isotopic discrimination technique and applied it in controlled as well as field conditions.

In short, using the well known relationship between ^{13}C isotopic discrimination and water stress, we could demonstrate in a pot experiment (Figure 3) where various water stress regimes were imposed, that $\delta^{13}C$ observations could be used to quantify water stress and its dynamics in maize (*Zea mays L.*) grown under low to high nitrogen availability. For reasons of comparison, the effect of water-N interactions on the ^{13}C signature was also assessed for a

C_3 plant, i.e. rice (*Oryza sativa L.*). From the results, it became clear that $\delta^{13}C$ values measured in different plant parts at harvest can be used as a historical account on how water availability varied during the entire cropping cycle. As a consequence, the tool can be used to assess water stress in a retrospective way in field grown plants and assist in investigating the water stress hypothesis in this context of I/O interactions.

Figure 3. MSc student Joseph Unogwu carrying out process work on organic/inorganic interactions in controlled conditions in the IITA screenhouse.

3. Understanding the mechanisms leading to positive interactions between organic matter and urea under field conditions in the West African moist savanna

(Details in annual reports 2004 and 2005 and in the MSc. thesis of Ms. D. Stuyckens)

In 2004 and 2005, the tool was tested in Sekou, in a field trial, where a staggered planting of maize was performed in the hope to have different water stress histories. Unfortunately, both crops suffered similarly from water stress due to the insufficient and poorly distributed rainfall, reducing the potential differences. Yet, despite the difficulties, similar trends as in the controlled experiment could be confirmed.

As a salient example, higher $\delta^{13}C$ values were measured in the maize plants of the mixed (both organic an inorganic sources of N) treatment with organic residues of *Senna siamea L.* incorporated, indicative for a lower water stress and better water uptake.

Reiterating the objectives of this research, we wanted to understand the mechanisms leading to positive interactions between organic matter and urea. The hypotheses investigated were:

(i) increased water availability resulting from OM application increases the N uptake efficiency of the urea-N; (ii) increased root development resulting from the application of OM increases the N uptake efficiency directly or indirectly.
In the mixed treatment where Senna was incorporated as a source of organic matter, we did observe an increased root weight density, root diameter and root length density only at the depth of incorporation, leading to a better uptake of water and nitrogen by the maize plants. We could link the better water and nitrogen uptake to a better water availability and root development at the depth where Senna was incorporated. Combined use of Senna and urea resources hence improved the water availability in the soil and resulted in a better development of maize roots, but only when the Senna was incorporated. However, the better root development and higher water availability in the treatment with Senna incorporated was not translated in added benefits in terms of grain yield.
On the long term, the combination of organic and inorganic inputs could lead to higher grain yields due to a better water availability during dry spells and a better N uptake due to an improved development of the roots. The $\delta\ ^{13}C$ values in the male flower could indicate differences between treatments and to assess if there was water stress during the flowering.

It is especially for this kind of state-of-the-art research that the link with KULeuven proved to be essential, where the facilities are available to measure $^{13}C/^{12}C$ ratios and the necessary know-how on these methods exists.

Activity 2. Quantification of soil processes (nitrification, N leaching, N uptake from deeper layers by shrubs, P sorption, dissolution etc.) affecting N and P nutrient cycling and balances.

1. Studies on rhizosphere or root-induced processes that may enhance P acquisition from sparingly soluble sources by grain (or pasture) legumes in West African savanna soils
(Details in the annual report 2003 and in Nwoke et al. 2005)

Certain plants are able to thrive under low-P conditions because they can acquire P from soil P pools or P fertilizers that are sparingly soluble such rock phosphate (RP). For example, some legumes are able to utilize P from RP by modifying the chemistry of their rhizosphere which enhances its solubility. The genotypic differences exhibited by grain legumes in the acquisition and utilization of sparingly soluble P present promising strategies that could be exploited in order to improve P availability, and thus enhance crop yields. Therefore, the use of P-efficient crop genotypes may be advantageous in the West African moist savanna where crop production is constrained by low levels of plant-available P. Although the mechanisms for low-P tolerance are not clearly understood, they may include the following: (1) a rooting system that enables extensive soil P exploration, and (2) exudation of organic acids which modify the rhizosphere, and interactions with soil microorganisms. Therefore, the determination and quantification of organic acids in the rhizosphere might provide an insight into the possible mechanisms. This might allow for the development of better screening methods to select for genotypes that can access sparingly soluble P.

Two greenhouse experiments were conducted to examine root-induced processes associated with P acquisition under limiting conditions, and also root characteristics (length and average diameter) at various levels of P availability. The root induced processes examined were accumulation of organic acids in the rhizosphere, changes in soil pH and anion exchange resin extractable P (resin-P). The accumulation of organic acids in the rhizosphere of soybean, cowpea and pigeon pea was evaluated in soil amended with or without RP, iron phosphate (Fe-P), aluminium phosphate (Al-P), calcium phosphate (Ca-P), and triple superphosphate (TSP). The root characteristics of soybean, cowpea, maize and sorghum were examined in three soils at different levels of P addition (0, 3, 6, 11 and 23 mg P kg^{-1}).

Figure 4. Cowpea growing in rhizopots for the assessment of organic acid accumulation

The results of the first experiment showed that citric acid was the only organic acid detected in measurable quantities in the rhizosphere of all plants tested and on average, soybean produced the largest concentration (17 μmol g^{-1} soil) followed by cowpea (10 μmol g^{-1} soil) and pigeon pea (4 μmol g^{-1} soil). Plants in the control treatment had very small amounts of citric acid. Addition of Fe-P, Ca-P, and TSP resulted in a significant increase in the shoot P content of soybean. However, the concentration of citric acid in the rhizosphere of soybean did not correlate significantly with its shoot P content. In the second experiment, the shoot dry matter yield (DMY) and shoot P accumulation of soybean, cowpea, maize, and sorghum were significantly enhanced with P application in all the soils and the amount of P applied played an important role. The shoot DMY and P accumulation correlated significantly ($R^2 = 0.7$) with the root length of cowpea but not of soybean, maize, and sorghum. The shoot DMY and P accumulation of sorghum correlated with the average diameter of its roots.

In conclusion, it is obvious from the results of the experiments that the cowpea genotype studied depends, to a large extent, on the morphology of its roots for soil P acquisition (even under limiting conditions). Nevertheless, the detection of citric acid in its rhizosphere signifies the partial involvement of other strategies. On the other hand, soybean tends to modify its rhizosphere chemistry by exuding citric acid. In essence, the secretion of citric acid appears important for P acquisition in P-limiting environments. However, further studies are necessary to elucidate genotypic variation in the exudation of citric acid by these grain legumes, and the possible relationships with crop growth under field conditions.

2. Determination of available P (Bray-1) threshold value below which soybean and cowpea respond to P in savanna soils

(Details in the annual report 2006)

As most of the soils in the West African savanna have low plant-available phosphorus, most high yielding crop varieties achieve low yields even though the region has the potential for increased and sustainable crop productivity. Therefore, P fertilization is required for optimal crop yields. Because inorganic fertilizers are scarce or unaffordable to the resource-poor farmers, inadequate amounts are often used on food crops. However, without the replenishment of P (and indeed other essential nutrients) exported in harvested crops, achieving the potential yields of crops might be a mirage. In this greenhouse study, the percentage of the potential yield of soybean achievable in savanna soils without P application was assessed in soils of varying available P levels collected from farmers' fields. For this experiment, the potential yield of soybean was defined as the shoot dry matter yield without any nutrient limitation in comparison with the yield achieved when only P was the limiting nutrient.

The plant-available P determined as Bray-1 P content was low in nearly all the soils studied. Only about 20% of the fields had values higher than the threshold level of 10 mg kg^{-1}. This indicates that these soybean fields were highly P deficient. However, the growth of soybean was significantly improved by the application of P fertilizer. The shoot dry matter yield of soybean grown without P application was less than 50% of the potential yield in soils with available P content of less than 20 mg kg^{-1}. The accumulation of P in the shoot biomass was significantly enhanced in all the soils by P application. The only exception was the soil which had a relatively high level of available P (32 mg kg^{-1}). The results of this study indicate that the capacity of these soils to supply P to growing crops was extremely low, and thus soybean production may be severely reduced if P fertilization is ignored. In some of the soils, the length of the soybean roots was significantly greater in the portions that received P application than in those that did not, and in some others the P status of the soil did not appear to have any significant effect. In addition, no correlation was found between P uptake and root length. There were no significant differences in the average diameter of the roots. From the results of this study it is unclear if the size of the roots of the soybean genotypes used played a direct role in enhancing P acquisition under limiting conditions. However, the situation might be different under field conditions where there is no restriction on root growth.

In conclusion, the realization of the potential yield of crops, particularly soybean in this zone is possible only with adequate P fertilization since available P in about 80% of the fields were below the threshold level. Farmers should, therefore, be encouraged to use adequate amounts of P fertilizer.

