IFDC

An International Center for Soil Fertility and Agricultural Development

Collaborative Research Programme for Soil Fertility Restoration and Management in Resource-Poor Areas of Sub-Saharan Africa

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ACFD

African Center for Fertilizer Development

Tropical Soil Biology and Fertility Programme

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Preface

Soil fertility depletion results in low agricultural productivity and poverty and is pervasive in production systems in sub-Saharan Africa (SSA). Recognizing the complexity of the issue, IFDC, African Center for Fertilizer Development (ACFD) and Tropical Soil Biology and Fertility Programme (TSBF), with financial support from the International Fund for Agricultural Development (IFAD), developed integrated soil fertility management (ISFM) options in concert with national partners in West and Southern Africa. One of the key attractions of ISFM is that a mixture of organic and/or inorganic soil amendments and inorganic fertilizers improves the efficiency of the latter, which, when used in isolation, is risky and not often profitable.

This report presents the results and achievements of a 3-year project. An effective way of tackling complex soil fertility problems, is to involve principal stakeholders in developing soil fertility management options and strategies. The main institutional players in this regard have been:

West Africa
IFDC–Africa (Lomé), Togo's Village Organisation and Development Project (PODV), the Togolese Institute for Agronomic Research (ITRA, Lomé), the Togolese NGO Recherche Appui et Formation aux Initiatives d'autodéveloppement (RAFIA) (Dapaong), and Niger's National Institute for Agronomic Research (INRAN, Niamey).

Southern Africa
TSBF (Nairobi), ACFD, the Dept. of Research and Specialist Services (DR&SS), the Africa University, University of Zimbabwe, Farming Systems Research Unit, the Chemistry and Soil Research Institute, and the Department of Agricultural Technical and Extension Services in Harare, the DR&SS of Zambia, the Dept. of Agricultural and Technical Services of Malawi, and Farmers' groups in Zimbabwe, Malawi and Zambia.

The overall coordinator of the project was Dr. Henk Breman. For the implementation of the project, the contribution of certain individuals must be acknowledged. They are: West Africa—Dr. Henk van Reuler (regional project coordinator), Dr. B. Fofana and Mr. A. Tamelokpo (agronomists), Mr. K. D. Gnakpénou and Mr. K. Koukoudé (technicians), and Mrs. I. Adzoh (secretary). H. Breman, M. K. Thompson, and Charles Yamoah edited the report. For Southern Africa, acknowledgment is given to Dr. Herbert Murwira (regional project coordinator).

The report's primary authors are Dr. Henk van Reuler and Dr. Herbert Murwira.

The steering committee has been composed of Henk Breman (Director, IFDC-Africa), Sam Muchena (Director, ACFD), Mike Swift (Director, TSBF), and Doug Wholey (IFAD). Shantanu Mathur (IFAD, Rome) and Amit Roy (President and Chief Executive Officer, IFDC, Muscle Shoals) contributed at crucial moments of the project.

Acknowledgment: T. Struif Bontkes, L. L. Hammond, A. H. Roy, and Charles Yamoah improved the document through their detailed comments. Various members of AfNet contributed to the results reported for Southern Africa. These include R. Chikowo, P. Chivenge, Farming Systems Research Unit (F.S.R.U.) team (Zimbabwe), J. Karigwindi, C. Kawimbe, A. Mapiki, F. Mugabe, K. Mutiro, M. Mwale, J. Nyamangara, N. Nhamo, J. K. Nzuma, G. Rugara, and D. Shumba.

Abbreviations

ACFD	African Centre for Fertilizer Development
AE	agronomic efficiency
BS	base saturation
CEC	cation exchange capacity
CIMMYT	International Maize and Wheat Improvement Center
CORAF	West & Central African Council for Agricultural Research & Development
DR&SS	Dept. of Research and Specialist Services
DSSAT	decision support system for agrotechnology transfer
DSSs	Decision support system (s)
DSS–FFU	Decision Support System – Feasibility Fertilizer Use
DSS–OM	Decision Support System – Organic Matter
DSS–PR	Decision Support System – Phosphate Rock
EU	efficiency of utilization
FAO	Food and Agriculture Organization of the United Nations
F.S.R.U.	Farming Systems Research Unit
GY	grain yields
HI	harvest index (grain yield/total biomass)
HMP	hexametaphosphate
IAE	Institute of Agricultural Engineering
IBSRAM	International Board for Soil Research and Management
ICRA	International Centre for Development Oriented Research in Agriculture
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IDRC	International Development Research Centre
IFAD	International Fund for Agricultural Development
IFDC	An International Center for Soil Fertility and Agricultural Development
IFDC-Africa	Africa Division of IFDC
IIED	International Institute for Environment & Development
IITA	International Institute for Tropical Agriculture
INRAB	Institut National de Recherche Agronomique du Bénin
INRAN	Institut National de Recherche Agronomique du Niger
ISFM	Integrated Soil Fertility Management
ITRA	Institut Togolais de Recherche Agronomique
JIRCAS	Japan International Research Center for Agricultural Sciences
KCl	potassium chloride/muriate of potash
KIT	Royal Tropical Institute
LSD	least significant difference
NARES	National Agricultural Research and Extension Systems
NGO(s)	non-governmental organization(s)
OM	organic matter
PODV	Projet d’Organisation et de Développement Villageois
PR	phosphate rock
QUEFTS	quantitative evaluation of the fertility of tropical soils
RAFIA	Recherche, Appui et Formation aux Initiatives d’Autodéveloppement

Abbreviations (Continued)

RAMR	recherche appliquée en milieu réel
RF	recovery fraction
SAP	structural adjustment program
SARI	Savanna Agricultural Research Institute, Tamale, Ghana
SG 2000	Sasakawa-Global 2000
SFI	Soil Fertility Initiative
SOM	soil organic matter
SSA	Sub-Saharan Africa
SSP	single superphosphate
TSBF	Tropical Soil Biology and Fertility programme
USDA	United States Department of Agriculture
TSP	triple superphosphate
VCR	value-cost ratio
VKP	Dutch Association of Fertilizer Producers
WAFMEN	West African Fertilizer Management and Evaluation Network
WAP	week after planting
WGEN	weather generator

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Collaborative Research Programme for Soil Fertility Restoration and Management in Resource-Poor Areas of Sub-Saharan Africa

SUMMARY

This report presents results from experiments and dissemination activities carried out in West and southern Africa over the past 3 years. The activities and results reported are for two to three growing seasons and concern Togo and Niger in West Africa and Malawi, Zambia, and Zimbabwe in southern Africa.

The objectives were to develop methodologies and practical interventions for improving the efficiency of organic matter (OM), other soil amendments, and inorganic fertilizers through integrated use. The integrated soil fertility management (ISFM) concentrated on a cover crop (mucuna) and on compost and manure in West Africa. In southern Africa manure management and the determination of fertilizer equivalency of manure received the most attention. Most of these studies were implemented in partnership with partners/network members. Farmer participatory trials were established as part of the dissemination activities.

West Africa

Existing methodologies concerning the use of mucuna in the West African Coastal Savannah to decrease the use of fertilizer-nitrogen and to suppress weeds have been transformed into an ISFM technology. The Coastal Savannah has two growing seasons: (1) relatively long and secure and (2) short and unreliable. Where others in the past have promoted the production of mucuna in the second season to decrease the dependency of expensive fertilizers, the International Fertilizer Development Center (IFDC) used this cover crop in combination with local phosphate rock (PR) to improve the efficiency of fertilizer nutrient use efficiency of the main crop (NPK fertilizer). Optimal management of mucuna biomass and of other OM (e.g., crop byproducts such as straw) was an indispensable part of the technology. To interest the farmers, the technology to be developed had to lead to a yield of the main crop in the first growing season higher than traditionally obtained in the two seasons together. Secondly, the efficiency of the use of fertilizer nutrients by the main crop had to reach a level that fertilizer use became economically attractive for farmers.

Maize was used as a primary test crop. The results have been so positive that an International Fund for Agricultural Development (IFAD)-funded rural development project in southern Togo (Projet d'Organisation et de Développement Villageois [PODV]) invited IFDC to establish demonstration plots in 60 of their villages. Two- to three-fold yield increases appear possible with the "maize-mucuna/PR-NPK system." A socioeconomic study in the PODV regions identified the constraints to adoption of this technology.

An effort was made to distinguish between the positive effect of biological N fixation and other advantages of legume-cereal rotation. Mucuna itself was used as a legume.

The second technology that was developed and promoted in West Africa concerns the use of inorganic fertilizer on compound fields. Compound fields surround homesteads and villages and receive household wastes, compost, and manure. An important fraction of the concerned OM and its nutrient content is taken from bush and bush fields, bringing crops, crop byproducts, and manure to the village. Therefore, the soils of compound fields are in general of higher quality than those of bush fields, and higher fertilizer use efficiency can be expected on the compound fields. In other words, the use of fertilizer should, in the first place, be developed and recommended for compound fields, an approach opposite of nongovernmental organizations' (NGOs) recommendations in the region. IFDC expected that, in particular, nitrogen fertilizer should be interesting, in view of nitrogen losses by volatilization and leaching. On-farm trials have shown that in the savannah as in the Sahel, fertilizer-N is twice as effective on compound fields as on bush fields.

The project contributed also to the development of two other technologies—the (integrated) use of P-fertilizers and PR and agroforestry, and of three decision support systems (DSSs). The DSSs will help farmers, extension services, NGOs, and private and public development planners in decisions related to the (potential) use of fertilizers, leguminous crops, and PR.

Southern Africa

Experiments were established to determine the fertilizer equivalency of organic resources, effects of combining organic and inorganic plant nutrient sources, synchrony and enhancing the quality of manure. Several technologies were tested in the three countries focusing on manure management and biomass transfer. Results are presented from Zimbabwe and Zambia and from the initial characterization work that was done in Malawi to develop a research agenda.

The results from the work in Zimbabwe showed clear benefits of en-

hancing manure quality and crop yields through improved manure storage practices. Pit storage of manure was found superior to the conventional heaping practiced by most farmers. In Zambia, beneficial effects of combining organic and inorganic plant nutrient sources were obtained. In experiments established to determine the effects of timing of application of high-quality leaf litter, there were no significant differences in the dry matter and grain yield of maize between treatments except the control. The practical implication of this is that farmers have a choice as to when to apply the pruning, either at planting or 1, 2, or 3 weeks after planting without fear of loss of yields. Farmers can time application of such high-quality organic resources when there is no critical demand for labor.

The preliminary survey results from Malawi indicate that use of cattle manure is important in the northern districts. Farmers use a rotational kraal system in which they plant crops 1 to 2 years after a kraal was shifted. The potential for improvement lies in improving the quality of the manure so that those farmers do not lose a year or two without making use of the manure. Farmers are implementing these interventions in addition to a drive for intensification of use of legumes.

The project made important contributions to a DSS developed for farmers and their advisers concerning the use of different forms of OM. Also the OM database, being part of the system, was extended due to the project.

THE PROJECT

IFAD, under T.A. Grant No. 322-IFDC/African Centre for Fertilizer Development (ACFD), funded the "Collaborative Research Programme for Soil Fertility Restoration and Management in Resource-Poor Areas of Sub-Saharan Africa" during 1996-2000. The project was implemented by a consortium of three international institutions:

- ACFD in Harare, Zimbabwe.
- International Institute for Soil Fertility Management (IFDC-Africa) in Lomé, Togo, which is the African Division of IFDC based in Muscle Shoals, Alabama, U.S.A.
- Tropical Soil Biology and Fertility Programme (TSBF) in Nairobi, Kenya.

The overall objective of the program was to develop appropriate technologies for soil fertility-induced agricultural production increases that are viable, sustainable, and socially acceptable. The specific objectives were:

- Increasing agricultural productivity among resource-poor farming systems through better use of on- and off-farm plant nutrients, organic and inorganic.
- Defining factors facilitating or constraining the adoption of sustainable nutrient management practices.

The program included the following components:

1. **Research**—Strengthening collaborative, applied on-farm research on soil fertility maintenance and improvement through participatory farmer-managed, multidisciplinary research.
2. **Development of technology packages for sustainable land management**—The development of these packages being based on biophysical on-farm research in the actual socioeconomic, institutional, and policy context.
3. **Development of information databases for sustainable land management**—The purpose of the databases is the identification of recommendation domains for the various packages. They have been used for or translated into DSSs.
4. **Strengthening national institutions and capacity for research and development**—Through meetings, training needs in the field of ISFM were identified, and staff members of collaborating institutions were trained.

General Introduction

The report is composed of three parts. First, the main principles related to the integrated use of soil amendments and inorganic fertilizers are presented. The work executed in West and in southern Africa is summarized separately, respecting the difference in character caused by differences between the regions, farmers' priorities, and the mandates of the executing institutes. This mode of presentation neglects, however, the cross fertilization that took place between the activities on both sides of the continent.

General Principles of Integrated Soil Fertility Management

Plant Growth and Nutrients

Plants need water, light, and nutrients for their growth. Generally, farmers can only change the quantities of nutrients and sometimes water. The availability of water can be increased through irrigation where water is available and to a certain extent by controlling rainfall runoff. Adding the needed nutrients and preventing their loss can influence the availability of nutrients to plants. There are 16 essential nutrients for plant growth, carbon, hydrogen, and oxygen are supplied to plants from air and water. The remaining 13 nutrients must be supplied from the soil. The amount of essential nutrients available determines the yield level that can be obtained if it is assumed that only nutrients limit the growth.

Most soils in sub-Saharan Africa (SSA) are poor in nutrients that can be absorbed by crops. Through weathering, nutrient-bearing minerals have disappeared and the dominating clay mineral has a low capacity to absorb nutrients. In these soils with a low chemical fertility, the soil organic matter (SOM) plays a very important role as a source of nutrients and for retaining nutrients. The physical fertility (water holding capacity, infiltration, etc.) is affected by the texture and soil structure. Again the SOM plays an important role as it strongly affects the physical properties.

Agricultural Intensification—Food crop production has not kept pace with population growth in many parts of SSA. One of the solutions for farmers to increase production is to take new land into cultivation and to shorten or even abandon fallow periods. However, in most regions the best land is already cultivated and only marginal land or land that can be protected better for ecological reasons remains. Shortening or abandoning the fallow period generally results in yield decline and is not a sustainable solution. Therefore, agricultural intensification—increasing the yield per unit surface—seems the only option for increasing food production in a sustainable way.

Intensification requires soil improvement and the application of nutrients. Nutrients can be added in organic or inorganic forms. Organic sources of nutrients include animal manure, compost, and plant materials. Besides procuring nutrients, they contribute to general soil improvement, with other soil amendments such as lime and PR. Inorganic fertilizers are produced as straight fertilizers that contain only one nutrient (nitrogen-N, phosphorus-P, or potassium-K), and compound or mixed fertilizers that contain more than one of these nutrients. Organic and inorganic sources of nutrients each have their advantages and disadvantages. In terms of plant utilization, the source of nutrients is not important; plants absorb the nutrient in the same form regardless of source (organic or inorganic).

The primary advantage of organic sources of nutrients is the combination of a gradual release of nutrients and the contribution to the SOM content. However, these two variables are conflicting (De Ridder and Van Keulen, 1990). Nutrients are released through decomposition of the organic materials and nutrient availability is optimized if the decomposition is rapid. In this case, however, the contribution to OM buildup is small. In the case where OM buildup is favored, i.e., slow decomposition, release of nutrients is slow. Moreover, the decomposition is strongly affected by soil moisture and temperature and cannot be controlled. In other words, nutrients may be released at times when the plant does not need them. Additionally, only a limited amount of OM is available in many regions and its nutrient content is generally low. Therefore, it is generally not possible to meet the nutrient demands of the crops through use of organic fertilizers alone.

In contrast, the nutrient content of mineral fertilizers is known and is comparatively high. Also, the timing of nutrient uptake by the crop can be reasonably well predicted. Disadvantages related to mineral fertilizers are higher costs and potential environmental risks if they are not well chosen and managed. The relatively high costs combined with low agronomic efficiency can make the use of mineral fertilizer in food crop production unprofitable for African farmers. The low efficiency is mainly associated with poor soil conditions and erratic rainfall, characterized by drought periods or torrential showers, which marginalizes the beneficial effects of fertilizer. Through soil fertility improvement, the efficiency of inputs can be increased.

Soil Fertility Improvement

The term "soil fertility improvement" often seems to automatically suggest the need to increase the use of mineral fertilizers. Without doubt, increased use of fertilizers can substantially increase production. However, due to low efficiency caused by high losses, the amounts required are often too high to be economically attractive to farmers. Moreover, the use of mineral fertilizers alone will not improve the soil and risks to have, in the long run, a negative impact on productivity in Africa (Pieri, 1989). The latter was one of the first to emphasize that soil fertility improvement could only be achieved through the integrated use of both soil amendments and mineral fertilizers. In Table 1 some soil fertility improvement techniques are presented. A soil amendment is here defined as a material that is applied for improving the soil conditions and not necessarily for directly supplying nutrients to crops.

The need for the different types of amendments that are available de-

Table 1. Soil Fertility Improvement: Three Types of Soil Amendments

Objectives	Amendments
Improvement of SOM status (quality and quantity)	OM: crop residues; (green) manure; compost; agroforestry
Improvement of P availability	PR; mineral fertilizer-P
Improvement of pH	Lime

pends on the limitations imposed by SOM status, P availability, and/or soil pH. Lime and gypsum are the most used products to improve soil pH but, as improvement of soil pH is not yet a significant limitation in the intervention zones, emphasis in this project was placed on the integrated management of organic materials, PR, and chemical fertilizers.

Soluble sources of P as PR can be used to increase the availability of P in a relatively short period of time. General improvement of the SOM status, however, is a much more difficult process. In principle, the solution is simple—use more and more adequate OM. In Africa, however, the availability of OM is limited due to poor quality of the natural resources, overpopulation, and the resulting over-exploitation of OM. Transport from elsewhere is too costly. However, the combination of inorganic fertilizers with recycling of crop residues, (green) manure, compost, fodder crops, or agroforestry can improve both availability and quality of OM over an extended period of time. As a result, soils improve, the efficiency of fertilizers increase, and their use becomes economically more feasible (Groot et al., 1998).