3. Phosphorus availability and P acquisition by maize and legumes in NGS soils – isotope-based methods

(Details in the annual reports 2003-2006, PhD thesis of Mr. P. Pypers and MSc. Thesis of Mr. M. Huybrighs, and in Pypers et al. 2006, 2007)

The research conducted aimed to identify the mechanisms and soil processes underlying the beneficial effects of legume-maize rotations on maize P acquisition. Soil P speciation was determined by isotope-based methods, allowing a mechanistic approach to P availability in

soils. The soil labile P quantity (E-value) was assessed by a technique combining isotopic exchange with resin extraction. A close correspondence was found between the plant-accessible P quantity (L-value) for maize and E-values determined independently in soil incubation experiments, indicating that maize was only able to utilize labile P. The E-value thus yields important information on the P fertility of the soil, as it corresponds to the quantity of soil P that is available to a non- P mobilizing cereal crop. Legume crops showed to have access to a larger P quantity than maize. In a soil from the Nigerian Northern Guinea savanna (Kasuwan Magani), elevated L-values were observed in controls and soils amended with sparingly soluble RP. In the control, L-values were 2 times larger for pigeon pea and 3 times larger for cowpea than the corresponding E-value. In a RP-applied soil, the L-value for pigeon pea was twice as large as the L-value for maize. However, although legumes proved to be able to draw P from a significantly larger P quantity in the soil, they were unable to take up more P from the soil, relative to maize. The available P quantity in the soil alone failed to predict P uptake by plants. P uptake appeared to be more strongly correlated to the P concentration in soil solution (a measure for the P intensity).
The relation between plant P uptake and soil P quantity and intensity factors was investigated in more detail. A pot trial was conducted in which pigeon pea was grown in soils with widely differing P buffering capacities, applied with soluble P at various rates. Plant P uptake could be closely simulated by a mechanistic nutrient uptake model. A sensitivity analysis on the modelled P uptakes showed that both the labile P quantity and the P intensity controlled P uptake, but the effect of the P intensity exceeded the effect of the P quantity. To accurately predict P availability, a measure of P intensity (e.g. the P concentration in a 10:1 0.01 M $CaCl_2$ extract) needs to be complemented with a measure of P quantity (e.g. the E-value) or a measure of the P buffering capacity (e.g. the K_D). The model also showed that at the small P quantities commonly found in the soils of West-Africa (E-value < 20 mg P kg^{-1}), large P concentrations in the pore water (C_P > 5 mg P L^{-1}) are required to increase P uptake. In unfertilized soils, P concentrations are generally below 0.01 mg P L^{-1}. It is unlikely that root-induced processes can cause such a large increase in P concentration in the rhizosphere, explaining why the increased accessible P quantity does not entail an increase in P uptake.

A similar plant growth trial was conducted to examine the response by maize and various legume species to P applied at various rates as a KH_2PO_4 solution. We found that maize required a 4 times smaller P concentration in the pore water than pigeon pea to obtain half of the maximal P uptake observed at the largest P application rate. It is commonly accepted that legumes, due to their P-mobilizing capacity, are more P-efficient than cereal crops. However, the lower external P requirement indicates that maize is more efficient at taking up labile soil P than legumes. Simulations with the mechanistic nutrient uptake model demonstrated that the morphology of the root system, in particular the presence of long root hairs, is crucial for taking up P at low P intensity and moderate to large P buffering capacity. Root hairs of maize were longer than root hairs of pigeon pea, which enabled maize to exploit the labile soil P more efficiently than pigeon pea. To ensure an efficient use of soil P, management strategies should thus focus on keeping the topsoil moist and allowing a good root development and root hair activity.

Figure 5. Velvet bean and maize grown in a screenhouse to study P speciation in rotation

Finally, this knowledge was used to study changes in soil P speciation in a velvet bean-maize rotation system compared to a maize-maize mono-cropping system with RP supplied to the first crop, set up under controlled conditions in a greenhouse. In a first season, maize and velvet bean responded similarly to RP application. At the end of the season, however, the soil P intensity and P quantity was only increased in RP-applied soils where previously velvet bean was grown. Contrary to maize, velvet bean was able to mobilize RP and enhance P availability in the soil, while it nevertheless also withdrew a significant amount of P from the soil. In the second season, we observed highly significant positive effects of previous legume growth, doubling maize yield and P uptake compared to maize following a first maize crop. Maize yields were also doubled by RP application within each system, but remained unaffected whether the residues of the first crop had been exported or incorporated into the topsoil at the beginning of the second season. Mineralization of velvet bean residues nevertheless released P and considerably increased the labile P quantity and P intensity in comparison with treatments where residues were exported. In RP-applied soils, the large pH increase ensuing the incorporation of legume residues likely reduced the availability of applied RP, while if residues were exported and the pH remained low, a slight acidification in the rhizosphere could aid RP dissolution and P uptake by the maize roots. As a result, incorporation of legume residues did not have a net effect on plant P uptake. In conclusion, growing a legume in RP-applied soil can markedly increase P availability in terms of labile P quantity and P intensity. P acquisition by the subsequent maize crop was, however, less affected by the rotation than predicted by the availability measures. Furthermore, we observed an increased utilization of P taken up by maize in the rotation system, compared to the maize-maize mono-cropping system, which strongly suggests that the legume growth counteracts another, possibly microbiological, growth-limiting factor, other than P limitation. Further research aiming at understanding these benefits is crucial to know when, where and how to implement these legume rotation systems.

Activity 3. Quantification and modelling of medium and long-term soil organic matter dynamics

(Details in the annual report 2003, and in Diels et al. 2003, 2004)

Modelling SOM dynamics was done after 16 years of the long term alley cropping trial that was started on the IITA campus in 1986, but continued throughout the entire project duration. The value of such LT-trials can not be overemphasized as it is the only way to fight persistent myths in African soil fertility science and have accurate information on the relationships between soil fertility management and the resulting soil quality.

Information on long-term soil organic matter (SOM) dynamics in the tropics is scanty and this hampers validation of SOM models for such conditions. We observed SOM content changes in a 16-year continuously-cropped agroforestry experiment in Ibadan, south-western Nigeria. The objectives were to quantify the effect of the cropping system and fertilizer additions on SOM contents, to investigate if ^{13}C abundance measurements could provide useful information in such complex system involving mixtures of C_3 and C_4 plant species, and to use the experimental data for testing the ROTHC soil organic carbon (SOC) model. It was found that two alley cropping (AC) systems, one with *Leucaena leucocephala* and one with *Senna siamea* hedgerows, sequestered an additional 5.0 Mg C ha^{-1} in the 15-cm topsoil after 11 years compared to the control treatment without trees. After 16 years, 5.2 Mg C ha^{-1} was sequestered. The addition of NPK fertilizer had little effect on the quantities of plant residues returned to the soil, and there was no evidence that the fertilizer affected the rate of SOC decomposition. The fact that both C_3 and C_4 plants returned organic matter to the soil in all cropping systems, but in contrasting proportions, led to clear contrasts in the ^{13}C abundance in the topsoil SOM. This ^{13}C information, together with the measured SOC contents, was used to test the ROTHC model. It was found that decomposition in this experiment was very fast, as is illustrated by the fact that we had to double all decomposition rate constants in the model in order to reproduce the measured contrasts in SOC content and $\delta^{13}C$ values. Possible reasons for this are (1) that the pruning materials from the legume trees and/or the extra rhizodeposition from the tree roots in the AC treatments accelerated the decomposition of the SOC present at the start of the experiment (true C-priming), and (2) that the physical protection of microbial biomass and metabolites by the clay fraction on this site, having a sandy top soil in which clay minerals are mainly of the 1:1 type, was lower than assumed by the model.

Table 1. Least-squares means of observed SOC contents and $\delta^{13}C$ values for the 2300 Mg ha^{-1} equivalent soil mass (~0-15cm) in 1997 and 2002 for the 3 cropping systems at 2 fertilizer levels.

Cropping system	Mg C ha^{-1} 1997	2002	$\delta^{13}C$ ‰ 1997	2002
No-tree control – NPK	12.6	9.4	-22.4	-22.6
No-tree control + NPK	12.0	10.4	-22.4	-21.5
Leucaena AC– NPK	16.1	13.8	-24.4	-24.3
Leucaena AC + NPK	17.9	14.8	124.7	-24.3
Senna AC – NPK	16.5	14.8	124.8	-24.8
Senna AC + NPK	18.6	17.2	-24.6	-24.8
SED [(1)]	1.0	1.4	0.3	0.2
Treatment differences:				
AC-control [(2)]	5.0 ± 1.3	5.2 ± 1.8	-2.32 + 0.38	-2.47 + 0.24
Senna AC – Leucaena AC [(3)]	0.6 = 1.5	1.7 ± 2.0	-0.10 ± 0.39	-0.53 + 0.28

(1) SED = Standard Error of the Difference (for comparison of treatments at same sampling time)
(2) Least squares estimate (with 95% confidence limits) of difference between the four alley cropping (AC) systems and the two control systems
(3) Least squares estimate (with 95% confidence limits) of difference between the two *Senna* AC systems and the two *Leucaena* AC systems

Activity 4. Long-term evaluation of BNMS technologies, specifically aimed at N and P recapitalisation and C sequestration