The SOM status, qualitatively and quantitatively, affects plant growth in different ways. Through decomposition of SOM, nutrients become available for uptake by crops. Indirectly, the SOM influences the plant's nutrition through its positive effects on many factors including soil structure, water-holding capacity, nutrient retention capacity, occupation of P-fixation sites, and biological activity. Together they result in higher fertilizer use efficiency. Improved pH (lime, gypsum, PR) does the same, ensuring that available nutrients are accessible for the plants. It improves, among other factors, the availability of P. The positive effect of both SOM status and pH improvement is often still insufficient in view of optimal use of N and K by plants. This is the reason for the attention paid by the project to PR and P fertilizer.

Fertilizer Use and Crop Residue Recycling—In SSA, fertilizer is often not used at all, or only used in inadequate amounts, resulting in low crop yields. Moreover, crop residues are often used as fuel despite the fact that crop residue recycling is essential for maintaining the SOM status. As crop production increases through the use of external inputs, not only the grain but also the stover production is increased which, when left on the field, makes a positive contribution to SOM buildup. Two practices enhance strongly the positive effect of crop residue recycling. Crop rotations are more effective than monocropping, and conservation tillage is more effective than traditional tillage. In case of crop rotations, the positive effect on fertilizer-use efficiency and crop yield is not only linked to soil improvement as such. The suppression of pests and diseases (weeds included), the stimulation of micro-organisms increasing the availability of N (e.g., rhizobia), and the accessibility of P (mycorrhiza) play roles.

Use of (Green) Manure—Recycling of crop residues can be reduced due to their use as cattle feed. Animal manures also have a positive effect on the SOM status, but the quality of the manure is affected by the quality of the cattle feed. An example from Burkina Faso is presented in Table 2 (Berger, 1996) and shows the strong variation among samples. Large amounts of manure are required to contribute significantly to the nutrition of crops. Additionally, manure is generally not deposited where it is most needed; this makes it necessary to collect, store, and apply the manure in the next growing season on the fields to be cultivated. This is complicated by a general lack of labor for this type of activity.

After crop cultivation, fields are generally abandoned and a temporary (weed) vegetation covers the field. Managing these so-called fallows is often proposed as a way to enhance the soil fertility restoration and improve SOM status; green manure or cover crops are planted. Leguminous species are promoted in the search for cheap N. Grasses, however, and other species with more slowly mineralizable OM contribute more to regeneration of the SOM status, while the effective use of legumes may be costly (e.g., costs of P and pest control). Sometimes the "fallow vegetation" is already planted during the growing season of the main crop and, after harvest of the latter the fallow species become a cover crop and produce the green manure for the next main crop. A very effective derivation of improved fallow/cover crop is the rotation within cropping systems with perennial pastures, using each of the different components for several years in a row.

Agroforestry—Agroforestry is a broad term that indicates combined growth of trees (or other perennials) and (other) crops (fodders and rangeland included) on the same field. Even fallow systems are sometimes considered as agroforestry. A whole series

Table 2. Average Nutrient Content of 30 Manure Samples Collected in Burkina Faso

	N	P	K
	- - - - - - - -	(kg/tonne)	- - - - - - - -
Manure	10	1.5	12

of agroforestry techniques exists, having different goals and being adapted to different environments. Alley cropping is a technique that has, until recently, been extensively promoted in West Africa. This technique proved to work well on-station with relatively fertile soils, but on-farm results were disappointing and farmers' adoption was low. Alley cropping is based on the idea that trees have a much deeper penetrating root system than food crops allowing the trees to absorb nutrients that are out of reach for food crops or nutrients that may be lost through leaching. These nutrients can be made accessible to the food crop through pruning of the trees and recycling the pruned material.

Although this technique would appear to be effective in principle, there are several constraints that limit the effectiveness in practice. For example, on less fertile soils even the roots of tree crops typically concentrate in the topsoil where the nutrients are most concentrated. Consequently, the roots of trees compete with roots of food crops for the same nutrients and water; this results in a negative effect on yields. Even on fertile soils, competition is easily a bottleneck. Intensive pruning during the cropping season decreases in the first instance the problem, but it leads in time to the loss of deep rooting and the dominance of a superficial rooting system where the crop roots are also found. Furthermore, the technique is very labor intensive. The indigenous park lands of the drier savannah and the multiple species—multilevel "gardens" of the humid tropics—may be more interesting approaches in the ISFM context (Breman and Kessler, 1996).

Increasing P Availability—Applying P in either an organic or mineral form is the most common way to increase the P availability in a soil. OM application can have a double role; it is a source of P, and it can occupy soil P-fixation sites instead of P. Under certain conditions (acid soils) correction of the soil pH by liming is also very effective in increasing the available-P.

While PR deposits are found in many African countries, only a few can be considered suitable for direct application. The other alternative is to apply commercially processed mineral fertilizer-P. These are effective fertilizers from which a portion is available in the year of application while subsequent crops may absorb additional amounts of the remaining P. Janssen and Wolf (1988) developed a simple equation for estimating this residual effect. It is important to consider both the initial and residual P availability in relation to anticipated target yield levels when developing application strategies. For example, one alternative strategy could be a one-time application of a large quantity versus annual application of small quantities. Economic considerations and fertilizer availability will have a decisive role in the selection of management practices. In both cases, the ultimate goal will have to be to ensure a minimum level of available-P, but high enough for the optimum use of N and K fertilizers.

ACTIVITIES

West Africa

Background

Biophysical Conditions

Geology and Geomorphology—West Africa can be divided into a northern zone where the marine and terrestrial sediments and rocks occur and a southern zone where rocks of the basement complex of Precambrian age predominate. The basement complex is comprised of granites and associated rocks of Precambrian age. This complex forms the African continental shield and underlies the whole of West Africa. The composition of the basement complex varies greatly. The sedimentary rocks are classified according to their age as they have been subjected to more than one weathering and erosion cycle and consist mainly of residual materials like quartz, kaolinite, and gibbsite. Within the varied complex of sedimentary deposits, weathering of sandstone results in very poor soils. Soils developed on shale tend to be more clayey and to some extent, chemically richer.

Within the basement complex, soils developed on metamorphic rocks (schists, amphibolites, etc.) are relatively fine-textured and are chemically richer than soils developed on granites. Moreover, soils on granite have coarser textures. The poorest basement soils are those developed on quartzite.

Large, nearly level plains formed by intensive erosion characterize the West African landscape. The remnants of the oldest peneplains occur as highlands that are strongly dissected and have a steep relief. The younger plains have an undulating relief and are dissected to various degrees by streams and rivers. Locally, remnants of the older plains occur as inselbergs. Ironstone hardpans are common.

Climate—Rainfall and its distribution are the most striking features of the climate of West Africa. Based on the temporal and spatial variations in precipitation and potential evapotranspiration, three climatic regimes can be distinguished:

- **Monomodal Regime**
  The monomodal regime is characterized by a single peak. The mean annual rainfall varies from less than 100 mm to over 3,000 mm.

- **Bimodal Regime**
  The mean annual rainfall varies from 750 to 2,000 mm. Two peaks characterize the distribution. The total humid period ranges from 5 to 9 months.

  In the coastal region between Accra and Lomé, the humid period is less than 5 months as the second rainy season is not very pronounced, and the precipitation does not exceed the potential evapotranspiration.

- **Pseudo-Modal Regime**
  The pseudo-modal regime is a transition between the regions with a mono- and bimodal regime. The mean annual amount of rainfall varies from 1,250 to 3,000 mm.

At least two other variables must be taken into account to understand West Africa's agro-ecology. In most of West Africa (the Sahel, the Sudanian, and Northern Guinea savannah), extremely high potential evapotranspiration causes an aridity of the dry season that is more extreme than anywhere else at the same total annual rainfall. The phenomenon is most extreme where rainfall is lowest (North Sahel). Going to the extreme southwest of West Africa, rainfall intensity increases with increasing rainfall. The coastal zone of Guinea, Liberia, and Sierra Leone have the most extreme rains. They are very erosive, and soil leaching was more severe than elsewhere.

Soils—Table 3 presents some characteristics of tropical West African soils typical of different agroecological zones, illustrating that West African soils are among the poorest in the world. It is not the intrinsic soil fertility alone that is limiting but also the combination of soil poverty and extreme aridity during the dry season, in particular for the Sahel and the Sudanian savannah. Therefore, the contribution of perennial species for a given average rainfall to the annual plant production, even in the case of undisturbed vegetation, is lower than elsewhere in the world for an identical quantity of annual rainfall. The SOM content is therefore the lowest known. Further complicating the situation is, among others, very low cation exchange capacity (CEC), high soil fragility (Penning de Vries and Djitèye, 1982; Breman and Kessler, 1996), low nutrient-holding capacity, and the water-holding capacity of most soils.

The most limiting factor for primary production (and for the derived animal production) is water where less than 250 mm/year infiltrates. As soon as more water infiltrates, N and P availability becomes more limiting than water. The total amount of N that can be absorbed annually by the aboveground biomass of food crops and vegetation without soil depletion increases from almost zero in the Sahara to 15-20 kg/ha in the Sudanian savannah. For P, the amount is about one tenth of the amount of N absorbed. Using the Quantitative Evaluation of the Fertilily of Tropical Soils (QUEFTS) model (Janssen et al., 1990), it can be estimated that the supply of N and P by the soil is more or less in equilibrium at a ratio of available P/organic C of $0.55x10^{-3}$. The average values are 1.33, 0.66, 0.58, and 0.45, respectively for the Sahel, the Sudanian and Guinea savannahs and the equatorial forest zone (Table 3). In other words, whereas P availability is very low in most of West Africa, N availability (a rather constant fraction of the organic C content) is even more limited than P availability in the Sahel.

Table 3 shows also that the average soil pH is not too extreme. Al- and Fe-toxicity, keeping the levels of available-P very low, are not dominant features of West African soils. The frequency of the phenomenon increases with increasing rainfall. (Guinea savannah and Equatorial forest zone have the lowest pH.) The most extreme values of soil acidity are found in the extremely leached southwest with its very intensive rainfall events.

Agroecological Zones—In West Africa five main agroecological zones can be distinguished. These zones are based on the length and the periodicity of the growing period:

- **Sahel**
  The Sahel zone is the transitional zone between the Sahara desert and the savannah zone. The vegetation cover is sparse. Livestock raising dominates over crop production. In the southern part with a growing period of >75 days, millet can be grown.

- **Sudanian Savannah**
  The Sudanian Savannah is found south of the Sahel. The length of the growing period varies from 90 to 165 days. The rainfall distribution is monomodal. A wide range of crops can be grown.

Table 3. Average Chemical Characteristics of West African Soils of the Different Agroecological Zones (After Penning de Vries and Djitèye, 1982; Luiten and Hakkeling, 1990; Christianson and Vlek, 1991; and Manu et al., 1991)

Agroecological Zone	pH	Organic C	Total N	Total P	P-Bray	CEC	Base Saturation
		------(g/kg)	------	-----(mg/kg)	----	(mmol/kg)	(%)
Equatorial forest	5.7	20	2.0	260	9	87	28
Guinea savannah	5.7	12	1.3	340	7	85	59
Sudanian savannah	6.7	6	0.5	210	4	81	69
Sahel	5.7	3	0.2	100	4	25	28

- **Guinea Savannah**
  The Guinea Savannah zone extends south of the Sudanian one. The length of the growing period varies from 165 to 270 days. The rainfall in this zone is not uniformly distributed. In the northern part the distribution is monomodal, whereas in the southern part the distribution has a bimodal pattern.

- **Equatorial Forest**
  The Equatorial Forest extends southeast and southwest of the Guinea Savannah zone. The length of the growing period is more than 270 days. The main constraints for crop production are the sub-optimum solar radiation and the high air humidity, causing high incidence of pests and diseases. Only in this region can extended plantations of tree crops be found. Most agriculture is practiced in the so-called "Derived Savannah," where crops, grass, and bush land replace the original forest.

- **Coastal Savannah**
  South of the Guinea Savannah and between both parts of the Equatorial Forest and its derived savannahs, the Coastal Savannah is found. The rainfall is considerably lower than in the Southern Guinea Savannah and has a bimodal distribution. As a consequence, the production of two crops per year is often difficult. Even the main season crops may suffer from drought. While the total rainfall is more or less the same as in the Sudanian savannah, high air humidity and relatively low potential evapotranspiration lead to a much less arid dry season. Therefore, perennial plant life is not seriously hindered and the soils are more comparable to those of the Guinea than those of the Sudanian savannah.

Two minor agroecological zones are worthwhile to be mentioned: the extreme southwest with its intensive rainfall and highly weathered and leached soils and the local zones of higher altitude. The first does not allow sustainable systems based on annual crops (only). The second has opportunities for crops favored by somewhat lower temperatures (e.g., coffee and potatoes).

Socioeconomic Conditions

Poor soils and difficult climates combine to produce a very poor-resource base for West African agriculture. Limited use of external inputs and lack of employment outside agriculture are causing strong overpopulation at low absolute population pressure (Table 4). Intensification of agriculture, using external inputs, is required while the conditions for change are not yet met: low road density and limited infrastructure development in general, poorly developed transport and distribution systems, and limited and slow development of domestic markets. Integrated soil fertility improvement and management will often be a condition *sine qua non* for agricultural intensification based on more sustainable cropping systems.

It was shown that even the expected population of Sahelian countries in the year 2010 can be fed in a sustainable way by domestic agricultural production if fertilizers are used and the soils are improved. To do so, the SOM status has to be brought into equilibrium with the intensity of fertilizer use, and the best agricultural practices have to be applied (Breman and Sissoko, 1998). This is not likely to occur, however, because at today's prices of inputs and outputs, the production levels required in the broadest sense will not be very attractive for the farmers. In the Sahel, the revenues being achieved by farmers today will not be attainable using the more intensive management required for sustainability, despite the fact that today's management systems are currently mining nutrients from the soil. Equivalent revenues may nearly be achieved in northern Sudan, but it is only in southern Sudan that revenue estimates are higher for the improved management practices. These economic comparisons, however, do not consider the cost for required investments in SOM status improvement.

It is difficult to assess what is most lacking in the region—naturally available OM or external inputs such as inorganic fertilizer. It was calculated that for a country like Mali, even in the most favorable region for agriculture (the "cotton zone"), the availability of OM for maintenance of the agricultural production level of the mid-eighties and its external input use is only one third of the requirement (Breman and Traoré, 1987). As far as inorganic fertilizer use is concerned, only about 10% of the amount required to achieve sustainability is being used in West African countries (Henao and Baanante, 1999), and this use is limited to certain cash crops such as cotton, irrigated rice, peri-urban veg-

Table 4. The Carrying Capacity of West African Ecosystems for Human Land Use and the Population Density

Zone	Carrying Capacity Per Exploitation System			Density in 1985
	Animal Husbandry	Arable Farming	Agropastoralism	
	-(inhabitants/km^2)-			
Northern Sahel	1	-	1	0 – 7
Southern Sahel	7	10	11	7 – 27
Sudanian savannah	7	34	37	7 – 66
Guinean savannah	3	48	51	approx. 25

Source: Breman, 1992.

etable production, and maize. Results with these crops, however, show that more general intensification is possible where the output prices are attractive and stable and where the input and output markets are organized in an integrated manner.

Until recently, agricultural policy in the region has not favored intensification with the exception of cotton. The availability and distribution of agricultural inputs were managed by the government and have been, in general, rather ineffective. Distribution of fertilizers of the correct composition is often not available at the right time or in adequate quantities. Even after subsidies have been eliminated through the influence of structural adjustment programs (SAPs), imported fertilizers are often found to be too expensive. As a result, fertilizer use is decreasing and nutrient mining continues (Gerner et al., 1998).

This situation may change after privatization and liberalization are in effect for a longer period and when more countries adopt and implement national “Soil Fertility Initiative” action plans. However, at current price levels and at the existing soil fertility status, high risks exist for marginal land and smallholders. Chances for change and for intensification exist mainly around important cities (peri-urban production of vegetables and fruits at a short distance from towns and cereals further away), in regions favorable for certain cash crops (soil x climate x accessibility), and for integrated crop-livestock production in relation to pastoral systems or cash crops (e.g., Schreurs et al., in press).

RESEARCH

Generalities

The task “Strengthening collaborative, applied on-farm research on soil fertility maintenance and improvement through participatory farmer-managed, multidisciplinary research” was fulfilled in West Africa through experiments at 10 locations in three different agroecological zones (Figure1). In Table 5 some details on the activities are presented.

The aim of the experiments was to gain insight in and to quantify the effect of soil fertility improvement on the efficiency of mineral fertilizers (N and P). Generally the experimental

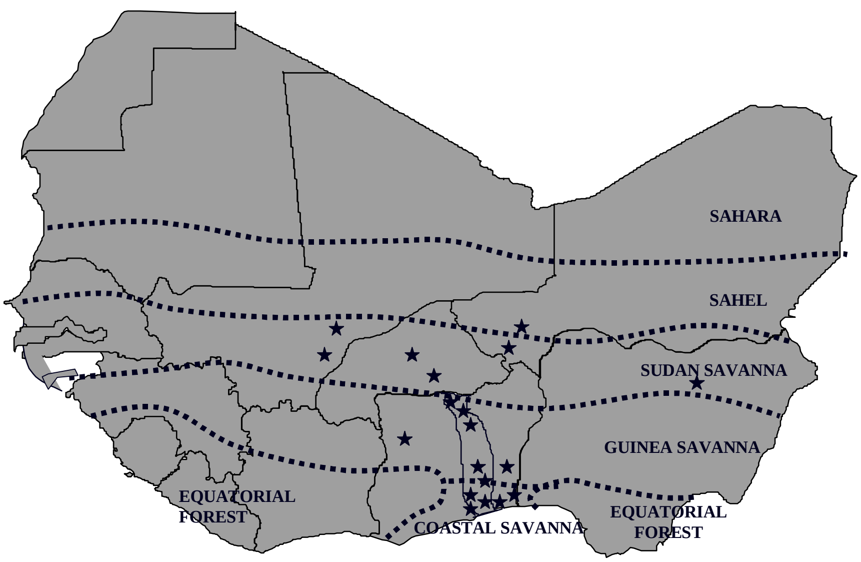


Figure 1. Experimental Sites in West Africa.