1. Long term alley-cropping trial at the IITA-campus in Ibadan

(Details in the annual report 2002-2006, Diels et al. 2004, and Vanlauwe et al. 2005)

The experiment was established in 1986 to compare *Leucaena leucocephala* and *Senna siamea* alley cropping (AC), and a *Mucuna pruriens* rotation system with a control system without trees or cover crops. Since 1986, these cropping systems have been continuously cropped with maize during the first growing season (May–July) and cowpea during the second growing season (September –November) except for 1992 when the field was left fallow in the second season. The soil type is an Episkeleti-Ferric Lixisol (Chromic) and is on the experimental farm of IITA in Ibadan. The trial was set up as a randomised complete block design with 5 replications and 6 treatments: the 3 cropping systems with and without fertilizer. Fertilizer treatment comprised yearly additions of urea (120 kg N ha^{-1}), single super phosphate (40 kg P ha^{-1}) and muriate of potash (25 kg K ha^{-1}). From 1994 onwards, these levels were decreased to 60 kg N ha^{-1}, 16.2 kg P ha^{-1}, and 15 kg K ha^{-1}. Tree prunings, excluding woody stems > 10cm, were left on the plots. Tillage consisted of loosening of 3-5 cm of topsoil with a hand hoe prior to planting and at each manual weeding operation. Weeds were managed with a combination of a single herbicide spraying before each maize, and cowpea planting and weed residues were left on the plots. Also at harvest, the maize stover and cowpea residues were left on the plots except in 1986 when maize residues were removed from the plots that received NPK fertilizer, and in 1988 and 1989 when residues were redistributed between all plots to obtain the same application rate in all plots.

The Senna and Leucaena plots that received NPK fertilizer (SEN high and LEU high) had similar grain yields of maize which were also higher than the yields of the other treatments (Figure 6). Over the years, the yields of SEN-high and LEU-high have been consistently higher than those of the other treatments. As expected, the absolute control treatment (CON low) had the poorest yield, and yields from all treatments were lower than the yields obtained in 1986. Indeed, the yields have remained lower than the initial yields of 1986 for over a decade, and appear to have stabilized within a particular range for each treatment (Figure 7). The inability of the various treatments to achieve maize grain yields higher than or similar to those of 1986 is worrisome. In 2005, a greenhouse study to identify the possible causes of the yield reduction excluded soil borne pathogens as important factors but emphasized that some (macro-and micro-) nutrients appeared to be limiting (see below). Understanding nutrient dynamics in the long term and factors contributing to the reduction in yield in such cropping systems in sub Saharan Africa remains a challenge.

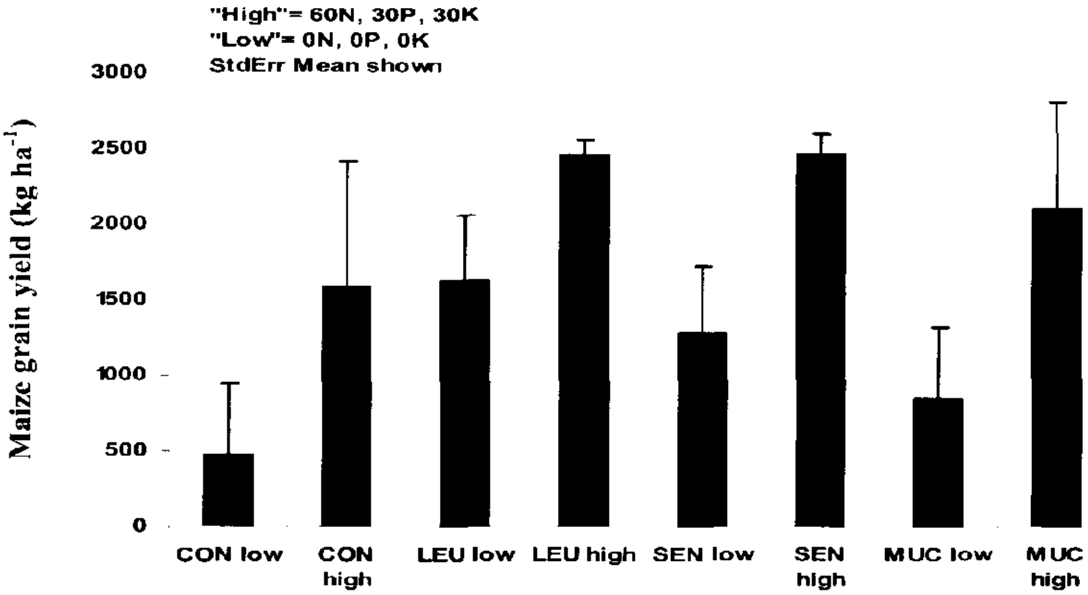

Figure 6. The grain yield of maize from the various treatments in 2006.

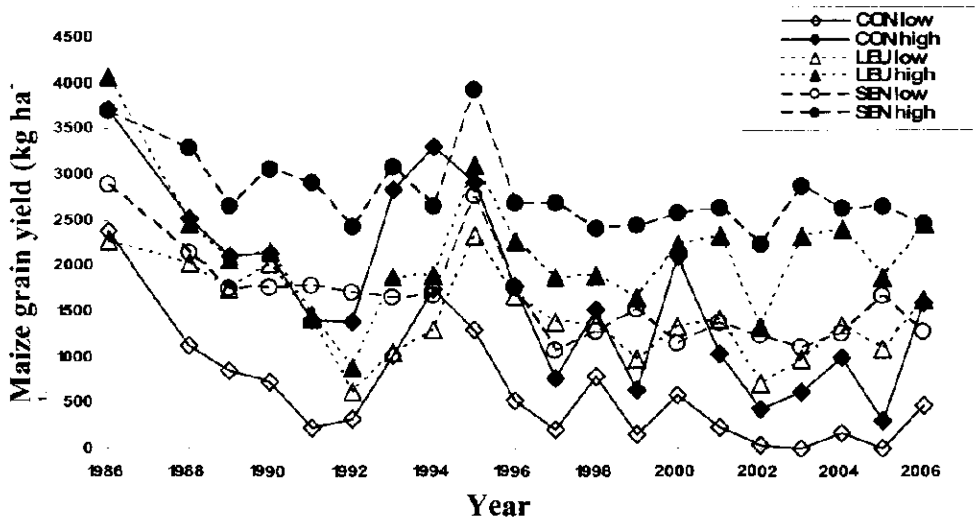

Figure 7. Maize grain yield from the various treatments for 20 years (1986–2006).

In short, the *Senna siamea* alley cropping with addition of NPK fertilizer was, consistently, the best system in terms of maize grain yield. Maize grain yields in the *Leucaena leucocephala* and *Senna siamea* alley cropping systems were similar only with the exclusion of inorganic fertilizers.The combination of organic matter (OM) and inorganic fertilizer is essential for maize production in this soil (as can be seen by comparing the treatments that received OM plus NPK (e.g., SEN high) with that which received either source alone.

Declining grain yield of maize: Are soil- borne pathogens responsible?

As stipulated above, maize grain yield has been observed to decline over the years, and has remained lower than the initial yield of 1986 in all the treatments. Some of the factors responsible for the low yields may include soil-borne pathogens which retard plant growth by depressing root development, causing injury to the root system, and limiting nutrient acquisition. In order to investigate the possible contribution of soil borne pathogens to the declining yield of maize, soils were taken from selected plots (i.e. where the lowest and the highest yields were recorded) for greenhouse studies. These plots were No-fertilizer (ConL), Inorganic fertilizer (ConH), Organic matter (SenL), and Organic matter +fertilizer (SenH).

To investigate this, topsoil (0-15 cm) was collected from the selected plots, air-dried and sieved (4 mm). The soil was weighed (3.5 kg) into plastic pots, moistened to 40% water holding capacity (WHC) with distilled water, and divided into 2 sets. One set was removed from the pot, wrapped with aluminum foil, sterilized in an autoclave for 2 hours, and returned to the pot. The sterilized soil and the un-sterilized portion were brought to 70% WHC, and amended with or without urea (60 kg N ha^{-1}), triple super phosphate (30 kgPha^{-1}) and muriate of potash (30 kg K ha^{-1}) as NPK fertilizers. In addition, a solution of micronutrients was added to one half of the pots that received NPK. Three seeds of maize (Oba super 2) were planted in each pot, thinned to one after emergence, and supplied with distilled water when necessary. The plants were harvested after 7 weeks; the roots were separated from soil and washed with water. Both the roots and the shoots were dried (65°C) and weighed.

There was no significant ($p > 0.05$) difference between the shoot dry matter yield of maize grown in the sterilized and un-sterilized soil. In addition, there was no visible sign of damage or impaired root development due to soil borne pathogens in the un-sterilized soil (data not shown). This suggests that the decline in the yield of maize over the years might not be due to pathogenic organisms in the soil.