Table 5. Experimental Sites, Cooperating Partners and Approach Tested

Country	Region	Agroclimatic Zone	Rainfall Distribution	Rainfall mm/year	Crops	Partner	Approach
Togo	Peri-urban	Coastal savannah	Bimodal	700	Vegetables, spices, herbs	Farmers' organizations	Organic+mineral fertilizers
	Zone maritime	Coastal savannah	Bimodal	800-1,100	Maize	NGOs, ITRA	Maize-mucuna-fertilizers Compost-farmyard manure
						PODV	Maize-mucuna-fertilizers-PR
						Station	Maize-mucuna-fertilizers
	Savannah	S. Guinea savannah	Monomodal	1,000-1,200	Maize	Station	Maize-legume rotation-fertilizer P-PR
	Savannah	N. Guinea savannah	Monomodal	1,000-1,200	Maize	NGO	Compost-farmyard manure
Ghana	Tamale	N. Guinea savannah	Monomodal	1,000-1,200	Maize	SARI	Compost-farmyard manure
Niger	Karabedji	Sahel	Monomodal	500	Millet	ICRISAT, INRAN	Compost-farmyard manure
	Tillaberi				Irrigated rice	INRAN	Compost

Table 6. Experimental Design for Testing the Effect of Soil Fertility Improvement on the Efficiency of Mineral Fertilizers

Treatment	N	P
	- - - - - -(kg/ha)	- - - - -
1	0	0
2	50	0
3	100	0
4	0	15
5	0	30
6	50	15
7	50	30
8	100	15
9	100	30

design was a 3^2 factorial (Table 6). The factors were N and P at three levels. The experiments were executed in three or four replicates, resulting in 27 or 36 experimental units per location. To avoid that potassium (K) or sulfur (S) is limiting the yield, each unit received 100 kg K applied as potassium sulfate (K_2SO_4, 42% K).

The nitrogen (urea) and potassium (potassium sulfate) were split in two equal quantities and applied about 2 weeks after sowing and at flowering. The phosphorus (triple superphosphate [TSP]) was applied about 2 weeks after sowing.

During the growing season the following observations were made: planting date plant density, tasseling initiation stage, and 50% silking date. At harvest, the grain and stover (straw + husks) yield, total biomass (grain yield + stover yield + empty cobs), yield components (number of ears), as well as the number of plants were measured. Samples were collected for analyzing the N and P content of the aboveground plant parts.

In order to study the effect of soil fertility improvement on the efficiency of mineral fertilizers the following concepts were used:

(Agronomic efficiency) = Economic yield/(quantity of nutrient applied)

The agronomic efficiency (AE) is a simple and effective indicator of nutrient effectiveness from an economic point of view but is strongly influenced by other growth conditions, such as water availability (climatic conditions) and other nutrients. Careful interpretation is required, e.g., low agronomic efficiency may be caused by loss of fertilizer nutrients (e.g., through surface runoff or leaching). Therefore, these types of observations are also required during the cropping season.

Another measure of fertilizer efficiency is the efficiency of utilization (EU) of absorbed nutrients (physiological efficiency).

Efficiency of utilization = (economic yield)/(fertilizer nutrients absorbed)

This calculation requires analysis of plant samples to calculate nutrient uptake and facilitates an understanding of nutrient use within the plant. It enables to determine the effect of other variables on the fertilizer; e.g. suboptimal growth when ample water is available. The uptake data can also be used to determine if nutrients other than the ones applied are limiting. The efficiency of utilization is affected by other growth factors (other nutrients, water, etc.).

The uptake enables calculation of the fraction of applied nutrients recovered by plant absorption (recovery fraction [RF]).

Recovery fraction = (fertilizer nutrients absorbed)/(fertilizer nutrients applied)

For practical reasons, generally only the uptake by the aboveground plant parts is measured, e.g., for cereals, the grain and straw uptake. The uptake by roots is neglected, i.e., this is roughly compensated by uptake of nutrients from sources other than the fertilizer. Therefore, it is better to refer to the recovery fraction as the apparent recovery fraction. In this report we follow this general practice. The recovery fraction indicates which part of the applied fertilizer nutrient is absorbed by the crop and is affected by other growth factors (other nutrients, water, etc.). These factors are affected by crop management such as weeding, timeliness of activities, and fertilizer management (type of fertilizer, method and rate, and time of application). Higher recovery data through fertilizer management will not automatically result in higher utilization efficiency data or higher yields. However, e.g., in fodder crops higher N recovery may result in a higher N content, which means a higher quality.

The agronomic efficiency, efficiency of utilization and recovery efficiency (fraction) can be graphically represented in a so-called three-quadrant graph (Siband et al., 1989). In general, for cereals the following values are found in relation to N, P, and K fertilization:

EU-N 30 – 70 (kg/kg)
EU-P 200 – 600
EU-K 30 –120
RF-N 0.3 – 0.5
RF-P 0.1 – 0.2 (+ residual effect)
RF-K (no generalization is possible)

Use of Models (Quantitative Evaluation of the Fertility of Tropical Soils, Decision Support System for Agrotechnology Transfer)

Soil-crop simulation models constitute one of the few tools that can be used to investigate the long-term soil fertility impact and economic feasibility of nutrient management practices in a given environment. With appropriate soil and long-term historical weather data, soil-crop simulation models can be used for studying sustainability issues at various sites. The management-oriented crop models and utility programs for analyzing simulation experiments involving annual crops in single-season or in multiple-season crop sequences, are featured in the Decision Support System for Agrotechnology Transfer (DSSAT) software package (Tsuji et al., 1994).

Potential growth is determined from photosynthetically active radiation and its interception, whereas suboptimal temperatures, soil-water deficits, and N and P stresses limit actual biomass production on any day. The soil submodels for water, N, and P balance operate on the basis of soil layers. The soil-water balance component simulates drainage, evaporation, irrigation, runoff, and root water uptake (Ritchie, 1998). The N subroutines simulate the processes of OM turnover and inorganic and organic N fertilizer application with the associated mineralization-immobilization, urea hydrolysis, nitrification, denitrification, nitrate leaching, and ammonia volatilization (Godwin and Singh, 1998). The P component simulates the processes of adsorption and desorption of P, organic P turnover, and the dissolution of rock and fertilizer phosphate (Singh and Godwin, 1989; Daroub et al., 1998).

The crop simulation was used to:

- Quantify the primary determinants of yield.
- Identify and implement less risky planting and management strategies.
- Evaluate the long-term effect of such decisions on agricultural productivity and sustainability and soil fertility status.

In other words, simulation was used to understand why yields are as they are. Some examples may illustrate the use of models, leading to a better understanding of the technologies presented later.

1. IFDC-Africa has been executing on-station experiments since its establishment in 1987. However, it was not known how the yields obtained were related to the potential yield. In other words, it was not known whether, e.g., one or more (micro-) nutrients were limiting the yield. Calculation of the rainfed yield potential (i.e., with temperature, solar radiation, rainfall, soil water-holding characteristics, and crop genotype influencing yield potential) appeared to be very close to maximum yields actually obtained with all nutrients applied.

   A comparison of observed and simulated potential rain limited maize grain yields for experiments conducted at project sites is shown in Figure 2. Both the observed and simulated grain yields given throughout the paper are reported

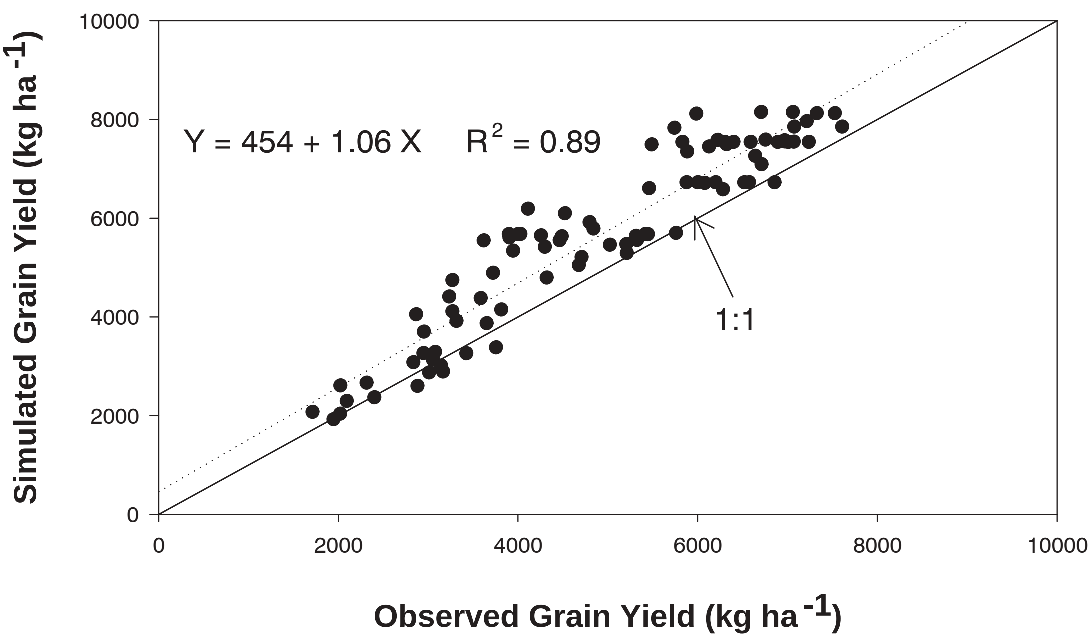


Figure 2. Comparison of Observed and Simulated Maize Grain Yields Based on 1:1 Line.

on a dry-weight basis. If the model were a perfect predictor and if there were no experimental error, all data points would lie on the 1:1 line. The spread around the 1:1 line also arose due to the presence of uncontrollable factors in some plots such as weeds and termites to which the model is not sensitive. The model's performance at different N rates and varieties at Koukombo and Davié is shown in Figure 3. The observed and simulated N response to maize at both sites was in general close. A certain overestimation of yields by the model is to be expected because control of experimental factors to which the model is insensitive could never be complete. The model captured the nonsignificant response to N application due to drought stress at Davié during the 1998 season.

2. Yields in southern Togo were severely depressed by drought during the main cropping season of 1998. The DSSAT model was used to study the effect of planting date on the yield. It appeared that even in 1998 planting early (March) would still lead to yields of about 2 tonnes maize per hectare, while planting late (April or May) would be almost useless. Both cases could be validated by farmers' practices and results!

3. The following simulation studies using long-term historical data for the past 12 years were undertaken for two sites in Togo, Koukombo in northern Togo and Davié in southern Togo, having monomodal and bimodal rainfall distribution, respectively (Table 7). Maize grain yields at (1) potential production level, that is with only temperature, solar radiation, and crop genotype influencing yield potential; (2) rainfed potential – with rainfall and soil water-holding characteristics also influencing the yield; and (3) nutrient-limited yield levels, as influenced by water and nutrient limitations, were investigated. Monthly plantings were scheduled in the model for the first of the month; however, under water-limited simulation sowing within the next 30 days was possible only when a soil

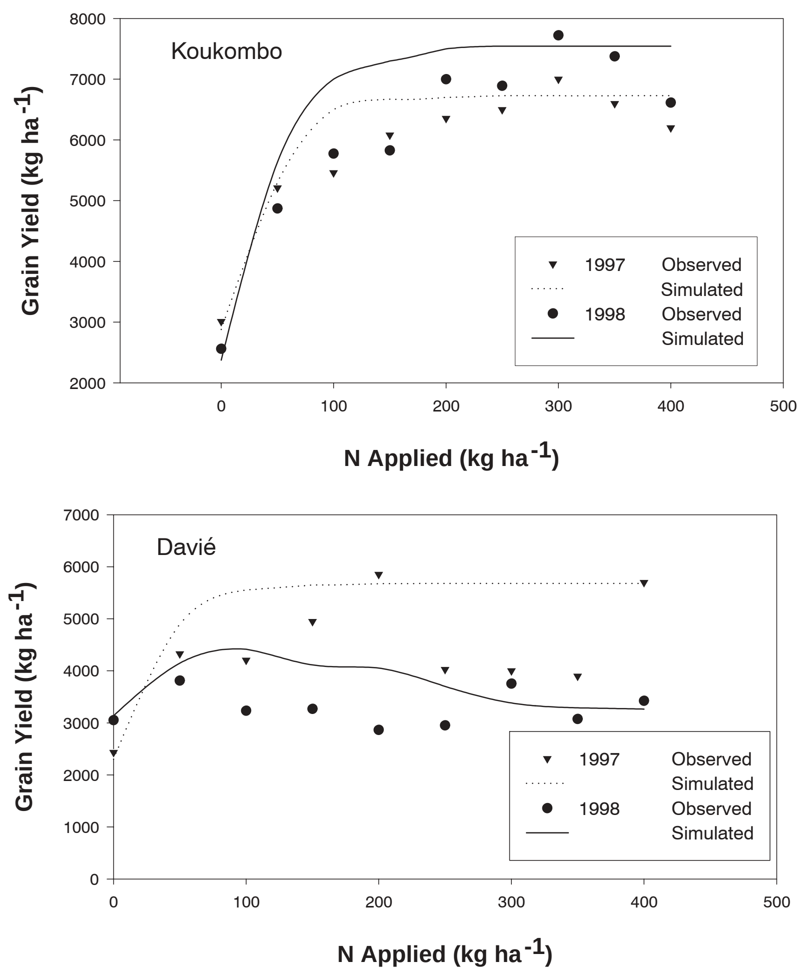


Figure 3. The Model's Performance at Different N Rates at Koukombo and Davié.

Table 7. Climatic Characteristics and Soil Types of Two Trial Sites in Togo

	Davié	Koukombo
Latitude (°) N	7.4	10.3
Longitude (°) E	1.2	0.42
Elevation (m)	76	110
Length of growing period (days)	240	190
Rainfall distribution	Bimodal	Monomodal
Mean growing period temperature (°C)	27.2	27.6
Mean annual precipitation (mm)	907	1,125
Mean number of dry months (less than 3 wet days/month)	3.0	5.0
Mean annual temperature (°C)	27.5	27.9
Mean minimum temperature of coolest month (°C)	22.9	19.2
Soil type	Ultisol	Alfisol
Plant extractable soil water (mm)	22	14
Available mineral N (kg/ha)	53	75

moisture condition of 40%-100% of field capacity for the top 30 cm was reached. Commonly grown genotypes, Podzarica (EV-8443) for Koukombo and Ikene (EV-8449) for Davié, were used.

Mean potential (non-limiting) production yields of up to 8 tonnes/ ha (±standard deviation of 1.2 tonnes/ ha) with maize genotype Podzarica were attained at Koukombo during April-September plantings. Comparatively, at Davié, the maize genotype Ikene attained mean yields of only up to 6 tonnes/ha (±standard deviation of 0.9 tonne/ha).

As evident from the mean-variance plot, the ideal planting timeframe for rainfed maize at Koukombo is the period, May-August (Figure 4a). During this period more than 85% of the potential yield is reached under rainfed conditions (Figure 4b). A sharp drop in yield is associated with late planting. Maize planting before May would result in increased risk associated with lower mean yields and increased variance. The planting window at Davié is wider — from March to September (Figure 5a). During this period, on an average, 70%-100% of the potential yield is reached under rainfed conditions (Figure 5b). However, planting in the first season (May-June) is associated with much lower variance. The results as expected show a well-defined planting window for monomodal environment and a less definite, broader planting window for bimodel rainfall environment.

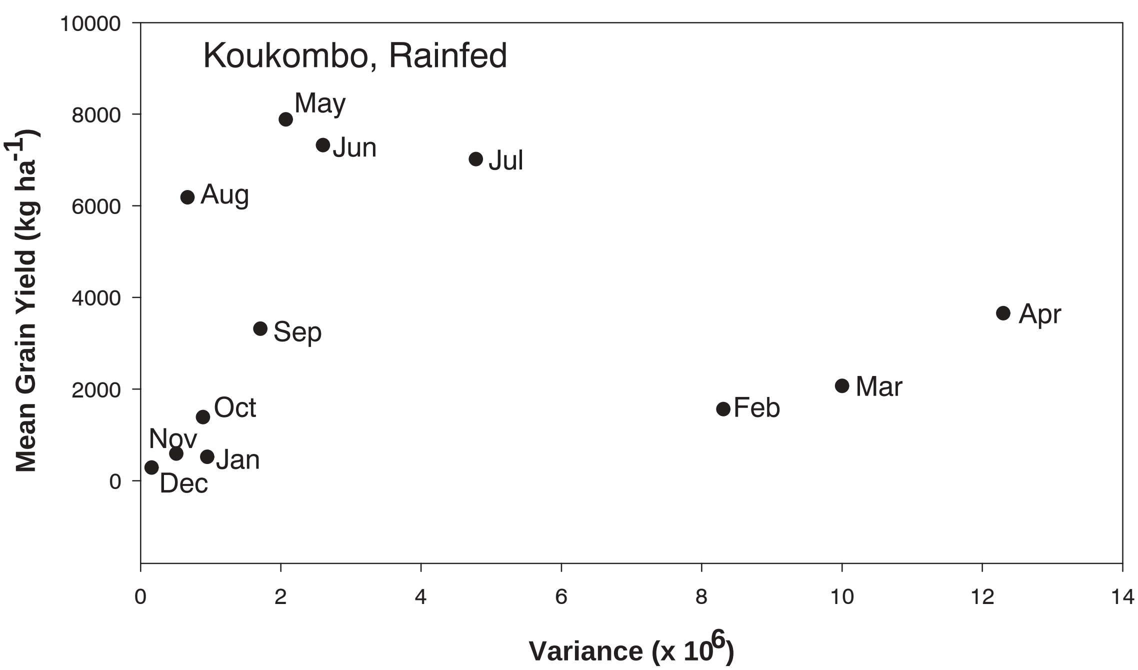


Figure 4a. Mean-Variance Plot of the Ideal Planting Timeframe for Rainfed Maize at Koukombo.