Performance of the trees in the alleys

The amount of biomass (dry matter) produced by *Leucaena leucocephala* between 1988 and 1990 (five years after establishment) was about 18 t/ha/yr, which was higher than the 11 t/ha/yr produced by *Senna siamea*. The prunings of the nitrogen-fixing *L. leucocephala* contained more N than the pruniings of *Senna siamea* which is not known to fix atmospheric nitrogen. In absolute terms, more than 300 kg N/ha/yr was contributed to the systems by *L. leucocephala* through prunings during the same period, and about 197 kg N/ha/yr was contributed by *S. siamea*. In 1991, the average N contribution from the trees was between 466 and 512 kg N/ha for *L. leucocephala* and between 239 and 293 for *S. siamea*. However, a gradual decline in biomass production (and hence N contribution) by both tree species was observed as the years progressed. Between 1991 and 2005, the average biomass production decreased from 12 t/ha to 6 t/ha for leucaena, and from 10 t/ha to 7 t/ha for the senna systems. The increased biomass production, particularly by *L. leucocephala*, in 1993 compared with other years from 1990 onwards was because pruning was conducted only twice in 1992 instead of the usual four times which greatly influenced the total biomass produced in 1993. The decline in biomass yield could, partly, be attributed to decreasing number of trees per row as some trees died with time. The effect of the reduction in the number of trees on biomass production was more pronounced on *L. leucocephala* than on *S. siamea*. Nevertheless, the *L. leucocephala* trees consistently contributed more N to the systems than the *S. siamea* trees.

Changes in selected soil characteristics in the alley cropping trial

There was a decrease in soil organic carbon with time in all the systems. This decrease was less striking in the treatments with trees than in those without trees due to the yearly additions of organic matter. Considerable loss of soil nitrogen was also evident in all the treatments which resulted in a dramatic increase in the C/N ratios compared to the 1986 values for both topsoil (0 5 cm) and subsoil (5–15 cm). Changes in available P (Bray-1) depicted fertilizer history rather than tree effect. Therefore, treatments with P addition showed higher concentrations of Bray-1 P than treatments without P addition. Soil pH was influenced by the treatments particularly in the subsoil (5–15 cm) where, on average, the alley treatments had pH values about 0.5 pH units higher than the control treatments. There was no significant change in exchangeable acidity but the alley treatments maintained exchangeable Ca, Mg and K (and thus ECEC) in both soil layers better than the control treatments. This was more obvious for Ca especially in the *Senna* treatments. Specifically, only slight reductions in exchangeable Ca, Mg and K were observed in the alley treatments whereas a reduction of about 50% occurred in the control treatments. In general, the results revealed the *Senna*-based alley system with fertilizers as the more resilient one.

2. Long term trial at Samaru (NGS, northern Nigeria) on the effects of combined applications of urea and organic matter

(Details in the annual reports 2002-2006)

In most BNMS trials, organic matter application rates were set at certain values, the commonest organic matter application rate having been 45 kg N ha^{-1}. However, in reality, farmers are unlikely to be able to redistribute organic matter to obtain a certain N application rate. It was therefore deemed necessary to evaluate the impact of in-situ produced organic matter combined with N fertilizer on maize grain production for the NGS in the medium term. A further objective was to investigate whether enough P and K can be assimilated in the vegetation during the biomass production phase to support a following maize crop.

The Samaru trial was established in 1997 to investigate the response of maize yield to application of organic matter and/or urea. The contribution of in-situ produced organic matter (supplemented or not with N, P, and/or K) to the yield of maize was quantified. Three cropping systems with an organic matter (OM) production phase were identified: (i) a maize-*Centrosema pascuorum* relay system, (ii) a maize-*Lablab purpureus* relay system, and (iii) a maize-cowpea relay system. The legumes were relayed into maize 6 weeks after planting and allowed to grow into the dry season. Maize-natural fallow systems were included as controls. During the maize crop following the OM production phase, the organic matter was supplemented with fertilizer N, P, and/or K. Another set of treatments involved various ratios of organic matter:urea-N. These treatments were implemented until 2006. Every plot received 10 kg P ha^{-1} (as TSP), 30 kg K ha^{-1} (as KCl), and 90 kg N ha^{-1} (as OM and/or urea) every year until 2003. Results of missing nutrient trial conducted in 2003 with this soil indicated possible limitations of Zn, K, S and Mg. Therefore, a yearly blanket application of 180 kg $MgSO_4$ ha^{-1}, and 3 kg $ZnSO_4$ ha^{-1} (corresponding to 3 kg Zn, 18 kg Mg, and 25 kg S ha^{-1}) in all plots commenced in 2004, and also K application rate increased from 30 to 50 kg K ha^{-1}. The treatments differ in terms of the type of OM used (cowdung, poultry manure, or *Parkia biglobosa* tree prunings), and in terms of the proportion of the 90 kg N ha^{-1} that is applied by urea and OM (90/0, 67.5/22.5, 45/45, 22.5/67.5 and 0/90).

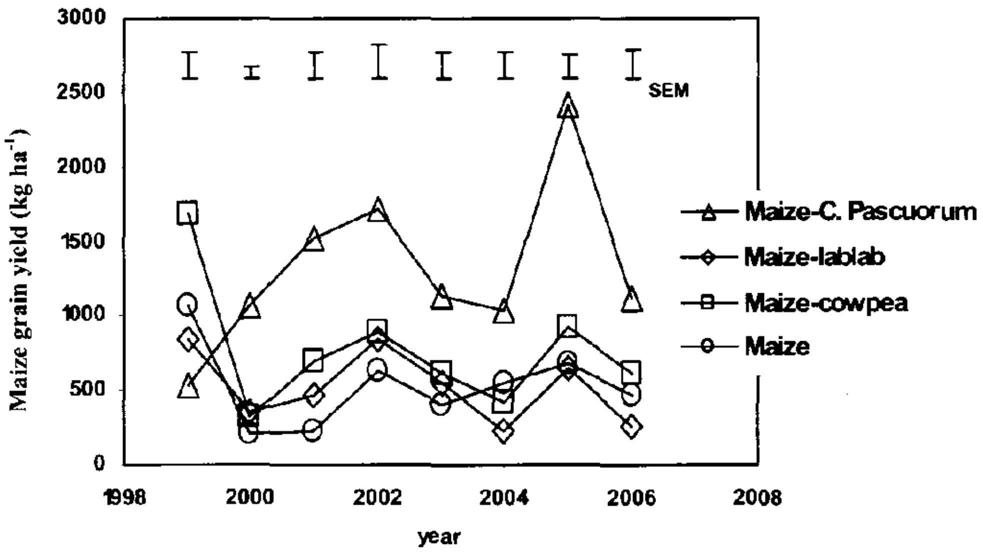

Figure 8. Maize grain yields in the maize-C. pascuorum, maize-lablab, maize-cowpea, and continuous maize cropping systems in Samaru. Error bars indicate standard errors of the treatment means (SEM).

Maize grain yields in 2006 were lower than the yields for 2005, but similar to those obtained in 2004. However, these yields were consistently lower than the initial yields at the outset of the experiments. Over the years, cropping system was the most influential experimental factor. A comparison of the various systems showed that higher maize grain yields were obtained in the maize-*Centrosema pascuorum* system than in the other systems (Figure 8). The superiority of this system over the maize-cowpea and the maize-lablab systems is assumed to stem from the ability *Centrosema pascuorum* to establish quickly after the first rains and cover the soil by the time maize is planted. Although maize grain yields in the other legume systems (maize-cowpea and maize-lablab) were, sometimes, not significantly different from that of the control treatment (no-legume), the yield of the control treatment was usually lower in absolute terms. The increase in the rate of K application did not result in higher grain yields in 2006. In fact, the effect of K was not visible in any of the cropping systems unlike in previous years when it had been visible but inconsistent. This could be seen by comparing maize grain yields of the treatments receiving 45N 10P 50K with those receiving 45N 10P 0K for the maize-*C. pascuorum*, maize-cowpea, and maize-lablab systems. The application rate was increased to 50 kg ha^{-1} from 30 kg ha^{-1} in 2004 based on the results of an earlier greenhouse study which suggested that K might become deficient despite the 30 kg ha^{-1} being applied.

In the second set of treatments, the highest grain yields of maize were usually obtained in the cowdung/urea system when OM and urea supplied N in the ratio of 1:3. These yields were also higher than those obtained with the sole application of urea. Other combinations of OM-N and urea-N did not result in significantly different yields either in the cowdung/urea or in the *Parkia biglobosa*/urea system. Nevertheless, they were slightly higher than those obtained with the sole application of OM. The application of poultry manure supplemented with inorganic N produced as much maize grain as the sole application of urea.

It can be concluded that *Centrosema pascuorum* seemed to be a better legume than *Lablab purpureus* or cowpea (*Vigna unguiculata*) for use in maize-legume relay systems. Also, the ideal ratio for the combination of OM-N and urea-N for the enhancement of maize grain yield depended on the nature of the OM. For example, the ratio of 1:3 in the cow manure system gave the best grain yield when compared with other combinations within the system or with the *Parkia* prunings system. Similarly, at a ratio of 1:1 the poultry manure appeared better than the cow manure or the *Parkia* prunings. The reasons for the reduction in maize grain yield encountered in all the systems should be investigated further.

3. Long term trial at Sekou (DS, Bénin) on the effects of combined applications of urea and organic matter

(Details in the annual reports 2002-2006, and in the MSc. thesis of Ms. S. Ponseele)

The Sékou trial was established in 1997 to investigate the response of maize to the application of organic matter and/or urea. Three cropping systems with an organic matter (OM) production phase were studied: (i) a maize-*Pigeon pea* (*Cajanus cajan*) intercrop in which the pigeon pea is allowed to grow during the second season, (ii) a maize-*Mucuna cochinchinensis* system in which *Mucuna* is relay cropped, 6 weeks after planting maize, and allowed to grow during the complete second season, and (iii) a maize-cowpea rotation. Maize-maize systems were included as controls. Maize grown after the OM production phase, was supplemented with N, P, and/or K from inorganic fertilizers. In 1998, another set of treatments were designed to determine whether, and at what OM:urea ratio, positive interactions occur between the two sources of N. The treatments differ in terms of the type of OM used (*Senna siamea* tree prunings or neem tree prunings), and in terms of the proportion of the 90 kg N ha^{-1} that is applied by urea and OM (90/0, 67.5/22.5, 45/45, 22.5/67.5 and 0/90).

Maize yields showed a statistically significant effect of cropping systems: highest yields were observed in the Maize/*Mucuna* system, followed by Maize/pigeon pea, Maize/cowpea, and Maize/maize (Figure 9). While yields varied considerably across the years, the effect of the cropping system were remarkably constant over time: Maize yields were always about 2000 kg ha^{-1} higher in the Maize/Mucuna system, compared with the Maize/cowpea, and Maize/maize systems. A urea-N response curve established in the maize/maize system indicates a clear response to 45 kg N ha^{-1}, and a smaller yield increase from 45 to 90 kg N ha^{-1}. In all 3 systems, there was no effect of K fertilizer. A P effect was only observed in the Maize-*Mucuna* system.

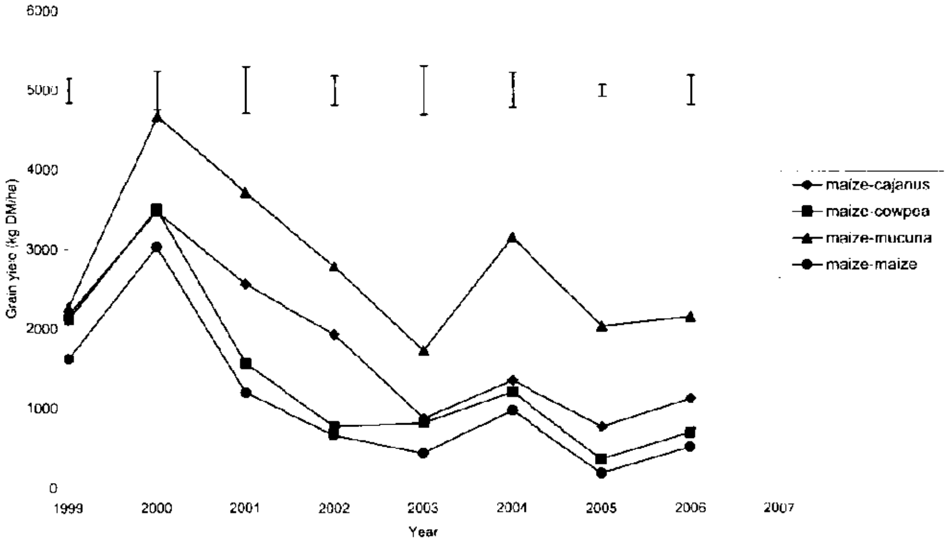

Figure 9. First season maize grain yields in the 4 cropping systems in Sékou. The data shown are averages of the "+R 0N 10P 30K" and "+R 45N 10P 30K" treatments in each system. Error bars indicate the standard errors of the treatment means.

In the treatments where *Senna* or neem residues were applied in combination with urea in various OM-N:urea-N ratios, the benefits of replacing at least part of the urea-N with OM-N were clear. But the optimal mixture ratio (OM-N:urea-N) differed across the years. *Senna* residues generated the highest yields especially if the *Senna* residues were incorporated.

The trial results indicated possible options to increase production in such continuous maize-based production systems. Throughout the seasons, Maize/*Mucuna* relay cropping gave an increase of at least 2000 kg ha^{-1} in yield relative to maize/maize cropping regardless of whether fertilizers were added in the maize/maize system. However farmers with limited land will probably not grow *Mucuna* despite its benefits because it does not provide grain. The Cajanus systems provided a gain in grain yield though far below that from Mucuna. However if improved and local genotypes with short duration cycle, high biomass production and resistance to diseases can be identified, the Maize/Cajanus system can become much attractive. Maize/cowpea system offers no gain over maize/maize cropping.

In conclusions, observations from long-term experiments have served as the basis for developing specific process studies to reveal the underlying mechanisms. These included the understanding of positive interactions between organic and inorganic N sources through isotope studies, rotations effects, nutrient limitations, and P and N availability and losses. The results from the process studies coupled with the local biophysical and socio-economic environment of farmers were used in designing interventions that ensure improved productivity and profitability of farming systems. In addition the long-term experiments provided an opportunity for assessing the sustainability of cropping systems.

Output 3: Farmer-managed testing and validation. Balanced nutrient management systems validated and adapted on-farm in benchmark areas

Objectives

- To evaluate the impact of combining organic and inorganic inputs on maize yield in intensified farming systems and explore the potential of selected annual and perennial species to produce organic matter which is needed to be combined with inorganic inputs.
- To validate improved BNMS systems in farming communities and to adapt these to the point where farmer to farmer dissemination is spontaneous.
- To establish a bottom - up feedback system of BNMS-related problem spotting and solving between stakeholders at all levels and to act in a product championship role in the extension of recommended technologies.

Activity 1. Field demonstrations on BNMS are established in selected villages in Benchmark areas and in pilot sites

(Details in the annual reports 2002-2005, and in Kolawole et al., 2007)

Following the recognition that the application of organic matter (OM) in combination with inorganic fertilizer is necessary to halt nutrient depletion in sub Saharan Africa, and the low adoption rate of options requiring high dose of inorganic fertilizer (i.e., huge initial investments by farmers), IITA-BNMS and IAR in collaboration with SG2000 initiated farmer-managed trials to demonstrate promising BNMS technologies in northern Nigeria in 2000. The BNMS options were based on the findings of the studies on combination of organic (i.e., manure, household waste, and crop residues) and inorganic nutrient sources. The on-farm demonstrations trials were established in six villages (Kaya, Danayamaka, Kuguru, Kutama, Naborda, Birshi, Billiri and Malleri) with 10 farmers participating. However, in 2002, the trials were established in 9 villages by 28 farmers. The demonstration trials compared 3 improved systems: continuous maize with sufficient fertilizer addition (SG-2000 package), continuous maize with less fertilizer than the SG-2000 package combined with organic amendments – BNMS-manure, and soybean-maize rotation, where in the second year of the rotation cycle, a reduced amount of fertilizer is applied to the maize crop. These were compared with the farmer's usual practice (FP). The objectives of the trials were to (i) demonstrate the three options for maize-based systems to farmers and extension workers, (ii) assess labour input, management practice and farmers' feedback, (iii) assess adoption/adaptation of the three packages for maize-based systems, and (iv) solicit the opinions of farmers and extension workers at field days.

For the adaptation trials, farmers based on their conviction, chose one or more of the improved technologies that had been demonstrated in their villages for 2 years. Farmers were free to choose any hybrid maize variety for their field and plant the same variety in all the 4 plots of their field. So, in 2002, some farmers in the villages where demonstration trials have been established for two years adopted and adapted one or more of the improved technologies to compare with their own practice.

Maize grain yields in the BNMS-manure technology were similar to the yields in the BNMS soybean-maize rotation and SG2000 technology, and significantly higher than the yield from the FP. However, the variability among farmers was large. Initially, maize yields from the three improved technologies were higher than the yield from FP by about 1000 kg ha^{-1} in both demonstration and adaptation trials. But in 2005, maize yields from the SG2000 technology and farmers' practice were similar. Although, as in previous years, some farmers applied as much fertilizer in FP as in the SG2000 package, the similarity in the yields in 2005 indicates improved management practices by most of the farmers. However, the lower maize yields obtained in the previous years (compared to 2005) were attributed to poor crop husbandry and management. Farmers expressed concern about manure availability which could be a major constraint for the BNMS-manure option. Nevertheless, there is no clear-cut choice for any of the improved systems. Hence the resources and situations of the farmers would determine which improved technology to adopt. In this wise, it would be better to promote them as basket of options where farmers could choose from depending on their resources and situations, and which they can adapt to their local circumstances.

Figure 10. Visit to a demonstration field in Northern Nigeria

Activity 2: Farmer-managed trials initiated in collaboration with farmers of both genders in selected villages in the benchmark areas

(Details in the annual reports 2005 and 2006)

Following the success of improved rotations of soybean and maize in northern Nigeria, the technology was tested in two villages of central Togo Affem and Sessaro. Prior to the establishment of the rotations, a screening of soybean varieties by farmers was conducted to select their preferred varieties. In total 6 varieties of soybean were tested during 2 seasons: a local variety and five improved varieties (Salintuya, TGX 1844-18E, TCX 1910-14F, TGX 1448-2E, TGX 1830-20E) with maize. Response of the varieties to P and S were as well tested. The TGX 1910-14F was appreciated by all farmers involved in the trials for providing high yields both for grain and stover. TGX 1830-20E was appreciated for its precocity.