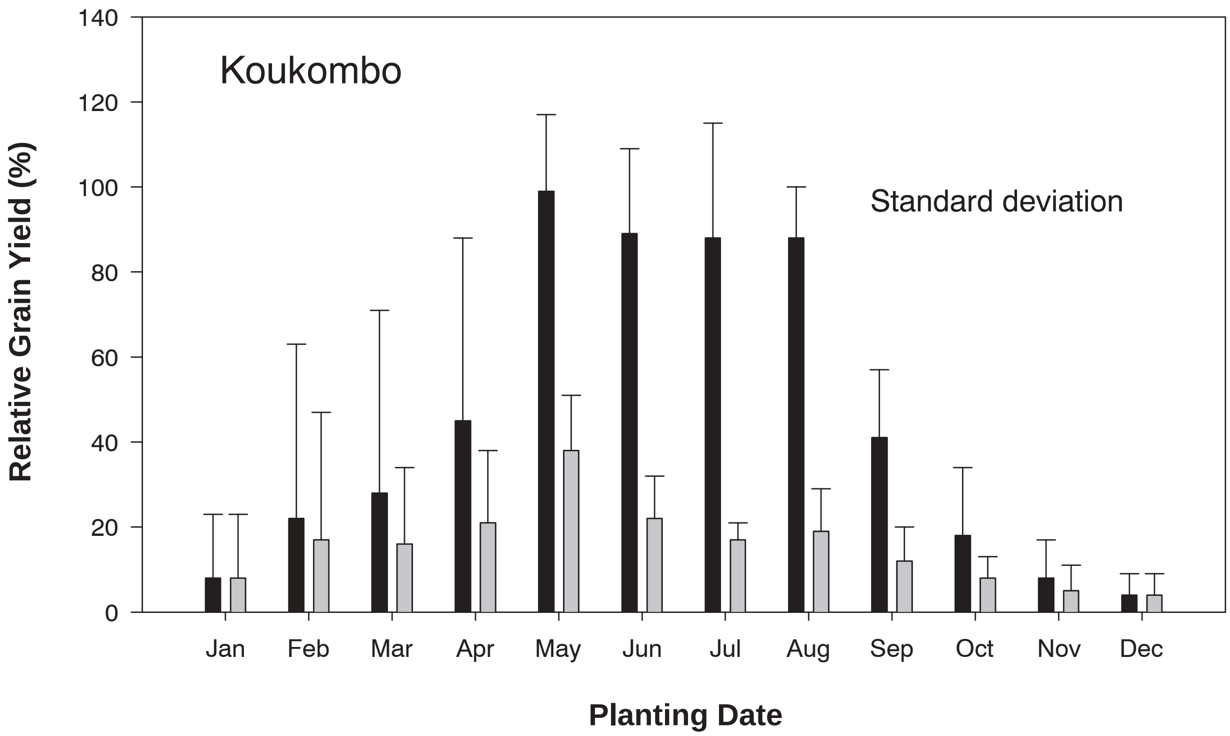


Figure 4b. Water-Limited Potential Yield and Nutrient-Limited Conditions at Koukombo.

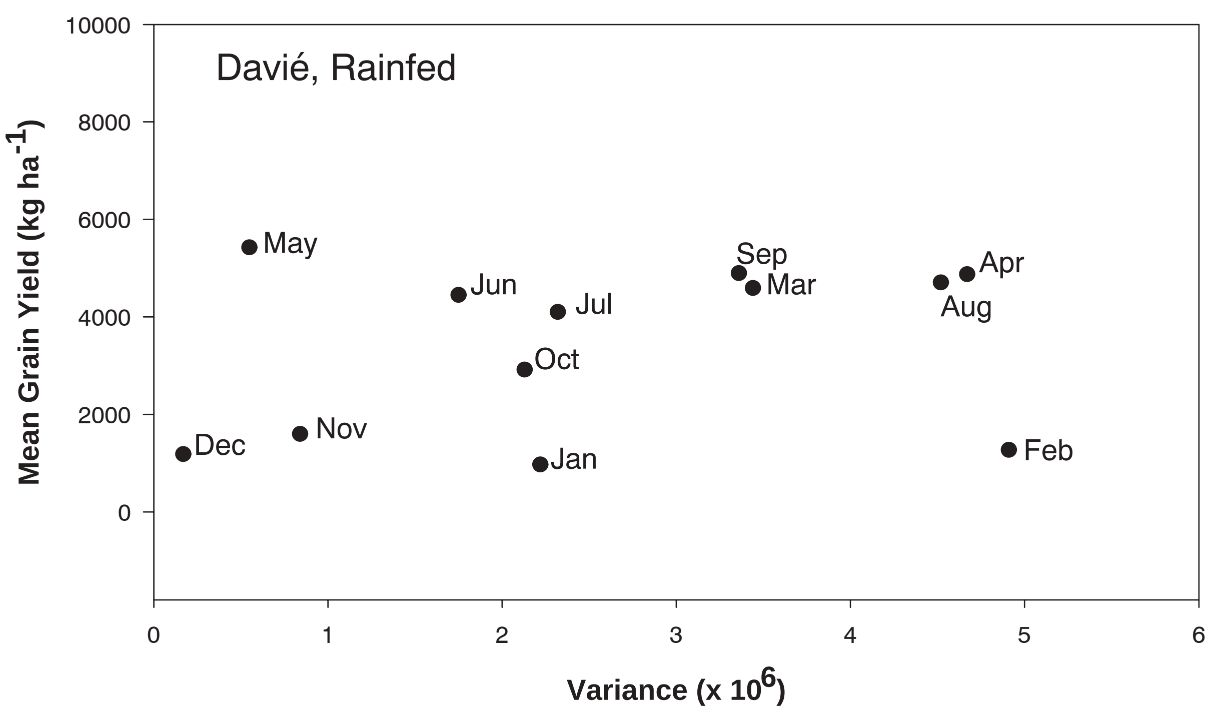


Figure 5a. Mean-Variance Plot of the Ideal Planting Timeframe for Rainfed Maize at Davié.

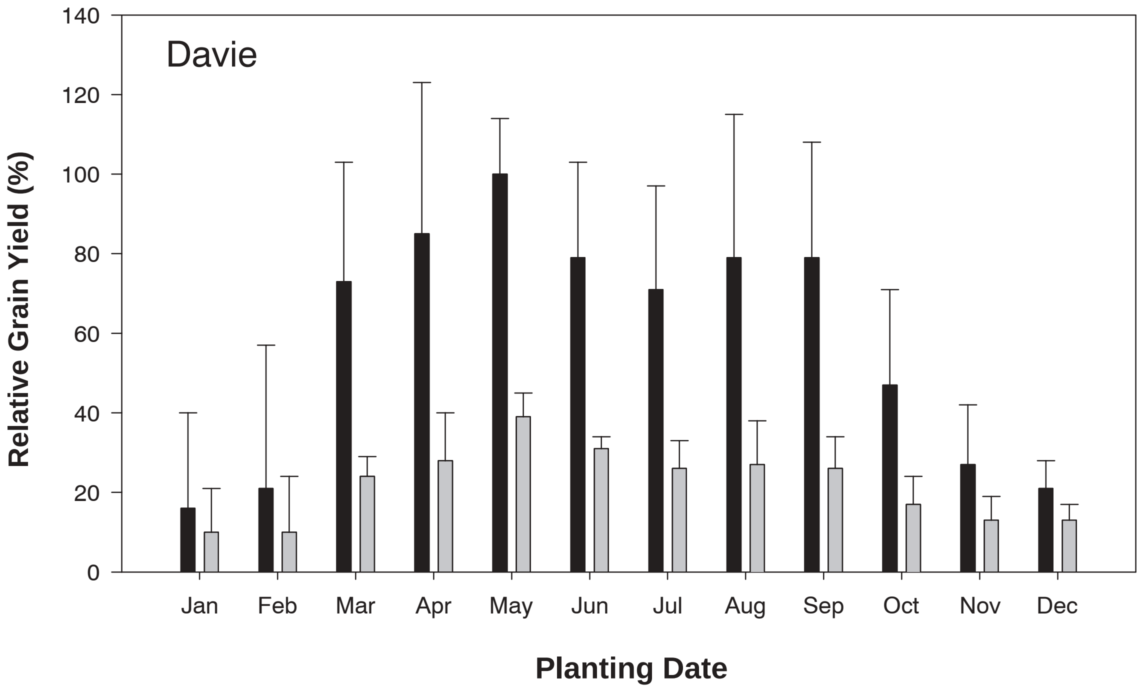


Figure 5b. Water-Limited Potential Yield and Nutrient-Limited Conditions at Davié.

4. Yield-gap under low-nutrient input production.

   In the above simulations we had assumed that nutrient availability was nonlimiting, and the maize yields at both the sites were limited by genotype and environment including rainfall. A more typical farmer condition was simulated using soils from Koukombo and Davié (Table 7) with the following N, P, and K input: 20 kg N/ha, 15 kg P_2O_5/ha, and 15 kg K_2O/ ha. We also assumed micronutrients, weeds, termites, and other pest and diseases were fully controlled so as not to influence the yield.

   Simulated mean yields under May-August plantings ranged from 1.5 to 3.2 tonnes/ha. In general these amounted to less than 30% of the potential grain yield for each of the planting dates (Figures 4b and 5b). These simulated results verify the counter-intuitive policies in SSA, focusing on water limitation with neglect of soil fertility improvement. With external nutrient input, appropriate planting date and genotype maize grain yields could be increased up to 6 times of the current farmers' yields.

5. Long-term analysis of maize-maize and maize-mucuna cropping systems.

   From the above analyses it is very clear that external nutrient input is essential for profitable and stable maize grain yields. Scientists have sought to answer the question, "Could a green-manure crop, such as mucuna, meet the N requirement for sustainable maize production?" It was determined that mucuna would be best suited for the second season in bimodal rainfall regions because the principal crop maize would be planted during the more favorable and stable first season. In monomodal rainfall regions, mucuna would compete for the resources: land, water, and nutrients with maize. In such an environment it would be difficult to protect mucuna mulch against burning, wind, and cattle grazing during the long dry season. Thus, the lowest adoption of mucuna in the northern provinces of Benin, as reported by Galiba and coworkers (1998), is not surprising given the monomodal rainfall distribution.

To compare maize-maize and maize-mucuna cropping sequences, the simulation experiment, conducted as a 20-year sequence, was replicated five times; simulated weather records for the Davié site were obtained by using a statistical weather generator (WGEN) (Richardson, 1985). The initial conditions are given in Table 7. In the maize-maize sequence, the first-season maize planting occurred during May as dictated by soil moisture status (40%-100% of field capacity). The second season planting occurred soon after the harvest of the first-season maize, given the moisture requirement for sowing was met. The cumulative nitrogen fertilizer application rates for both the seasons ranged from 0 to 200 kg N/ha. Cumulative P and K rates of 75 kg P_2O_5 and 80 kg K_2O/ha were applied. The short-duration maize genotype Ikene with a mean growth duration of 85-90 days at Davié was used.

In the maize-mucuna simulation, maize was planted during the first season in May and followed by mucuna during the second season. The amount of N supplied by mucuna ranged from 10 to 110 kg N/ha. The P and K rates for maize was 45 kg P_2O_5 and 50 kg K_2O, respectively, and for mucuna 30 kg P_2O_5 and 30 kg K_2O. A second simulation experiment on maize-mucuna was conducted using the maize genotype Podzarica with a mean growth duration of 110-115 days at Davié. In the above simulation experiments, it was assumed that all other nutrient elements were available in nonlimiting quantities over the 20-year period.

The mean cumulative yield for the two seasons in the maize-maize sequence ranged from 2.2 to 3.3 tonnes/ha without N application (Figure 6). The cumulative yield increased to 5.0-6.3 tonnes/ha at 80-kg cumulative N/ha rate and to 7.4-10.1 tonnes/ha at 240-kg cumulative N/ha. The yield over time showed a stable production trend at each of the above N rates. During the maize (Ikene)-mucuna sequence (Figure 7), a 20 kg N/ha contribution from mucuna resulted in a maize yield of 2.1-3.5 tonnes/ha. Mucuna N contributions of 80 and 120 kg N/ha resulted in grain yields of 3.8-5.3 and 4.6-5.7 tonnes/ha, respectively. With longer duration, Podzarica, the grain yield was 2.4-4.3, 4.8-6.4, and 6.1-7.2 tonnes/ha with N contributions of 20, 80, and 120 kg N/ha by mucuna, respectively. An increased mucuna application that was equivalent to 240 kg N/ha resulted in yields of 6.8-8.3 tonnes/ha.

The maize grain yields for both Ikene and Podzarica tended to increase with mucuna application dur-

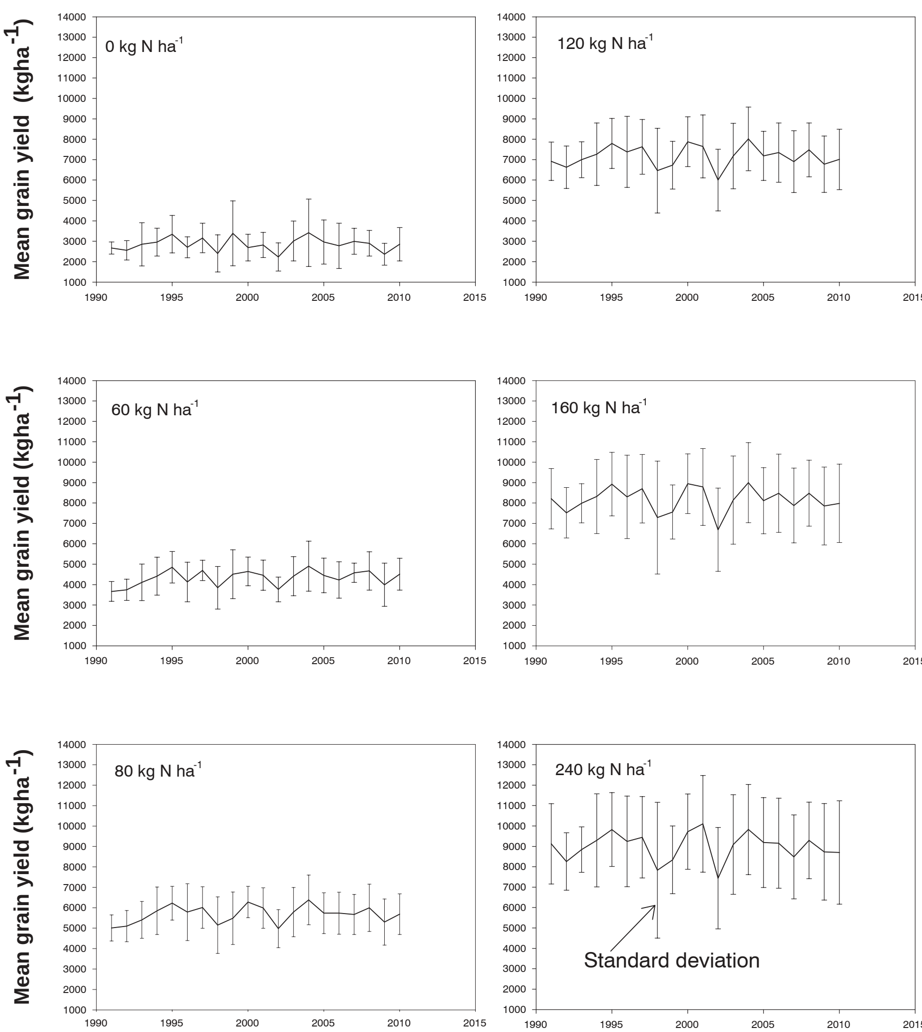


Figure 6. Yield Trend Simulation for Fertilizer N Application at Davié for 20 Years of Maize-Maize Sequence. Mean Grain Yield Represents a Combined Yield for Both Seasons.