Figure 11. Screening of soybean varieties in central Togo

Based on this selection, the variety TGX 1910-14F was used in rotation trials with maize. In the first season of the rotation, 4 treatments were imposed to check the response of soybean to S and to P. Two P sources were used, SSP and TSP, and P was applied at equal P rate of 30 kg P ha^{-1}. SSP supplied sulphur in addition to P. A control with no P application was included. In addition a treatment managed entirely by the farmers as they wished was included and was referred to as Farmer Practice (FP) treatment. In the FP treatment, farmers grew varieties of their choice. In the second season, maize was grown. However, plots were split into 2, to allow two doses of N applications to maize: the recommended dose in the area (45 kg N ha^{-1}) and a reduced dose (30 kg N ha^{-1}) to check any contribution of the previous soybean to N supply.

There was a highly significant response of soybean to phosphorus application in grain yield. In addition, applying SSP resulted in yields higher than the yield obtained from the TSP treatment. This suggested a need to supply sulfur on soybean.

Soybean root biomass was higher in the treatment that received P as SSP than in those that received P as TSP but only in Sessaro. Yields of maize grown after soybean were lower in the

FP treatment than in the treatment receiving P. In both villages, there was no difference between the application of 30 and 45 kg N ha^{-1}. This indicates that the soybean has contributed by at least 15 kg N ha^{-1} to the N supply to maize.

Activity 3: Organize meetings on BNMS in selected villages in the benchmark areas and Monitoring and evaluation of activities to provide feedback to guide on going research

On-farm activities (demonstration and adaptation trials) were considered as community-based activities. Before the establishment of the trials, a meeting was held with farmers at community level to discuss the technology to be tested. After the meeting, farmers volunteered to participate in the trials to represent the community. After the establishment of the trials, field days were organized to check progress, to explain again the technologies and their benefits, and to solicit feedback from the farmers. This feedback is essential for improving the technologies, and the interaction with the farming community.

Figure 12 Farmer explaining to researchers, policymakers and other farmers the management of his farm in improved soybean-maize rotations

Moreover, at the end of the season, the results obtained have to be presented to the farmers. For example, for the demonstration trials in Danayamaka which include soybean/maize rotation and a combination of manure and fertilizer as treatments, yields obtained in one of the farmers' fields and a simplified partial budget analysis were presented to the farmers. The results, presented as drawings on large flip charts, attracted considerable interest and discussion among the farmers (Figure 13). Majority of the farmers appreciated the benefits derivable from the BNMS treatment (manure+fertilizer), but pointed out that it may be difficult to obtain enough manure to apply. The soybean/maize rotation system attracted a lot of attention among farmers because of its low cost in terms of external inputs (no fertilizer to soybean, reduced rate to maize following soybean). The drudgery involved in drilling the soybean seed during planting was a point of concern mentioned by the farmers.

Figure 13. Presentation of results to farmers using flip chart

Various field visits were made by IITA BNMS staff and partners to on-farms trials to monitor the progress of the trials and get view of farmers. The observations from the trials as well as the feedback from the farmers were taken into consideration while designing other researchable issues.

Output 4: Socio-economic evaluation and impact assessment

(Socio-economic evaluation and impact assessment of best-bet BNMS technologies quantified and published)

Objective

- To conduct socio-economic and impact evaluation of the best-bet BNMS technologies.

Activity 1. Analysis of the costs and benefits of new technologies in terms of labor use, inorganic fertilizer use, environmental constraints, and crop productivity

(Details in the annual reports 2003 and 2005, in the MSc. theses of Mr. K. Wallays and Mr. O. Ugbabe, and in Ugbabe et al. 2007)

In an attempt to improve soil fertility and enhance crop yields in West Africa, several balanced nutrient management options have been tested and implemented in the northern Guinea savanna (NGS) region. The BNMS technologies had two major packages: a combined application of inorganic fertilizer and manure (BNMS-manure) and a soybean/maize rotation practice (BNMS-rotation). The potential economic benefits of the BNMS technologies were assessed in the NGS of Nigeria using economic surplus model. Baseline, farm-level, and secondary data were used.

In a closed economy model, BNMS-manure will yield a consumer surplus of about US$ 56 million by 2030 in Nigeria. The net present value (NPV) of the investment in BNMS-manure is estimated to be in the range of $ 84-107 million, the internal rate of return (IRR) between 24 and 36%; and the benefit: cost (B: C) ratio anywhere from 14.4-47.3, depending on which baseline assumptions of ceiling adoption rates and total research and extension costs used. Under the same conditions, BNMS-rotation is expected to yield net present value in the range of $ 1.06 billion to US$ 1.46 billion with the IRR between 44-57% and the B: C ratio of 211-638. However, in a small open economy model under the same period, Nigeria is estimated to gain $ 118 million, Ghana US$ 38 million, Togo $ 18 million and Benin $ 29 million from investment in BNMS-manure upon proper dissemination. The NPV of investment in BNMS-manure is estimated to be between $ 127 million and $ 190 million with the IRR ranging from 27 to 41% and B: C ratio of 9.14 to 31.40 based on the baseline assumptions. The results for BNMS-rotation were productively more encouraging than for BNMS-manure.

The net economic gain to Nigeria as a result of adoption of BNMS-rotation is projected to be over $1.5 billion. This is about 1.5 times what can be obtained in a closed system. The projected economic gain to Ghana in 34 years (up to 2030) is $532 million. It is $259 million for Togo within the same period. For Benin, the projection is $404 million. On average, the annual net benefits are projected at $46.6 million for Nigeria, $15.6 million for Ghana, 7.6 million for Togo, and $11.9 million for Benin. These estimates are about 13 times more than the projections for BNMS-manure in the same scenario of open economy model. Nigeria has about 57% of the total economic benefits of BNMS-rotation in WA, Ghana has about 19%, Togo has about 9%, and Benin has about 14%. The NPV for the entire period is about $2.7 billion with the IRR of 55 %. The average annual NPV is about $81 million. These estimates indicate that BNMS-rotation has great potential to turn around the economic fortune of the NGS of WA if adopted.

Activity 2. Identification and quantification of factors for potential adoption of BNMS technologies by male or female farmers

(Details in the annual reports 2003 and 2006, and in the PhD thesis of Mr. A. Akinola)

A household survey was conducted in the eight villages (Fatika, Kaya, Danayamaka, Buruku, Kufana, Kroasha, Kadiri Gwari, and Kayarda) that participated in the demonstration and adaptation trials of the BNMS technologies. The survey involved 400 household heads (HH) who were interviewed with the aid of a well-structured questionnaire. The HH were randomly selected from a list of all HH in each village and the size per village depended on the population of the village. The household survey was supplemented with a community-level survey using the focus group discussion (FGD) method. The dependent variable was the land area under each of the BNMS technologies. The respondents were classified into non-adopters of land-improving technologies, users of inorganic fertilizers, adopters of BNMS-manure, and adopters of BNMS-rotation based on the quantities of inorganic fertilizer (at least 30kg N/ha) and organic inputs (at least 3000 kg/ha of manure) used by farmers in the area.

There were variations in the demographic and socio-economic characteristics among adopters of BNMS technologies as well as between the adopters and non-adopters. The average age of all respondents in the study was 42.5 years. The average age of the adopters ranged from 40.8 to 44.5 years while the average age of non-adopters was 50 years. Age is a significant determinant of the adoption of agricultural innovations in Africa. The overall average literacy rate was 46.3% and the literacy rate of technology adopters (43.3% to 48.4%) was higher than that of non-adopters (33.3%). Adopters of BNMS-manure had the highest level of literacy, followed by the adopters of inorganic fertilizer only and the adopters of BNMS-rotation. The average years of formal education completed by the HH were 7.6. The average number of years of formal education completed by technology adopters (7.3–8) was higher than the average number completed by non-adopters (5). The average household size in the study area was large (11.5 persons/household). For all the adopters, average household size was more than 10 persons while for non-adopters it was below 10. Overall average number of adult males (>15) was 3.5 per household. Among the adopters, the average number of adult males (>15) was highest for the adopters of BNMS-manure (3.7 per household) followed by adopters of BNMS rotation (3.9 per household) and adopters of inorganic fertilizer only (3 per household). Non-adopters have fewer adult males (>15) per household than the adopters.