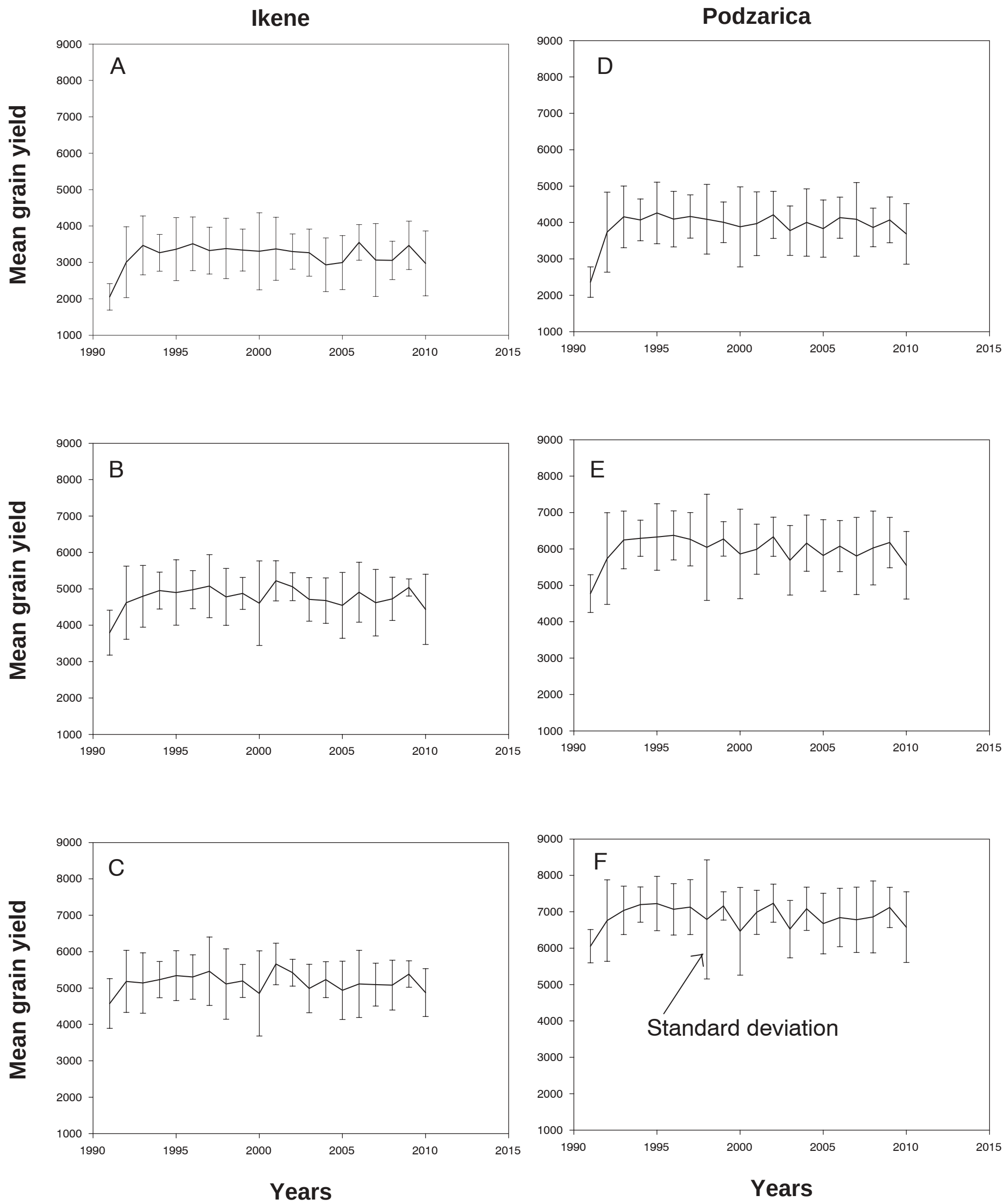


Figure 7. Simulated Yield Trend Under a Maize-Mucuna System for Maize Genotype Ikene at 20 (A), 80 (B), and 120 (C), and Podzarica at 20 (D), 80 (E), and 120 (F) kg N/ha Supplied Through Mucuna.

ing the first 5-6 years as the residual soil N content increased. Thereafter, the yield trend stabilized (Figure 7). Based on mean-Gini stochastic dominance, monetary returns are greater with maize-mucuna system if maize genotype Podzarica is used and 120 kg N/ha is supplied by mucuna. The mean-Gini analysis, however, does not consider the farmers' preference for maize genotype, disease, and insect resistance. The principal criteria for a farmer's preference for Ikene over Podzarica at Davié is its shorter duration for double-maize cropping season. Initially, farmers may also be reluctant to substitute a food crop with a cover crop and apply fertilizers, particularly P, to that cover crop. The shift from double maize cropping to a single crop would also affect prices, storage, and distribution. The availability of external nutrient during the season also becomes a critical concern.

DEVELOPMENT OF TECHNOLOGY PACKAGES FOR SUSTAINABLE LAND MANAGEMENT

Introduction

The project developed and/or improved a series of technologies for ISFM, using desk studies and agroecological research (mainly on-farm). Attention was paid to the socioeconomic, institutional, and policy context. The activities extend from the Coastal Savannah (from South Togo) to Guinea Savannah (in North Togo and Ghana) to Nigerian Sahel. In the last case both rainfed and irrigated farming was studied.

In these different agroecological zones different packages were developed using different soil amendments for different cropping systems. The main attention was given to the integrated use of organic matter and inorganic fertilizers, but in some cases also PR was part of the package. As sources of OM, leguminous cover and grain crops have been used, manure and compost, crop residues, an aquatic weed and a woody species, *Leucena leucocephala*. Crops that received attention were cereals (maize, millet, and rice), groundnut and cowpea, cassava, and vegetables.

Green Manure

The Coastal Savannah of Togo and Benin is characterized by the same agroecological conditions and by a very high population density in relation to the carrying capacity. The rainfall distribution is bimodal. The primary rainy season lasts from April to July and the minor season from September to November. The region is characterized by soils with a low inherent fertility. The traditional agricultural system is based on shifting cultivation. Due to population pressure the long fallow periods have been shortened or completely disappeared and as a consequence soils are degrading. The main soil type, locally indicated as “terre de barre,” is characterized in Table 8, showing also the effects of different degrees of degradation.

In the nineties, mucuna was introduced on a large scale in southern Benin by INRAB, the International Institute for Tropical Agriculture (IITA) (Ibadan), and the Royal Tropical Institute (Amsterdam) in the framework of the recherche appliquée en milieu réel (RAMR) project and later by Sasakawa-Global 2000 (SG-2000). As mentioned, the agroecological conditions in this region are the same as in southern Togo. The aim of the mucuna introduction was to increase the N availability for the maize and to (partially) replace mineral fertilizer-N. Versteeg and Koudokpon (1993) reported many positive results of the introduction of this cropping system, e.g., a yield increase of the subsequent maize crop. However, an important consequence of mucuna use is that no food crops during the second season can be grown, while the yield increase in the following primary season not easily compensated for the loss of the minor season. Nevertheless, a certain degree of adoption is observed, often explained by the interest of farmers to tackle effectively the weed *Imperata cylindrica*.

This green manure system for the Coastal Savannah was further developed in southern Togo. To be attractive to farmers, the benefits of such a system should be greater than those of other systems in which the second season food crops are grown. The project chose to change the use of mucuna. Instead of using it as an alternative for fertilizer, it was developed as a tool to improve the efficiency of fertilizer, thus, application of it becomes economically interesting for farmers. In that way, enough food can be produced during the main growing season. As already mentioned, the bimodal rainfall often enables cultivation of two crops. However, the rainfall during the second season is erratic and crop failure is common. Common cropping systems are maize–maize, maize–cassava, or maize– cowpea. Maize is planted in the primary season, generally in association with cassava, developing further after the harvest of maize. A second maize crop in the minor season or, for example cowpea, has less chance to succeed than the cassava. The general fertilizer recommendation for cereals is 200 kg compound fertilizer (15-15-15) and 100 kg urea per hectare. In practice no fertilizer at all is applied or the amounts are (much) lower than the recommended doses.

In the green manure system that was developed, during the second season no consumable crops are produced; rather green manure for the

Table 8. Characteristics of Soils in Southern Togo

Classification:	Southern Togo		
French:	Sol ferralitique faiblement lessivé		
USDA:	Ustox/Tropept		
FAO:	Rhodic Ferralsol/Eutric Cambisol		
	Degraded	Semi-Degraded	Non-Degraded
pH-H_2O	5.7	6.5	6.2
SOM, g/kg	4.0	6.5	10.5
Total N, g/kg	0.3	0.5	0.7
P-Olsen, mg/kg	6.3	4.1	
CEC, mmol/kg	19.4	36.0	50.3
Exch bases, mmol/kg			
Ca	11.4	23.4	30.4
Mg	5.6	9.9	11.1
K	0.9	1.9	2.1
Na	0.5	0.7	0.8
Base Saturation, %	93	99	95

improvement of the OM resource base of production systems is provided. Mucuna was used as green manure. This legume contributes in several ways to ISFM, through fixing of atmospheric N, improving the accessibility of P, some OM build up, and interruptions of the development of populations of pest organisms (nematodes, striga). Its growth and development is boosted using the Togolese PR (36% P_2O_5) leading to an increasing efficiency of fertilizer use by the crop in the main season. Maize was used as such crop during the development of the system. Therefore, the system is called the "maize – mucuna – external inputs system." For other crops, the green manure system can be made effective.

In the experimental area, maize is planted in March/April depending on the onset of the rains. It is recommended that 40-45 days later the mucuna is interplanted. Earlier planting will result in lower maize yields (Galiba et al., 1998b). After the harvest of the maize in July, the mucuna will continue growing and die in December. The soil will then be covered by a thick mulch of vegetative material. Research has shown no significant difference between the effect of incorporating this material or leaving as mulch on subsequent maize yields (Carsky et al., 1998). At the end of the dry season, fields are traditionally cleared by fire and precautions should be taken that fire does not engulf fields with mulch. Farmers clear planting lines for sowing maize at the start of the next growing season. It is necessary to remove mucuna regrowth soon after planting the maize to avoid interference.

Mucuna can fix atmospheric N. The amounts fixed are highly variable and depend strongly on factors including P availability. The N is released when the mulch is decomposed. The moment of release, however, cannot be managed and does not necessarily coincide with the plant's need for N.

Recently in southern Togo it was observed in a trial with Togolese PR that a maize-mucuna system resulted in significantly higher yields than a maize monocropping system (Tossah, 2000). If this finding can be confirmed at other sites, use of PR becomes much more attractive as replacement of mineral fertilizer-P.

Mucuna is known for physical suppression of weeds such as speargrass (*Imperata cylindrica*). In southern Benin this was a main reason for farmers to plant mucuna (Manyong et al., 1996). Through root exudation and/or residue decomposition, chemical substances may be released that have also a growth-reducing effect, not only of weed species but also of agricultural crops. However, Carsky et al. (1998) note that these allelopathic effects are probably limited under field conditions where the toxins are decomposed, diluted, and leached. The same authors report that the effects of mucuna on nematode suppression are erratic.

Actually mucuna seeds are rarely eaten or used as animal feed due to its toxic content (L-DOPA). Consequently, the main part of the biomass remains on the field. The main toxin can be used in the treatment of Parkinson's disease. In the future, this may become an important commercial use of mucuna seeds (Carsky et al., 1998).

IFDC-Africa's "maize-mucuna-external inputs system" (Table 9) combines the use of PR and mineral fertilizers. The fertilizer rates are based on a target yield of 3 – 3.5 tonnes maize/ha while the actual yield level is about 1 tonne/ha.

In some respects the crop management is different from the traditional system. The proposed maize variety is known to have a yield potential of about 5 tonnes/ha and to respond

Table 9. Maize – Mucuna Package Promoted by IFDC-Africa in Southern Togo and Benin (Van Reuler, 1999)

Maize and Inputs:

- Before planting 300 kg/ha PR is applied.
- Maize variety Ikenne is recommended (90 days).
- At the start of the main rainy season, maize is planted (80 cm x 25 cm) with two grains per hole. After 2 weeks the maize is thinned to 1 plant per hole.
- In the first year the following mineral fertilizer application is proposed per hectare 100 kg N, 45 kg P, and 50 kg K. In view of the residual effect of mineral fertilizer-P and release of PR-P, in the following years no P has to be applied. After 3 years the PR application has to be repeated.
- N and K application is split into two equal parts—first application at thinning and second about 45 days after planting (flowering). P is applied at thinning.
- Two rounds of weeding are recommended—the first round at thinning and second round about 45 days after planting.
- After harvest, crop residues are left on the field.

Mucuna Management (Carsky et al., 1998):

- Sow mucuna 45 days after sowing maize at a density of 0.8 m by 0.8 m (1 seed per hole). This should be done at second weeding so that the mucuna is planted in rows between the maize in a clean seedbed.
- To avoid burning of the mucuna biomass, a firebreak should be made around the plot at the end of the rainy season.
- Harvest the mucuna pods after drying and before shattering.

well to nutrient application. Plant density and thinning to one plant per hole and weeding is required for obtaining high yields. In southern Togo, maize stalks are used as fuel, and efforts should be made in convincing farmers to recycle these residues for maintaining the soil fertility level.

The system was tested on-farm during 3 successive years, but only the results of 1998 and 1999 are already accessible for publication. Besides, the system was demonstrated in the context of the IFAD-funded rural development project PODV.

Results 1998

The long-term average of the amount of rainfall in the main season amounts to about 700 mm. In 1998 only 295 mm was recorded. It is clear that this drought severely affected yields. An experiment was executed on a field where in two preceding seasons mucuna was grown and on an adjoining field without mucuna in the preceding seasons. No response to the different fertilizer treatments was found and in Table 10 a summary of the yield data is presented.

On the mucuna plots, grain yields were 0.4 tonne/ha higher than the plots without mucuna. The difference in straw yields was over 1.5 tonnes/ha. The lack of response to fertilizer application is probably due to the drought because normally in this region responses are found. The harvest index (HI) defined as the grain yield (GY) as a fraction of the total aboveground biomass, generally for an improved variety is about 0.5. At the plots with mucuna the HI is significantly lower than on the plots without mucuna. It is possible that in the former the vegetative growth was better and led to more water use, and, therefore, at the critical growth stage drought hindered grain formation.

Table 10. Effect of Mucuna in the Preceding Season and Mineral Fertilizer-P (TSP) on Maize Yields (kg/ha) and Harvest Index (HI) Fertilizer-N and -K Were Applied in Sufficient Amounts

	Yield					
	–Without Mucuna			+With Mucuna		
P	Grain	Straw	HI	Grain	Straw	HI
(kg/ha)	- - - - (kg/ha) - - - -			- - - - (kg/ha)- - - -		
0	1,943	2,235	0.47	2,593	3,973	0.39
15	1,866	2,081	0.47	2,244	3,519	0.39
30	1,981	1,972	0.50	2,351	3,647	0.39
45	1,909	2,264	0.46	2,164	3,609	0.37
Average	1,925	2,138	0.47	2,338	3,687	0.39

Table 11. Effect of Mucuna in Preceding Season on Maize Grain Yields (GY) (kg/ha) and on Agronomic Efficiency (AE) of Urea-N (kg/kg) in Relation to the Degree of Soil Degradation in Southern Togo (1999)

	Degree of Degradation							
	Severe (Djakakopé)				Nondegraded (Seve-Kpota)			
	–Without Mucuna		+With Mucuna		–Without Mucuna		+With Mucuna	
	GY	AE	GY	AE	GY	AE	GY	AE
Control	352		568		3,325		3,250	
0 N	509		539		3,442		3,133	
50 N	1,342	17	1,700	23	3,617	4	3,867	15
100 N	1,767	13	1,925	14	4,250	8	4,217	11

Results 1999

In 1999 in southern Togo, three instead of two degrees of soil degradation were distinguished—severely, medium, and nondegraded. The same factorial experiment as in 1998 was executed at sites located in the three zones. The results of the experiments in the severely and nondegraded zones are presented in Table 11.

The degree of degradation is strongly related to the inherent fertility of the soils as indicated by the yield of the control treatment (Table 11). At both sites, a significant response to N application was found, and at both sites the agronomic efficiency was higher on the site with mucuna than on sites without mucuna.

Mucuna fixes N and while the amount of fixation under on-farm conditions is not known, it is estimated to be low (Sanginga, 1996). Probably on the sites with mucuna more N is available than sites without mucuna. The difference in yield at the 0 N level may be attributed to the N supply by mucuna. Consequently, the differences in agronomic efficiency at higher N rates are due to other factors. It is not possible to indicate which factor is most important but probably a number of factors are responsible. At the +mucuna sites the soil at planting is covered by mulch, often causing an improved crop establishment. Also the evaporation is reduced and weed growth is suppressed. The mucuna mulch may improve the SOM status and in this way increase the water-holding capacity and CEC; the effect will, however, be limited in view of the high mineralization rate of mucuna straw. Another factor might be the soil biological activity that positively affects the porosity and structure and in this way the rooting volume of the subsequent maize crop. Probably the rooting volume on the +mucuna plots is more extensive than on the –mucuna plots. In this way more nutrients and water are available and leaching of fertilizer-N is reduced. Finally the suppression of pests like striga and nematodes will play a role.

It is at this stage impossible to quantify the effect of each factor or the influence of other variables on these factors (i.e., the importance of different factors may depend on the conditions during the growing season). For example, during dry spells at flowering of the maize some extra soil moisture will be important, while in season with excessive rainfall the extra rooting volume will be more important.

"Projet d'Organisation et de Développement Villageois"

One of the specific objectives of the project was increasing the agricultural productivity among resource-poor farmers through better use of plant nutrients—organic and inorganic. Preferably, this activity was to be carried out in collaboration with IFAD-funded investment projects. Therefore, in southern Togo, contacts were established with the PODV. This project is financed by a loan of IFAD to the Togolese Government. The main objectives are protection of natural resources, increased and diversified agricultural revenues, and reduced constraints related to land tenure. The target group of the project is farmers in relatively densely populated areas with farms of 1 – 2 ha on degraded soils resulting in low yields. Another criterion is that the farmers are to some degree organized. Special attention is paid to women without secure access to land.

This project requested IFDC-Africa to install some demonstration plots in southern Togo. The aim of these plots is to show how soil fertility can be improved. This activity was and still is carried out in close cooperation with ITRA. The inherent fertility of soils in southern Togo is low, and inputs are essential for increasing yields. The availability of organic fertilizers is mainly limited to low-quality straw since cattle raising is not possible due to sleeping sickness. Mineral fertilizers are relatively expensive and have a low efficiency. In consultation with project staff and farmers, it was decided to use at the demonstration plots a package of maize – mucuna – mineral fertilizer + PR. The amounts applied were:

- 300 kg PR/ha (47 kg P/ha) applied 2 weeks before planting.
- 200 kg urea/ha (92 kg N/ha)–split application of two equal parts.
- 200 kg TSP/ha (40 kg P/ha).
- 100 kg muriate of potash/ha (50 kg K/ha).

As above, the rates are based on the amount of nutrients exported with a maize grain yield of 3.0 - 3.5 tonnes/ha; this compensates for the sacrificing of the second rainy season for the production of mucuna.

Togolese PR was applied for improving the P status of the soils. It is anticipated that in subsequent seasons the P application can be substantially reduced. Currently, only urea and a compound fertilizer (15-15-15) are available in Togo. However, in the framework of the PODV project and anticipating a liberalization of the fertilizer market as happened in neighboring Ghana and in Côte d'Ivoire, it was decided to use straight fertilizers because the plant needs for nutrients can be much better met. It is difficult to replace the amounts of exported nutrients through compound fertilizers.