The adoption of the BNMS technologies started in 2001 at a very slow pace. At the end of 2002, less than 10% of the households have adopted either of the BNMS technologies. In 2003 about 20% of the farmers in the BNMS-rotation category adopted it in one form or the other while about 30% in the BNMS-manure category adopted. In 2004, there was a significant increase in the number of adopters: 37% for BNMS-rotation and 46% for BNMS-manure (Figure 14). This implies that a greater proportion of the sample household adopted the BNMS-manure. In 2005, the numbers increased to 40% (BNMS-rotation) and 48% (BNMS-manure). In terms of land area, BNMS-manure occupied 35%, BNMS-rotation covered 12%, and inorganic fertilizer occupied about half of the total maize land in the study area

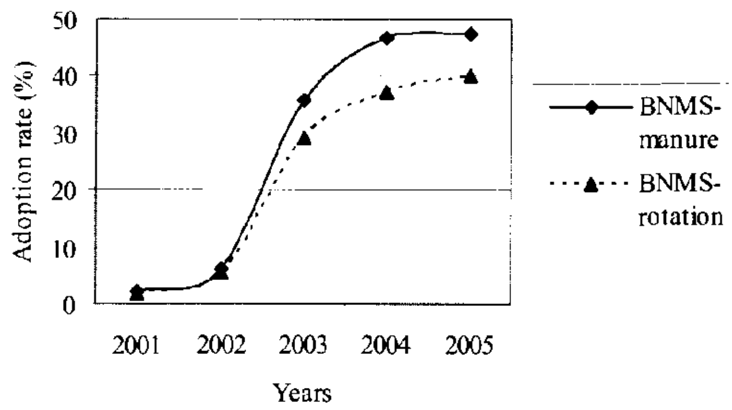

Figure 14. Cumulative adoption of BNMS technologies in Nigeria Northern Guinea Savanna

The provision of extension services appeared important in the adoption and use intensity of the BNMS technologies. Therefore, improved access to extension services, and improved service delivery from the extension agents should be considered. Apart from this, farmers should also be visited regularly at the point of introduction of the new technologies.

The organization of field days was a good strategy for promoting the adoption of BNMS technologies. Fields days provide the farmers, extension agents, and researchers with the opportunity to interact and share ideas and experiences on a given technology. The concept of farmer-to-farmer diffusion of new technologies was also useful in promoting the BNMS technologies. This concept involves building the capacity of lead farmers by first demonstrating the technologies to them so that they will adopt the technologies themselves, and then training them on what and how they should communicate to others.

Access to credit and household assets endowment were important factors in the decision to increase land areas under the BNMS-manure technology. Household assets represent an alternative source of credit to the rural dwellers in northern Nigeria that helps in solving liquidity problems. Both household assets and formal and informal credit facilities enable the farmers to buy needed fertilizer and hire labor during critical periods of the year when cash is scarce. Also, off-farm income enables them to buy improved seeds of soybean. In addition, farmers' perception of the state of land degradation influenced farmers' adoption decisions on BNMS-manure, whereas off-farm income was found to be significant in determining farmers' adoption decisions on BNMS-rotation.

Activity 3. Manure Marketing and Fertilizer Use in Northern Nigeria

Details in the annual reports 2005 and 2006, and in the MSc. thesis of Mr. O. Olayide)

The demonstration of BNMS technologies revealed that the use of animal manure and the rotation of soybean and maize generate good yields and attracted much attention from participating farmers. A subsequent socio-economic analysis indicated that the profitability of the manure technology would depend on the availability of manure. It was therefore expected that the expansion of the BNMS-Manure treatment would create demand and increase the price of manure which will lead to the development of manure market. The present study was undertaken to assess the importance, constraints, conduct, structure, and performance of the market and marketing systems of manure, as well as to identify the determinants of manure and mineral fertilizer use in northern Nigeria.

The study, carried out in 16 villages in Kaduna and Kano States of northern Nigeria, developed and utilized the Socio-economic-ecological modeling (SEEM) framework, which relates the socio-economic characteristics of population density and market access to the agroecological zones (AEZ), giving as well their interactions. Based on this socio-economic characteristics and on geographic position, four resource use domains were identified and used in the study: high population density and high market access (HPHM), high population density and low market access (HPLM), low population density and high market access (LPHM), and low population density and low market access (LPLM). A total of 20 farm households were randomly selected from each of the 16 villages made up of 2 representatives in each resource use domain, resulting in a total of 320 farm households for the study area. Data analyses were carried out using descriptive statistics, Gini coefficient and Lorenz curve analyses, and Tobit regression model estimation.

The average age of the sampled farmers in the study area was 47 years, with a household size of 12 people and a dependency ratio of 1.4. The large household size offered an important labour force for the transportation and field application of manure. The mean cultivated land area by the household was 5.9 ha. Most of the respondents had only 2.5 years of formal education, and earned a yearly income of ₦103,030. Population and market access were identified as key variables driving manure market in the study area. Cereal-legume systems received the bulk of the applied manure in the study area; therefore manure has important implications for food security and agricultural commercialization as well as policy on agricultural expansion or intensification in the study area.

Manure is a by-product of livestock/poultry keeping which is occurring in predetermined locations. Also, manure supplies are fixed because livestock/poultry farmers must dispose of all manure. However, most manure buyers do not own livestock and have choice of using manure or mineral fertilizer to meet crop nutrient needs. The study revealed that the manure applied by the farmers was mostly own-farm generated, as livestock was integrated into the agricultural production systems by 95% of the farmers in the study area; the mean tropical livestock unit of the farmers was 4.0. Manure was also generated and available at the commercial livestock farms, Fulani settlements (*Ruga Fulani*), abattoirs, even as manure agents facilitated the distribution of the highly valued poultry manure both at the local and the district levels. Informal trading in manure predominated in the study area. However, emerging developments in the poultry manure market was observed as manure agents facilitated the transaction of manure from the commercial livestock farmers to the farmers at a competitive and exogenous price.

Insufficient production of manure at the household level was complemented by outsourcing of manure. Eighty percent of the total manure applied were own-farm generated, 11 % came from crop residues exchange for manure arrangement with herdsmen and 9 % were purchases, in the study area. The outsourced manure was mostly obtained through informal means, for instance, 88 % of the farmers who sold manure exchanged it with other farmers in their own village. The largely informal manure market offered little transaction costs and high employment of family labour especially in transportation and spreading on the crop farm, and further suggests a asymmetrical information flow on manure marketing or the markets. All the groups that were involved in manure marketing handled some proportions of sales. Results show that none of the manure agents was sufficient in exercising monopoly power in the manure markets. There exists considerable inequality in the manure markets across the agro-ecological zones, resource use domains and for the entire study area. Manure agents also transacted manure, especially poultry manure. Manure marketing is highly profitable as every ₦1.00 invested returned additional ₦0.33. However, manure marketing is found to be inefficient, and transaction costs account for a high proportion of the selling price of manure in the study area.

Tobit regression model revealed that age, livestock ownership, own land cultivated, distance to tarred road, crop residues exchange for manure influenced the use of manure positively, while ecological zone, land area cropped, and crop diversification activities influenced the probability of adoption and intensity of manure use negatively in the study area. Also, household size, crop nutrient demand, and availability of mineral fertilizer influenced the probability of adoption and use intensity of mineral fertilizer positively, while land area cropped, and distance of farm land to homestead influenced the probability of adoption and use intensity of mineral fertilizer negatively in the study area. Therefore, other things being equal, farmers with large household size, greater availability of mineral fertilizer, who cultivated crops of high nutrient demand (mainly cereals); but cultivated small area of land (small farm size), and with less distant farmlands had a higher probability of adoption and use intensity of mineral fertilizer use in the study area. The study showed that farmers' use intensities of manure and mineral fertilizer technologies were the most important component of the total elasticity of adoption. These results therefore emphasized the need of policy on soil fertility improvement technologies such as the adoption of manure and mineral fertilizer to focus on the current users of the technologies.

In conclusion, the positive effect and interactions livestock size and livestock management for manure use suggests that farmers are not optimizing the natural resources at their disposal in order to achieve self-sufficiency in manure production, and lack of a well-developed formal manure market in the study area. A manure market is however emerging and highly profitable, but manure marketing is inefficient in the study area. The study also provided a basis for the scaling out of the BNMS-Manure as promising and sustainable technology package. Also, the BNMS Maize/soybean rotation as crop diversification option should also be scaled out as technology package to mitigate the shortfall in manure use, and to enhance sustainable agricultural production in the study area.

Output 5: Guidelines for Balanced Nutrient Management

(Guidelines for BNMS developed and disseminated by extension organizations)

Objective

- To explain the principles and benefits of the proposed BNMS technologies to extension officers and provide guidelines for application and adaptation to local biophysical conditions and farmer circumstances.

On-farm technologies were developed and implemented in partnership with NARS and extension services. Promising technologies were transferred to extension services who took the lead in demonstration and adaption trials. Technologies such as improved soybean/maize rotation and improved crop-livestock integration including a manure production component, were transferred to SG2000 for demonstrations in the States where SG2000 operates.

Activity 1. Development and production of extension materials

(Details in the annual report 2006, and in the extension booklets and posters)

One of the technologies developed and tested on farm is the improved soybean-maize rotation which proved to be productive and profitable for farmers in north Nigeria. For its wide dissemination, it was judged important to produce extension materials (posters and booklets) in collaboration with extension services. Posters were designed to emphasize on the benefits of such rotation system whereas the booklets provide detailed guidelines on how to grow each of the 2 crops in rotation (from the preparation of the land to the storage of the harvested product) to achieve the stated benefits.