Yields in 1998 were severely depressed by drought (Table 12). A yield of more than 1.5 tonnes/ha was obtained at only one out of twenty plots, and farmers often obtained no yield at all. PODV requested to increase the number of plots to 60 in 1999. Yields in 1999 were substantially higher than in 1998, and at 17 plots the target yield was obtained. The average yield over all plots was, however, 2,550 kg/ha. The average yield of the 20 plots in their second year of treatment was with 2,610 kg/ha, which is slightly higher than that of the 40 plots in their first year (2,510 kg/ha). It was also among those 20 "old" plots that the highest yield (4,000 kg/ha) was obtained. Maximum and minimum yields for the 40 "new" plots were 3,870 and 810 kg/ha, respectively. Yields in the year 2000 were not ready at the time of preparation of this report.

The technical merits of systems involving mucuna are highlighted in

Table 12. Frequency Distribution of Maize Yields on the Demonstration Plots in 1998 and 1999

Maize Yield (tonne/ha)	1998	1999 (Same Plots as in 1998)	1999 (New Plots)
<1	9	0	2
1.0 - 1.5	10	2	1
1.5 - 2.0	1	0	7
2.0 - 2.5	0	7	9
2.5 - 3.0	0	5	10
3.0 - 3.5	0	6	8
>3.5	0	0	3
Total No. of Plots	20	20	40

many studies (among others Buckles, et al., 1998). However, these merits do not imply that farmers will actually adopt such a maize-mucuna technological package. In reality, the number of farmers that continue using mucuna after a project activity has stopped is rather low. Therefore, we decided to study the reasons for the low adoption rate and the adoption potential for a system involving the cover crop mucuna.

In 1999, at the request of IFDC-Africa, a socioeconomic study was executed by a group of participants of an International Centre for Development Oriented Research in Agriculture (ICRA)-training program. The aim was to study the intensification of food crop cultivation in southern Togo with emphasis on the adoption potential of a maize – mucuna – external inputs system. The ICRA study distinguished three levels of adoption potential (Table 13). The group with the highest adoption potential is households that are relatively well educated and have much contact with extensionists, etc. In other words, households that are relatively prosperous. The age of the chief of the households with a medium adoption potential is relatively low, and he is well educated. It is expected that the potential of this group at a later stage will increase. The group with the lowest potential is not very well educated, has little contact with extension services, and will probably at a later stage not be interested in adopting the system.

Because the main target group of the PODV project is women who do not own land, a high adoption rate among the target group cannot be expected. Each year the women have to rent an area and the length of the contract is to be negotiated. However, it is often not certain whether the owner will respect the contract, especially when yields are not as high as anticipated. Consequently, the interest of the target group in soil fertility improvement, a long-term process, is not great.

Table 13. Households in Southern Togo Classified According to Their Adoption Potential of a Maize – Mucuna – External Input System

Adoption Potential	Age Household Chief (Years)	Surface Cultivated (ha)	Education (%)	Contact With Extensionists (%)	Degree of Organization
High	42 - 52	2.3	56	100	Organized
Medium	24 - 42	1.5	67	33	Not yet
Low	44 - 54	1.7	17	17	Not interested

Table 14. Potential Constraints to Adoption of a Maize – Mucuna – External Input System and Their Relative Importance in Relation to Land Tenure

Constraint	Land Owners	Land Tenants
Availability of money or credit	4	6
Land tenure		5
Mucuna seeds	4	4
Maize marketing	3	
Storage facilities	1	3
Improved maize seed		2
Loss of second season		1

A ranking indicates degree of importance, 1 – lowest, 6 – highest.

In making an inventory of the constraints for adopting a maize–mucuna–external input system, a distinction between landowners and tenants was made (Table 14). For both groups, the availability of money or credit appeared to be the main constraint for adoption. Logically, for people without land, the tenure system was an important constraint. The constraint of availability of mucuna seeds may be alleviated when the system is adopted at a large scale, as the seeds are not eaten. Constraints with a lower relative importance were availability of improved maize seeds, storage facilities, and loss of the second season. The reported constraints make it very clear that introducing such a system requires an integrated approach as indicated by the relative importance of a credit system and maize storage facilities. Therefore, intensive cooperation between all actors (NGOs, National Agricultural Research and Extension Systems [NARES], farmers, etc.) seems a prerequisite for a successful introduction.

The main conclusion of the study was that interest in the region does exist among a group of households in adopting the maize – mucuna – external input system. However, it was also observed that the target group of the PODV project has a low adoption potential and that the main constraints cannot easily be alleviated. This result necessitates that the approach followed within the project needs to be adapted to these conditions.

Another important result of this study was that the actors involved in development-oriented activities in southern Togo were brought together. Contacts between these actors and also coordination of activities are often not optimal. The final report was discussed with these partners and at this meeting it was decided to meet regularly.

Cereal-Legume Rotation

Crop rotations are crucial elements of ISFM. They do not simply replace mixed cropping, which becomes less and less effective during progressive improvement of soil fertility and nutrient availability. A crucial role is the interruption of growing cycles of a certain crop, avoiding the build up of crop specific pests and diseases. The use of legumes to interrupt cereal cropping has its advantages and disadvantages. As far as the latter is concerned, the most important is the high mineralization rate of leguminous biomass; legumes will not contribute significantly to the build up of OM (Boonman, 1999). An important advantage is biological nitrogen fixation.

The former paragraph treated one of the forms of a leguminous crop rotation, using the cover crop mucuna. The fact that a species was chosen from the region and not consumed by man or his livestock has the advantage that all biomass production can be used for improvement of the soil and for the production of the following cereal crop. It has the disadvantage that a cropping season is lost for direct production goals. Breman and van Reuler (in press) estimate that in case of intensive production, mucuna (and other legumes that are not consumed at all) will increase the yield of the next cereal crop by about 50%. When a legume is used from which at least the seeds are consumed, the increase will not easily be more than an average 25%. As a consequence, the value of leguminous production must be considerably higher than 50% and 25%, respectively, of the value of the cereal crop produced as monoculture (Breman and van Reuler, in press). In case of mucuna in the previous paragraph, the benefit that was viewed concerned improved nutrient use efficiency by the cereal crop and decreased N requirements. Here the rotation with a consumable legume is being studied; the beans are harvested, the crop residue is recirculated.

In the period 1996-99, in cooperation with the University of Hohenheim (Germany) at two IFDC-managed stations in Togo, Kaboli and Koukombo, an extensive soil fertility field trial was executed. The aim of the experiments was to study the effect of PR on crop yields and mineral fertilizer application, crop residue management, and crop rotation. The same experiment was also executed in Niger (2 locations) and in Burkina Faso. In the latter countries the trials were managed by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Niamey, Niger. The interpretation of data is in progress, and in this chapter some results of the effect of rotation on maize yields in Togo will be presented.

Figure 8 shows how the effect of crop rotation (maize - legume) compared to continuous cultivation of maize or a legume was studied.

In 1996 at Kaboli (Southern Guinean savannah) a legume cowpea, and at Koukombo (Northern Guinean savannah) groundnut was grown. In subsequent years at both sites legumes/groundnut was cultivated. The results presented in Table 15 are the average yield effects of two application rates of crop residues,

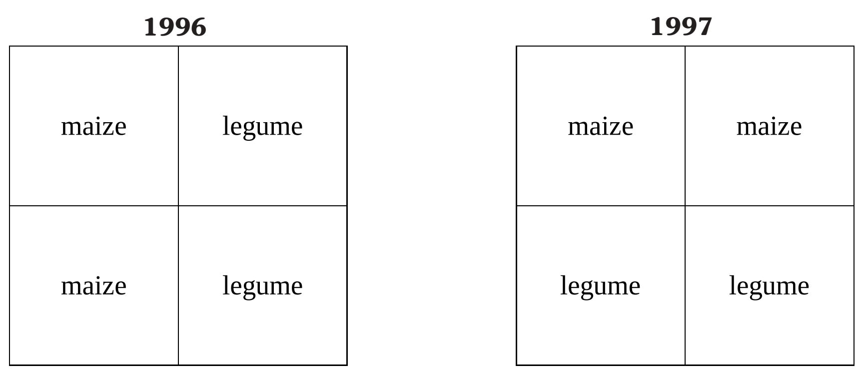


Figure 8. Experimental Layout in Two Subsequent Years (1996 and 1997).

Table 15. Effect of Rotation on Maize Grain Yields Compared With Maize Grown Continuously at Kaboli and Koukombo

		Year		
		1997	1998	1999
		- - - - - - - - - - (kg/ha)- - - - - - - -		
Kaboli	Continuously	1,765	2,466	1,924
	Rotation	2,070	3,088	3,220
	Rel. increase, %	**17**	**25**	**67**
Koukombo	Continuously	2,282	3,004	2,813
	Rotation	2,635	3,374	3,440
	Rel. increase, %	**15**	**12**	**22**

four doses of N, and two sources of P.

In all 3 years maize yields grown in rotation with a legume were higher than yields of maize grown continuously, and in five out of six cases the effect was equal to or less than the average maximum of 25% suggested by Breman and van Reuler (in press). The effect is stronger at Kaboli than at Koukombo and seems to increase at both sites with time. The yield level obtained at Kaboli is higher than at Koukombo. The difference between Kaboli and Koukombo may be explained by ironstone that limits the root development at Kaboli. Consequently, also the water-holding capacity is limited. Any improvement of the SOM status on this site will have a relatively strong effect on crop yields. Bagayoko (1999) stressed the site specificity of certain factors involved in legume-cereal rotation.

As indicated before, biological N-fixation is among the reasons why a rotation has a positive effect on subsequent maize yield. Its importance is studied below through the analysis of the effect of rotation at increasing N-fertilization of the maize crop. In case the increase in N availability, thanks to the legume is the main reason for the yield increase of maize then the effect will be less at higher fertilizer-N rates.

Two cases are studied separately—first the case where single superphosphate (SSP) was used as P-source (13 kg/ha/year of P), then the case where Tahoua PR was applied.

In Table 16, the effect of rotation on maize grain yields and on the agronomic efficiency of urea-N is presented, using SSP as the P source.

At both sites there is a response to N application up to a dose of 150 kg/ha of N. At both sites yields of corresponding treatments show that in all cases except one rotation positively affects yields. The effect at Kaboli seems to be stronger than at Koukombo: rotation increases the control yield (0 N) with 95%, against an average increase of 41% for the N treatments. For Koukombo, these figures are 50% and 14%, respectively. If the rotation effect is mainly an effect of the N fixed by the legume it would disappear at higher N application rates.

Table 16 shows indeed, as indicated, a difference between the effect of rotation on the control and on the N-treatments, but among the N-treatments the difference in the effect of rotation is insignificant. In other words, effects other than the N made available through the leguminous residues are dominant. Provided the difference in relative rotation effect on control and N-treatments can be explained by the N from legumes, the contribution of N from the legume to the maize crop is estimated to be about 7 and 9 kg/ha for Kaboli and Koukombo, respectively. In view of the agronomic efficiency of fertilizer-N at doses of 60 and 90 kg/ha and expecting an average yield increase of 68 kg of grain per kilogram of absorbed fertilizer-N in case of crop residue recirculation, the fertilizer-N has had a recovery of 30% and 33%, respectively for Kaboli and Koukombo. Expecting the same recovery for N from legumes, the crop residues delivered 23 and 27 kg/ha of N after being incorporated in the soil.

Studying the details of Table 16, the difference in the level of the relative effect on crop rotation between Kaboli and Koukombo becomes obvious. Whereas at Kaboli the agronomic efficiency of fertilizer-N seems to be improved in all 3 years, at Koukombo no significant and regu-

Table 16. Effect of Rotation on Maize Grain Yield (GY) (kg/ha) and Agronomic Efficiency of Urea-N (AEN) (kg/kg) Compared to Continuously Grown Maize at Two Sites in Togo. All Treatments Received 13 kg P/ha Applied as SSP

	1997 Cont.		1997 Rot.		1998 Cont.		1998 Rot.		1999 Cont.		1999 Rot.	
N	GY	AEN	GY	AEN	GY	AEN	GY	AEN	GY	AEN	GY	AEN
Kaboli												
0	618		1,023		701		996		604		1,673	
60	1,477	14	1,832	13	2,213	25	2,682	28	1,395	13	2,202	9
90	1,673	12	2,460	16	3,013	26	4,037	34	1,569	11	3,815	24
150	2,414	12	2,717	11	3,608	19	4,304	22	2,864	15	3,941	15
Koukombo												
0	991		881		1,593		2,319		931		2,214	
60	2,502	25	2,537	28	3,112	25	3,543	20	2,783	31	3,419	20
90	2,797	20	3,603	30	4,039	27	4,042	19	3,506	29	3,962	19
150	3,167	15	4,360	23	5,243	24	5,020	18	3,877	20	4,336	14

lar differences are observed. In Kaboli, there is no significant improvement of the rotation effect on the AEN over time in the 3-year period. As far as the absolute yield increases are concerned, they are at Kaboli systematically higher in the case of N-treatments than in the case of the control. At Koukombo again there were no significant and regular differences.

In other studies it was often reported that legumes have a positive effect on the availability of P from PR. Most findings are based on pot trials but Tossah (2000) reports a positive effect in a field trial. Table 17 is comparable to Table 16 with the exception that a single dose of Tahoua PR is applied at the start of the experiment (39 kg/ha of P) instead of the annual dose of 13 kg/ha P from SSP.

Tables 16 and 17 show that at Koukombo yields with PR-P are always lower than yields with SSP-P. At Kaboli this difference has disappeared in 1998 for the rotation treatments and in 1999 for the continuous and rotation treatments. Apparently conditions at the Kaboli site are more favorable for solubilizing P from Tahoua PR than at Koukombo. At Kaboli in all 3 years and at Koukombo from 1998 onward the yields of the maize grown in rotation are higher than those of the maize grown continuously. The data suggest that rotation has a positive effect on making PR-P available for uptake by maize, a finding comparable to the one reported by Tossah (2000) based on a field trial in southern Togo. As far as the other effects of rotation are concerned, no real differences exist between Table 16 and Table 17 as soon as enough P is available.

Manure and Compost

The use of animal manure and/or compost was studied in three different agroecological zones, in the Northern Guinea Savannah (northern Togo), in an irrigation zone in the Sahel, and in the Southern Sahel on a rainfed crop. Three different crops–maize, rice, and millet, respectively have been used.

Northern Guinea Savannah

In northern Togo ("région des savannes"), the climate is characterized by a dry and a rainy season. The rainy season lasts from June to October, and August is generally the wettest month. The months—November until May—are dry. The average amount of annual rainfall varies between 1,000 and 1,350 mm.

The natural vegetation has almost disappeared everywhere due to population pressure. The population density has increased from 35 persons/km^2 in 1981 to over 50 persons/km^2 in 1995. Subsistence agriculture is the dominant practice, and the main crops are maize, sorghum, millet, voandzou, and yam. Cash crops are cotton and groundnut. The traditional system based on shifting cultivation was replaced by a more or less permanent land use. Animal husbandry comprises poultry, pigs, and cattle.

In this zone the influence of soil improvement, due to compost and manure, on the efficiency of mineral fertilizers was studied by comparing fertilizer use on both the "so-called" compound and bush fields. The compound fields ("champs de case") are located near the homesteads and on these plots household wastes, manure, crop residues, etc., are regularly applied. Recently, compost preparation was introduced in the region. Organic materials are collected and composted in pits (2 x 1.5

Table 17. Effect of Rotation on Maize Grain Yield (GY) (kg/ha) and Agronomic Efficiency of Urea-N (AEN) (kg/kg) Compared to Continuously Grown Maize at Two Sites in Togo. All Treatments Received 39 kg P/ha Applied as PR (Tahoua, Niger)

	1997 Cont.		1997 Rot.		1998 Cont.		1998 Rot.		1999 Cont.		1999 Rot.	
N	GY	AEN	GY	AEN	GY	AEN	GY	AEN	GY	AEN	GY	AEN
Kaboli												
0	469		488		425		1,039		630		1,231	
60	1,327	14	1,812	22	1,823	23	2,630	27	1,269	11	2,255	17
90	1,617	13	2,167	19	2,469	23	3,075	23	1,512	10	3,768	28
150	2,027	10	2,071	11	2,880	16	4,426	23	2,603	13	4,047	19
Koukombo												
0	950		812		1,208		1,739		843		2,178	
60	1,465	9	1,533	12	1,697	8	2,810	18	2,371	25	3,162	16
90	1,742	9	1,880	12	2,148	10	3,075	15	3,001	24	3,068	10
150	1,998	7	2,483	11	2,658	10	3,505	12	3,210	16	3,866	11

m wide and about 1 m deep). The compost is applied at the start of the next growing season, mainly on compound fields. Through these applications, the SOM content is maintained or even increases and also other soil properties are influenced. The bush fields ("champs de brousse") are located further away from the homesteads and no organic materials have been applied to these plots. On the contrary, one may expect a certain impoverishment of time through the export of crops; through grazing; and through the collection of wood, wild fruits, etc. Most land use all over West Africa is such that OM and plant nutrients that it contains are transported by animals and man in the direction of homesteads and villages.

Special cases are the fields located near the homesteads of the Fulani who are the traditional cattlemen. During the day the herd is in search of food in the region. At night the cows are kept in an enclosed plot near the houses. Manure accumulates in these plots resulting in improved soil fertility. The Peuhl also collect manure that is composted and at the start of the next growing season sold to interested farmers.

Some typical soil characteristics of the bush and compound fields are presented in Table 18, showing the strong differences in C and N content.

The efficiency of mineral fertilizers on bush and compound fields was studied in 1998 in Dapaong, and in 1999 in Dapaong and Mango (about 100 km south of Dapaong). The experimental design was 3^2 factorial with three repetitions. The factors investigated were N (0, 50, and 100 kg N/ha as urea) and P (0, 15, and 30 kg P/ha as TSP). The different treatments are presented in Table 6. All plots received 100 kg K/ha as K_2SO_4 to avoid that either K or S would limit the yields.

The only significant response observed in 1998 was to application of N (Table 19). The yield data are the overall average of all treatments without N, with 50 kg N, and with 100 kg N/ha, respectively. The total N uptake is the uptake of all aboveground plant parts. All grain samples and a limited number of straw samples have been analyzed. The total N uptake of the plots of which only the grain sample was analyzed was calculated through linear regression.

The difference in inherent soil fertility between the bush and compound fields is expressed by the difference in yield level of the corresponding treatments and the total N uptake of the 0 N treatment. Also, the agronomic efficiency of applied fertilizer-N differs substantially, 7 versus 20 at 50 N. This means that, at the compound fields, approximately three times as much grain per kilogram applied N was produced as on the bush fields. The difference between the efficiency of utilization of absorbed N at both sites is not large; about the same amounts of grain are produced per kilogram absorbed N. However, there is a substantial difference in recovery fraction of fertilizer-N on the two sites, 0.14 versus 0.32 at 50 N. This indicates that on the bush fields a much higher amount of applied N is lost than on the compound fields. A number of reasons might be responsible for this difference. For example, the higher SOM content of the compound fields result in a better soil structure that enables a deeper penetrating root system. The higher SOM content also stimulates the soil biological activity,

Table 18. Soil Characteristics (0-20 cm) of Experimental Sites in 1998 in Dapaong, Northern Togo (Southern Guinea Savannah)

	Bush Field	Compound Field
pH - H_2O	6.0	6.3
pH - KCl	5.2	5.6
Organic C (g/kg)	3.0	5.3
Total N (mg/kg)	199	325
C/N	15	16

Table 19. Effect of Soil Fertility Improvement on Maize Grain Yield (kg/ha), Agronomic Efficiency (AE) (kg/kg), Total N Uptake (kg/ha), Efficiency of N Utilization (EU) (kg/kg) and Recovery Fraction (RF) of Applied Urea-N in Northern Togo (Dapaong) in 1998

	Bush Field					Compound Field				
N	Grain Yield	AE	Total N Uptake	EU	RF	Grain Yield	AE	Total N Uptake	EU	RF
0	1,289		20.0	64		1,491		26.5	56	
50	1,656	7	26.8	62	0.14	2,471	20	42.6	58	0.32
100	2,353	11	41.5	57	0.22	2,878	14	51.9	55	0.25

and increases the water-holding capacity and cation exchange capacity of the soils. It cannot be excluded that the SOM supplies nutrients other than the ones applied to the crop and that limit the yields. It is not possible to indicate which factor is most important but probably the difference is caused by a combined effect, and the relative importance of each factor depends on specific conditions during the growing season.

The same experiment was executed in 1999 in Dapaong at different fields and 100 km to the south in Mango. The yield data are presented in Tables 20 and 21.

As was observed in 1998, the only significant response at either site during 1999 was to application of N. In 1999 the difference in inherent soil fertility between the bush and compound fields was much more distinct than in 1998. In Dapaong, the agronomic efficiency of fertilizer-N on the compound field was substantially higher than on the bush field, while in Mango no difference in agronomic efficiency of fertilizer-N was found. The latter can probably be explained by the relatively high inherent fertility of the bush field. In other words there is a difference in inherent fertility as expressed by the yields between the bush and compound field but at both sites a great part of the applied fertilizer-N can be absorbed.

Table 20. Effect of Soil Fertility Improvement on the Response of Maize (kg/ha) to Urea-N Application (kg/ha) and Agronomic Efficiency of Fertilizer–N (AE) (kg/kg) in Dapaong, Northern Togo (1999)

	Bush Field		Compound Field	
N	Grain Yield	AE	Grain Yield	AE
0	823		2,001	
50	1,824	20	3,273	25
100	2,527	17	3,787	18

Table 21. Effect of Soil Fertility Improvement on the Response of Maize (kg/ha) to Urea-N Application (kg N/ha) and Agronomic Efficiency of Fertilizer–N (AE) (kg/kg) in Mango, Northern Togo (1999)

	Bush Field		Compound Field	
N	Grain Yield	AE	Grain Yield	AE
0	1,331		2,306	
50	2,652	26	3,651	27
100	3,350	20	4,489	22

Table 22. The Effect of Compost Application on Rice Grain Yields (tonne/ha) and Agronomic Efficiency of Fertilizer-N (AE) and P (kg/kg) in Niger as Affected by Compost Application

	- Compost		+ Compost	
Control	Grain Yield	AE	Grain Yield	AE
Control	3.61		4.86	
N 0	4.00		5.09	
N 30	4.83	28	6.10	37
N 60	5.87	31	7.02	32
P 0	4.17		5.66	
P 15	5.26	73	6.37	47
P 30	5.27	37	6.18	17

Irrigation Area in the Sahel

In cooperation with INRAN an experiment was conducted in an irrigated rice scheme along the Niger River about 150 km northwest of Niamey. At certain periods of the year this river is filled with water hyacinths. These plants are threatening to block the downstream hydroelectric turbines located in Nigeria. At the request of the Nigerian Government, efforts are being made to clear the river. Until recently, nothing was done about the plant residues. An INRAN researcher took the initiative to use the water hyacinths for composting. Therefore the plants are being mixed with available organic materials. In 1999, an experiment with three replications was conducted to test the effect of compost on the efficiency of applied mineral fertilizers on four farms. The design is the same as used in rainfed experiments in Togo, Ghana, and Niger (Table 6). The rice grain yields are presented in Table 22. The data are the average of 12 observations.

In this first year's experiment, compost application resulted in higher yields due to the release of nutrients. The agronomic efficiency of fertilizer-N was improved by the compost but degraded in case of fertilizer-P. Grain, straw, soil, and compost samples have been collected for chemical analyses. However, the results of N and P recovery are not yet available. Also, the results of the socioeconomic survey are not yet available.

Dryland Farming in the Sahel

In the Sahel, millet is the main food crop. The average yield obtained by farmers is about 0.3 - 0.6 tonne/ha. Generally, no external inputs are applied.

The effect of soil fertility improvement on the efficiency of mineral fertilizers was tested near the village Karabedji located a few kilometers to the south of Niamey. Three farmers were selected with bush and compound fields in cooperation with ICRISAT's Sahelian Center in Niger. At these sites, an experiment with a 3^2 factorial design was executed. The factors investigated were N (0, 30, and 60 kg N/ha as urea) and P (0, 15, and 30 kg P/ha as SSP). In contrast to the experiments discussed earlier, no K was applied because this nutrient is generally not considered as a yield-limiting factor in the region. Probably as a consequence, no straight potassium fertilizers are available in Niger.

The soil characteristics of the bush and compound fields are reported in Table 23. There is a consistent, although sometimes small, difference between the two types of fields.

Table 23. Soil Characteristics (0-20 cm) of Experimental Sites in Karabedji, Niger (1999)

	Bush Field	Compound Field
pH-H_2O	4.8	5.1
pH-KCl	4.3	4.9
Organic C (g/kg)	1.5	1.6
Total-N (mg/kg)	118	135
P-Olsen (mg/kg)	1.6	2.5
P-Bray^{-1} (mg/kg)	4.4	6.2
Ca^{2+} (mmol/kg)	2.41	3.67
K^{+1} (mmol/kg)	2.06	3.48
Mg^{2+} (mmol/kg)	1.35	1.95
Na^{+} (mmol/kg)	0.39	0.37
H^{+} (mmol/kg)	1.38	0.58
Al^{3+} (mmol/kg)	1.73	0.51

Table 24. Effect of Soil Fertility Improvement[a] on Millet Maize Yields (kg/ha) and Agronomic Efficiency of Fertilizer–P (AEP) (kg/kg) in Karabedji, Niger (Sahel) in 1999

	Bush Fields	AEP	Compound Fields	AEP
N0P0	183		479	
N0P15	773	39	914	29
N0P30	660	16	1,195	24
N30P0	368		735	
N30P15	738	25	1,325	39
N30P30	1,325	32	1,698	32
N60P0	261		563	
N60P15	1,146	59	1,407	56
N60P30	2,087	61	2,391	61

a. Each yield data is the average of nine observations.
LSD (0.05 = 245); LSD (0.01 = 324)

The N0P0 treatment is the absolute control as no other nutrients are applied. A significant response to N and P application is found at both sites and also the N*P interaction is significant. At the highest N level, the agronomic efficiency of fertilizer-P is about 60 (Table 24). If we assume a recovery fraction of 0.1, then the efficiency of utilization of absorbed P is approximately 600, which is considered the maximum for maize. As expected in view of the soil characteristics (Table 23), the compound fields show a higher yield than the bush fields. The difference is about 340 kg/ha. However, the compost does not influence the efficiency of fertilizer-P.

In Table 25, the agronomic efficiency of fertilizer-N is presented. At the highest P level the agronomic efficiency of fertilizer-N is approximately 20 (30 kg N). If we assume a recovery fraction of about 0.4, then the efficiency of utilization of absorbed N (EUN) is approximately 50. For maize the efficiency of utilization of absorbed N ranges from 30 to 70. The plant uptake data when available will show whether the above assumptions are correct. The yield data show that highest yields are obtained with application of both N and P. Compost improves the average agronomic efficiency of fertilizer-N only slightly (less than 20%). But this increases, nevertheless, the value:cost ratio (VCR) from 1.9 to 2.2. This may just decrease the threshold for fertilizer use enough.

The background of the VCRs is as follows. The prices of a 50-kg bag of urea (46% N) and SSP (18% P_2O_5 = 8% P) are currently FCFA 6,500 and FCFA 8,500, respectively. The price of 1 kg of millet ranges between FCFA 115 and 150; a price of FCFA 125 is used for the calculation. Calculation of the VCR (Table 26) shows that application of 30 kg/ha of N on the compound fields results in the highest economic benefits. However, it is anticipated that yields will be limited by P after several seasons of in-

Table 25. Effect of Soil Fertility Improvement on Millet Maize Yields (kg/ha) and Agronomic Efficiency of Fertilizer-N (AEN) (kg/kg) in Karabedji, Niger (Sahel) in 1999. The Yield Data Are the Average of Nine Observations

	Bush Fields	AEN	Compound Fields	AEN
P0N0	183		479	
P0N30	368	6	735	9
P0N60	261	1	563	1
P15N0	773		914	
P15N30	738	-1	1,325	14
P15N60	1,146	6	1,407	8
P30N0	660		1,195	
P30N30	1,325	22	1,698	17
P30N60	2,087	24	2,391	20

LSD (0.05 = 245); LSD (0.01 = 324).

Table 26. Value-Cost Ratio (VCR) for the Different Fertilizer Treatments as Affected by Soil Fertility Improvement in Karabedji, Niger (Sahel) in 1999

	Bush Fields		Compound Fields	
	Grain Yield (kg/ha)	VCR	Grain Yield (kg/ha)	VCR
N0P0	183		479	
N0P15	773	2.3	914	1.7
N0P30	660	0.9	1,195	1.4
N30P0	368	2.7	735	3.8
N30P15	738	1.7	1,325	2.6
N30P30	1,325	1.7	1,698	1.9
N60P0	261	0.6	563	0.6
N60P15	1,146	2.4	1,407	2.4
N60P30	2,087	2.9	2,391	2.9

tensified N application. Therefore, in the long term, the N30P15 treatment will probably be most profitable, especially since it will not be necessary to repeat the P application each year due to the residual effect. Higher application rates (N60P30) also resulted in relatively high VCR values in 1999.

The traditional practice is growing millet on a large scale without use of inputs. However, in the long term this results in soil degradation as can already be observed in some areas. It is necessary, therefore, to study alternative sources of fertilization for sustainable food crop cultivation. Niger is a landlocked country and transport is a substantial cost factor. Use of TSP (46% P_2O_5 = 20% P) instead of SSP (18% P_2O_5= 8% P) can reduce the transport costs per kilogram P substantially (i.e., application of 15 P/ha requires four bags of SSP as opposed to two bags of TSP). Use of locally available PR (Tahoua) might even be a cheaper alternative.

FROM DATABASES TO DECISION SUPPORT SYSTEMS

At the start of the project, the idea existed to define recommendation domains of the different options in the form of matrices, exploiting several databases as sources for variables that will be used. Recognizing that such an approach should be too static and too general, another approach was chosen, that is, development of tools making the identification of recommendation domains an activity of the potential user or its adviser (extension services, NGOs, etc.). Human capital to be invested in the development of matrices was used to reinforce the work on DSSs. The project contributed to four different DSSs, three of which have been built on original databases in IFDC and TSBF. It concerns DSSs concerning the question when and where to use for which goal:

- Organic matter (DSS-OM).
- Fertilizer (DSS-FFU = feasibility fertilizer use).
- Leguminous species (DSS-legumes).
- PR (DSS-PR).

TSBF concentrated on the DSS-OM, IFDC on the three others. Two of the DSSs—those for fertilizer and those for legume use—are now only available for the West African context. Because funding has been received from other donors, the DSSs have been published elsewhere (Breman and van Reuler, 2001; Singh et al., 2001).

An initiative of TSBF led to the start of the project to a first matrix as foreseen for the identification of recommendation domains for the integrated use of OM and inorganic fertilizer (Carter, 1997). IFDC completed it with two tables (Anonymous, 1997) in use for the selection of villages and regions for successful participatory development of ISFM practices. The tables were developed into a real approach, presented, and published recently (Schreurs, 2001).

STRENGTHENING NATIONAL INSTITUTIONS AND CAPACITY FOR RESEARCH AND DEVELOPMENT

On the job and through meetings, staff members of collaborating institutions were trained in the field of ISFM. At the start of the project (November 11-18, 1997, Lomé), IFDC organized an international training program on the development of fertilizer recommendations based on field experiments and soil-crop models, in Lomé, Togo. Five staff members of collaborating institutions were sponsored to participate in this program.

In many countries the system of fertilizer recommendations is poorly developed. The recommendations do not generally consider farmers' goals; availability of local nutrient sources; and differences in soils, climatic conditions, crops, and production levels anticipated. Consequently the agronomic efficiency of mineral fertilizers is low, and the nutrient losses to the environment are high. This low efficiency, combined with relatively high prices, results in unprofitable use of mineral fertilizer.

System analysis was used with staff from partner institutes as a tool for the development of fertilizer recommendations that are based on biophysical and economic conditions. The vicious cycle of low soil fertility, low efficiency, and unfavorable economics can be broken in that way. Generally speaking, the use of models in West Africa is very low. Therefore, an important subject of the course was to show some models in the field of crop growth-fertilization that are available, with their potential and constraints.

IFDC established the West African Fertilizer Management and Evaluation Network (WAFMEN) in 1983 as an institutional framework to promote sustainable agricultural production in West Africa through collaborative research and information exchange on fertilizer use technologies among agricultural scientists. It was shown in several on-station experiments that mineral fertilizer use could be made profitable by soil fertility improvement (Table 1). The method to be applied depends on the agroecological and socioeconomic conditions.

A common criticism of donors on agricultural research is that on-station research has not resulted in higher yields at the farmer level. Institutes have long neglected the translation for farmers of scientific data obtained in on-station trials. IFDC shares the opinion that it is essential to involve farmers and other important stakeholders actively in agricultural research. The challenge is to develop in a participatory way packages composed of measures for soil fertility improvement and mineral fertilizer use, and of socioeconomic measures leading to increased accessibility of agricultural inputs. An adapted WAFMEN can play a role in the elaboration of these packages in case the partner institutes adopt the participatory research approach. Therefore, a note was written entitled "From fertilizer evaluation to integrated nutrient management—WAFMEN." The aim of this note was to inform WAFMEN members about changes in approach to motivate them to adapt the network and to invite others to join it. A summary of the note was published in the CORAF magazine. Several of the former members are now active partners of IFDC-Africa's ISFM-programme, aiming to exploit the results of the present project.

Southern Africa

The project was implemented in partnership with staff in IFAD-financed investment projects and AfNET (TSBF's African Soil Biology network) members in Malawi, Zambia, and Zimbabwe. Activities were restricted to Central and Northern Malawi and Central and Southern Provinces in Zambia. These areas receive annual rainfall of between 900 mm and 1,200 mm.

In Southern Zambia, the study was conducted in the Muziyo area of the Sinazongwe district and the Moboola area of the Namwala district. Both areas have problems associated with soil and land degradation. The Muziyo area has a unique problem as a result of its hilly terrain, and interventions of soil conservation are apparently critical. Both areas are equally affected by the SAP in terms of lack of inputs and poor marketing conditions as a result of the removal of government-supported marketing and input distribution mechanisms that accompanied the change of government in 1991.

In Zimbabwe, the study was conducted at three sites (Chivi, Mangwende, and Shurugwi). Chivi is a dry area with a mean rainfall of 650 mm, Mangwende (900 mm), and Shurugwi, a medium-potential area receiving a mean rainfall of 750 mm. The yields in many of the study sites are low, due to low inherent fertility and a decline in soil fertility particularly in the wetter and higher yield potential areas. The low rainfall in some parts of the region also limits potential productivity of the soils and their management using high input strategies. This necessitates maximizing use of locally available, low-cost resources such as manure and supplementing them with applications of purchased inputs where available.

The main activities in the project were:

- Improving farmers' management of nutrient flows on-farm, e.g., through improving quality and effectiveness of locally available organic resources.
- Using decision support tools.
- Developing protocols for combining organic and inorganic nutrient

sources, especially determining fertilizer equivalencies of organic inputs, and synchronizing nutrient supply and demand by manipulating timing of application of organic/inorganic inputs.
- Evaluating the long-term effects of tillage and nutrient management on SOM fractions and their practical implications.
- Developing alternative methods for working with farmers, such as plot-level experiments, participatory research tools to aid farmer-led analysis, and assessment of practical interventions.
- Valuing the subsidy that organic resources provide to the cropping system using quantitative economic analysis and farmer criteria.