Figure 15. Cover page of the extension brochure on maize-soybean rotation disseminated in Northern Nigeria.

Output 6: NARS capacity building

(*Capability of NARS to undertake BNMS research enhanced*)

Objective

- To increase and strengthen the research capabilities of collaborating NARES institutions (Private Sector, NGOs, Farmers, Universities and Government Institutions) to implement BNMS technologies in farmers' circumstances.

Activity 1. Organize degree related training and research activities for the NARS

A full list of degrees acquired through the BNMSII project is given in Section III. Both Belgian and African students have been able to obtain degrees at both Belgian and African universities. Over the entire 20-years collaboration, this list is even more impressive, while it remains difficult to find sufficient well trained candidates both for PhD and MSc training.

Activity 2. Organize non-degree related on-the-job training of national extension service staff and farmers on BNMS technologies through joint field visits to BNMS on-farm trials and follow-up interactions

A number of students who graduated from university have been on attachment on the project at the IITA Ibadan for the youth corps services. NARS collaborators visited IITA to learn methodologies related to data handling and paper writing.

All the experiments, on-farm and on-station, and surveys conducted on the project are collaborative activities jointly undertaken by the NARS partners and the project team in IITA Ibadan and KULeuven.

The team from Ibadan made regular visits to the field trials in Bénin, Togo, and northern Nigeria for discussions in the field with NARS collaborators, extension service staff and farmers.

Activity 3. Actively involve NARS, extension services, and NGOs, and farmers in yearly evaluation and planning workshops of the BNMS2 project

(Details in the annual reports 2002-2006)

Every year, all stakeholders and project partners participated in an evaluation and planning workshop to conduct a logframe review together. This proved essential to agree on the planned activities, to discuss the scientific rationale and especially to maintain the strength of the network.

Figure 16. Group picture of the stakeholders meeting of the BNMS project in 2006.

III. Training

Besides degree-related training, both for Belgian and African students as summarized below, on-the-job training of NARS collaborators and technicians in the fields of agronomy, trial supervision, and data analysis formed an integral part of the BNMS-NARS collaboration. It can not be sufficiently emphasized how important these activities are.

K. Aihou (PhD, Universiteit Gent): 'Interaction between organic input by *Cajanus cajan* (L) Millsp. and inorganic fertilization to maize in the derived savanna of the Benin Republic' (defended in June, 2003).

A. Akinola (PhD, Obafemi Awolowo University, Ile-Ife, Nigeria) "Adoption and Impact of Balanced Nutrient Management Systems (BNMS) Technologies in Northern Nigeria". (ongoing).

E. Clymans (MSc, KULeuven) "Methods to determine nutrient-water interactions in maize in West Africa" (defended in June 2004).

M. Huybrighs (MSc, KULeuven) "Are beneficial effects of rock phosphate application in a legume rotation system on phosphorus uptake of subsequent maize crop a direct consequence of improved phosphorus availability?" (defended in 2006).

O. C. Nwoke (PhD, University of Ibadan, Nigeria) "Assessment of germplasm adaptation to low P environments in the benchmark areas of the moist savanna zone of West-Africa" (thesis defended in December 2003).

O. Olayide (MSc, University of Ibadan, Nigeria) "Manure marketing in northern Nigeria" (defended in 2007).

S. Ponseele (MSc, KULeuven) "Assessment of the N-losses from urea applied alone or in combination with organic matter"(defended in 2006).

P. Pypers (PhD, KULeuven). "Phosphorus acquisition by tropical legumes in soils with differing P intensity and P quantity" (defended in 2006).

D. Stuyckens (MSc, KULeuven) "Assessment of mechanisms leading to positive interactions between organic matter and urea in the West African Moist Savannah" (defended in 2006)

F. O. Tabi (PhD, University of Ibadan, Nigeria): 'The development of a land information system for agrotechnology transfer' (thesis submitted and defended in 2004).

O. Ugbabe (MSc, ABU, Samaru, Nigeria): "Economic analysis of constraints for promising balanced nutrient management systems in Northern Nigeria" (defended in 2005).

J. O. Unogwu (MSc, KULeuven) "Assessment of mechanisms leading to positive interactions between organic matter (*Senna Siamea*) and chemical fertilizer (urea) in the moist savanna zone of west Africa" (defended in 2005).

I. Vandeplas (MSc, KULeuven): 'Enhancement of maize-based production systems through rotation with grain legumes in Northern Nigeria; a participatory approach' (defended in May 2003).

S. Van Houdt (MSc, Katholieke HogeSchool Kempen) "Nutrient deficiencies in maize and its relation with soil type and land use in West Africa" (defended in 2005).

L. Van Loon (MSc, KULeuven) 'Improvement of phosphorus availability in strongly weathered soils through adapted cereal-legume rotations' (defended in June 2004).

K. Wallays (MSc, KULeuven) "Socio-economic analysis of promising Balanced Nutrient Management Systems in Northern Nigeria" (defended in May 2003).

IV. Scientific publications (2002-2007)

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V. Conclusions

As stipulated at the outset, the final report of this BNMSII project encompasses more than a mere report of a 6-years R4D (research for development) project. Because it also spans a series of subsequent DGDC sponsored interventions with basically the same partners, it calls for a deeper analysis at the end of it all.

As mentioned before, the history of this project also reflects to some extent the **evolution in the R4D paradigm**, that in the early eighties – when the first phase of this sequel was conceptualized was very much still a purely research driven approach, without giving much thought to the human dimension of it. Research was very much designed by the scientists, not always alienated from the real problems, but in any case without sufficient reflection and partnership with the stakeholders, farmers in particular. Yet, not all that was done proved irrelevant; it only grew richer and more adapted to the real conditions of the targeted beneficiaries. As such, it can be seen that in the 20 years of this collaboration between KULeuven and IITA and its partners, we moved from process-based research activities towards on-farm activities and impact assessments, without abandoning the basic research.

Again, and as emphasized before, the **long-term perspective** of this "sequel" proved to be essential for its success. Not only did this allow us to conduct **long-term trials** – which are the key to understanding natural resource management issues - , but also it created **strong partnerships** and a long-term investment in **capacity building**. As concerns the latter, the number of scientists trained is large and most of them, both Belgian and African, have made their career in agricultural research in a developing context. As concerns the long-term trials, after 20 years of the one at the IITA campus, we can only recommend that at least this one should be continued. Long-term trials are the only way to provide accurate information between the effects of specific management interventions (e.g. organic versus inorganic fertilization; tillage versus no-tillage; residue retention versus removal, specific rotations) on the long term. We can only regret that most of the decision making in agricultural policies is based on poor data, empirical and ill-validated in a longer time perspective. This leads to myths and unacceptable interventions that may be attractive to the donor community, but do not provide solutions in the long run.

During the 20 years of this collaboration, we were able to organize **2 international symposia**, one in Leuven in 1991, one in Cotonou, Benin in 2000. Together with a very long list of **international publications** in the best journals within our field, this confirms that these projects have been at the forefront of soil fertility research for Africa. The material published on soil organic matter modeling, the state-of-the-art application of stable isotope methods in this context of weathered soil management has found wide appreciation in the international soil science community.

In the more applied area, the BNMS projects have pioneered a number of **promising interventions** while it has also demystified other often suggested interventions. The project has clearly shown that sustainable yields can only be obtained by combining organic and inorganic sources of nutrients. While a purely organic approach remains technically possible, it quickly meets constraints as to the amount of organic material needed, which is strongly limited, due to ecological reasons and due to competing demands for it. On the other hand, a purely fertilizer based approach also leads to yield decline after a number of years, leaving only the option of combining both sources. The project has given ample proof of the existence of positive interactions between the two sources and did significant process work to understand the underlying reasons.

Figure 17. Happy farmers in a groundnut field designed for legume-cereal rotation

It also became obvious that P is a major constraint to crop production in the West-African savanna and the subsequent project phases have given a number of possible approaches to counteract this. The positive effects on P-availability by legumes in the rotation have been demonstrated in field trials and the underlying mechanisms unraveled in laboratory experiments in scenarios of increasing complexity. Besides this main P-issue, missing nutrient trials carried out at a large scale also identified other nutrient imbalances that would have to be taken into account when a proper fertilizer recommendation has to be made in this region.

Figure 18. Farmers preparing soybean recipe

The **improved crop rotations** with soybean and cereals that resulted from all the above findings also took firm root in the north of Nigeria, in part also due to a considerable marketing effort of soybean as a cash crop. An adoption study carried out in 2005 showed that within a sample of households in the northern Guinea Savanna of Nigeria, up to 40% of the households had **adopted** the BNMS soybean-cereal rotation while up to 48% had adopted the combined inorganic fertilizer/manure technology brought by the BNMS project.

In conclusion, after 20 years, the subsequent interventions have contributed significantly both to the advancement of the science of tropical soil fertility as well to the improvement of the income of households in selected parts of the West-African savanna. It should also not be seen as an end to this kind of research, but rather as a starting point. The number of people trained, the partnerships forged and the significant findings guarantee that BNMS will continue, perhaps in different places with different challenges but in the belief that the tools are created and ready to use.