The above activities were carried out through: (1) on-farm surveys on organic resource availability and use and (2) on-farm research and farmer participatory trials using improved manure. The on-farm surveys and participatory rural appraisals were done to identify problems and opportunities for interventions within IFAD supported rural development projects. These are reported below.

ON-FARM SURVEYS ON ORGANIC RESOURCE AVAILABILITY AND USE

Nzuma, Murwira and Mpepereki (1998) reported the results of a participatory survey on manure management that was done in Zimbabwe. They showed a widespread use of crop residues in kraals. Heaping is widely used as a curing method for manure before application to the fields. Other manure storage and handling techniques that farmers used were: (1) keeping the manure in the kraal until ready for application in the fields, (2) building kraals on anthills (termitaria mounds) to enhance quality, and (3) digging of trenches into which dung and run-off from kraals drained into during the rainy season, etc. On the basis of the surveys and discussions with farmers, it was decided to introduce pit storage of manure as an improved technique for enhancing quality of manure. The testing of the technology is reported below.

In Zambia, participatory appraisal techniques were used to elicit information on various issues on soil fertility to determine to what extent it is a constraint and how it ranked in relation to other constraints. Tools used included mapping, pair-wise ranking, trend analysis, focus group discussions, and time-line analysis. The following topics were exhaustively discussed with farmers:

- History and settlement patterns.
- Crops and their production trends.
- Soil maps, names, and potential use.
- Soil management practices.
- Soil conservation practices.
- Crop livestock interaction.
- Soil fertility trends.
- Constraints to improved soil management.

It was observed in the exercises that farmers maintain their cultivated soils by practicing ill-defined rotations, for example, three crops of maize followed by cotton, cowpeas, maize, groundnuts, etc. Farmers have learned to apply anthill soil or a combination of this and manure to their fields, though not so in Muziyo. Sites treated in this way were said to remain supportive of good crop growth for as long as 5 years. Anthills with dense growth of Hyperrhanea grass are targeted for degraded soil improvement based on the local saying "Bulemu bwa chuulu mbwizu'' which literally translates to "the respect of an anthill lies in the amount of grass growing on it." Once fields are degraded farmers in Muziyo tend to abandon the fields leaving them to many years of natural fallow while opening up new land. The steady increase in settlement has led to rapid deforestation and its associated soil erosion.

A cause-effect analysis was done with a group of women in the Southern Province. The main objective was to gain an understanding of the relationships that exist among the various factors that affect crop production negatively. In addition, this was to enable women to identify the most appropriate stage of intervention. Exhausted soils were identified as the greatest constraint to increased crop production as in Figure 9.

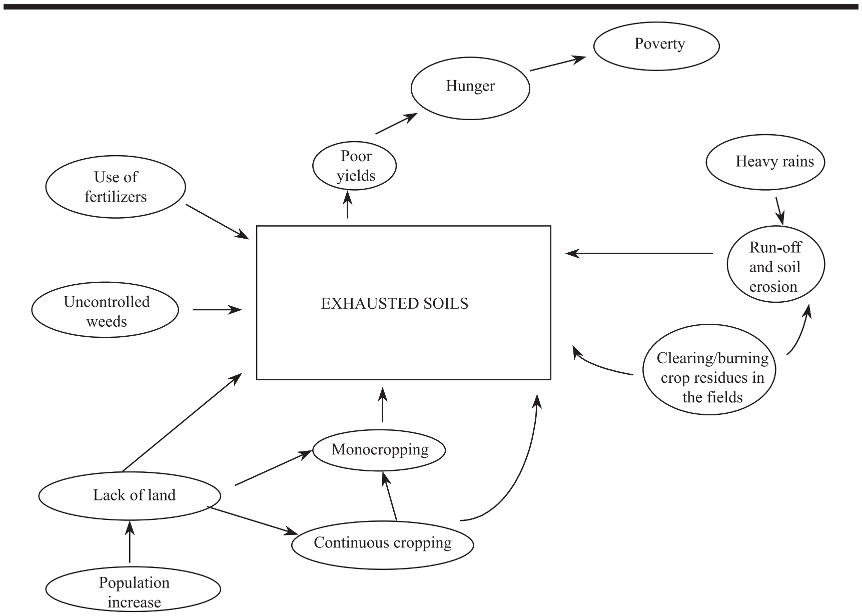


Figure 9. Cause-Effect Analysis of the Problem of Exhausted Soils as Perceived by Women Farmers in Southern Zambia.

One of the underlying causes of exhausted soils was the increase in human population and little or no application of fertility inputs. Due to the increase in population, land available for crop production has diminished (lack of land). This situation encourages continuous cropping. In most households the largest field is given to maize, which is the staple crop while other crops are given the remaining parts of land, and this trend is repeated over the years.

The outbreak of Theileriosis (Corridor) disease has drastically reduced the cattle population in the province, and most households do not have alternative draught power. This implies smaller fields and lower yields. In addition, the use of kraal manure has diminished drastically for most households, thereby further exacerbating the need for fertilizers.

The preliminary survey results from Malawi indicate that the use of cattle manure is important in the northern districts. Manure storage and management practices emphasize the shifting of kholas (kraals) on an annual basis. Farmers only cultivate on these khola patches after 1 or 2 years as they allegedly get crop burn if they plant in the first season. This is different from farmers' practices in Zimbabwe. The potential for improvement lies in improving the quality of the manure so those farmers do not lose a year or two without making use of the manure. Use of crop residues for soil fertility improvement is limited with most of the cattle owners preferring to graze them to livestock.

ON-FARM RESEARCH TRIALS

Manure Storage Experiments

In the first phase of these studies, biological processes were manipulated during storage of cattle manure to reduce N losses by volatilization to enhance quality. The emphasis on these studies was on pit storage of manure, which was evaluated against the conventional heaping practice. The effect of crop residue incorporation prior to storage and duration of composting was also investigated.

First-year conclusions were that:

- Pit storage without crop residues significantly increases N concentration of manure more so than that from heaped storage systems.
- There is an incremental benefit of 1% N (10 kg N/tonne manure) if manure is pit stored without crop residues in July (dry season) rather than in April (late rain season).
- The incorporation of straw during storage encourages aeration, which results in higher N losses and subsequent reduction in quality of the manure (Murwira and Nzuma, 1999; Nzuma and Murwira, 1999).

Experiments were therefore set up to evaluate the efficacy of pit-stored manures in improving maize productivity. This section will focus on:

- Comparative effectiveness of manure produced from different storage techniques in improving maize yields.
- Residual N effects of manure from different storage systems on maize yield.

The hypotheses central to these studies were:

- Improved crop response to manure application can be obtained when crop residues have been added to kraals and manures have been composted anaerobically for 3 months or less.
- Manure from pit storage systems is of higher quality and will give higher yields in the first season, but subsequent benefits from pit manures are lower than from heaps.

First Season Trials (1997/98)

In the first season eight manures from different storage systems were evaluated. The manures had been composted either in April or July. All manures were analyzed for total N before application to the fields in October. The manure was applied in bands at amounts equivalent to 60 kg N/ha on a dry matter basis. Treatments were: manure stored in either April or July from heaps with or without residues and pit storage with or without residues. The experiment was a randomized complete block design with three replicates at each site. The trial was further replicated on four sites at Chipunza, Mukudu, Musegedi, and Nhapi. The chemical characteristics of these sites are given in Table 27. All sites were on medium-grained sandy soils, low pH, low exchangeable bases, and deficient in N. Plot sizes were 6.5 m x 4.5 m with plant spacing of 0.9 m between

Table 27. Initial Soil Characteristics of Trial Sites

Site	Texture	pH ($CaCl_2$)	N	P_2O_5	K	Ca	Mg
			- - - (g/kg)- -		- - - - ($cmol+kg^{-1}$) - - - -		
1997/98							
Nhapi	S	4.1	44	39	0.50	1.56	0.82
Musegedi	S	4.2	38	29	0.30	1.63	0.42
Chipunza	S	4.5	28	24	0.28	2.10	0.63
Mukudu	S	3.7	27	26	0.08	0.64	0.17
1998/99							
Muzavazi	S	4.3	19	32	0.14	1.23	0.29
Manyani	S	4.1	8	11	0.09	0.64	0.14
Musegedi	S	4.2	10	6	0.13	0.88	0.24

S = sand.

rows and 0.30 m in-row. All plots received a uniform topdressing of 40 kg N/ha at 6 weeks after planting. After harvest, plots were maintained the following season for assessment of residual effects. Statistical analysis was done using two-way ANOVA procedures in GENSTAT for each site.

The results from the first season trials (1997/98) are presented in Figure10 (Mukudu site 1 and Chipunza site 2) and Figure 11 (Musegedi site 3 and Nhapi site 4). Results were similar at all sites. The results show that the main effect of manures from different storage techniques is significant at 1% level. There was a positive crop response following application of pit-stored manure than from heaps that depressed yields in all cases. The addition of pit-stored manure without crop residues significantly increased ($P<0.01$) maize yield more than any other treatment. There is an additional benefit of applying pit manure without straw stored in July compared with that in April. The incremental benefit was at least 2 tonnes/ha of grain at all sites. The high yields obtained suggest that the high-quality pit-stored manure is more effective in supplying N during the growing season. The depressed yields from low N manure obtained from conventional heaping can be attributed to immobilization of N which induces a nutrient deficiency to the crop.

Second Season Validation Trials (1998/99)

These trials were conducted to validate results from the first season. The second season trials (1998/99) are shown in Figures 12, 13, and 14. The results show indeed that the application of pit-stored manure without residues significantly gives ($P<0.01$) higher yields than heaped manures. This can probably be attributed to the pit manure being more decomposable. This in part is reflected by the higher N concentrations in pit manure (1.7% to 2.2% N) than in heaped manure (<1.2% N).

In results from previous studies, Nzuma and Murwira (1999) showed that losses of N through volatilization were higher in manures incorporated with straw. This was one explanation why manure with straw had a lower N content. In the validation trials, an additional storage treatment on method of incorporation of straw was included. The straw was incorporated in layers or thoroughly mixed with manure during storage. The results obtained did not show any significant differences in N content between the manures. This was also reflected in the yields obtained after applying the manure (from mixed or layered straw) at the three sites (Figures 12, 13 and 14. There was no statistically significant difference between methods of

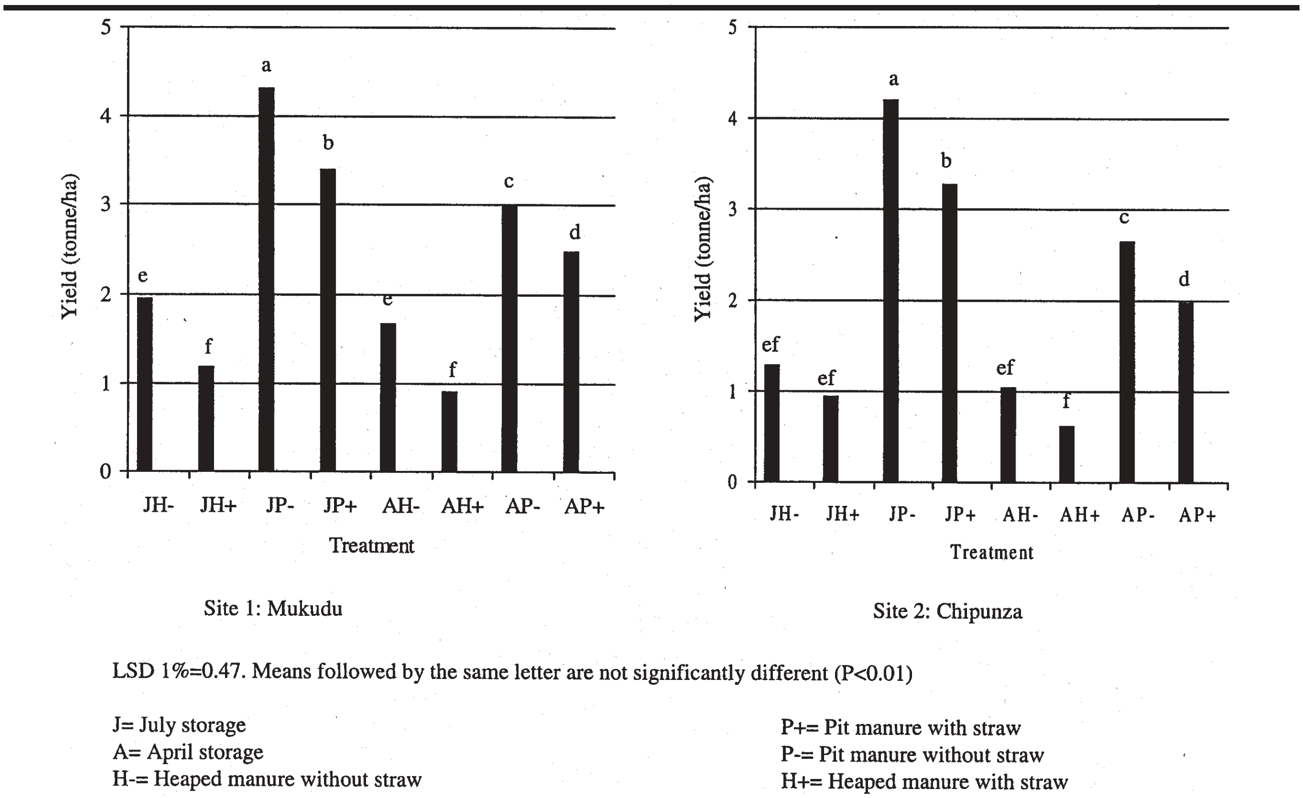
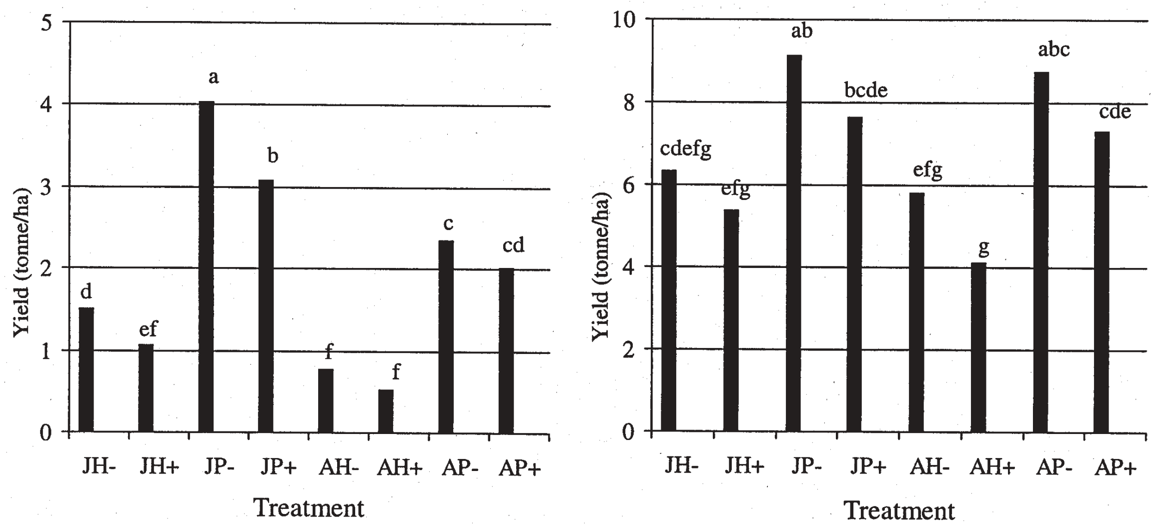


Figure 10. Effect of Storage Systems, Crop Residue Incorporation, and Duration of Storage on Maize Yield (1997/98 Cropping Season).



Site 3: Musegedi

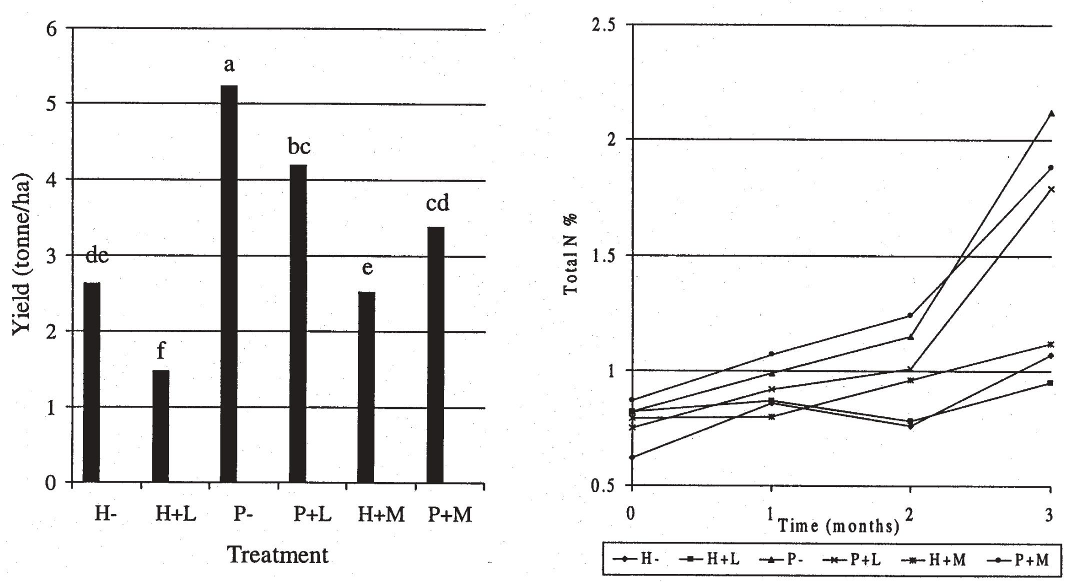
Site 4: Nhapi

LSD 1%=0.47. Means followed by the same letter are not significantly different (P<0.01)

J= July storage
A= April storage
H-= Heaped manure without straw
P+= Pit manure with straw
P-= Pit manure without straw
H+= Heaped manure with straw

Figure 11. Effect of Storage Systems, Crop Residue Incorporation, and Duration of Storage on Maize Yield (1997/98 Cropping Season).

Site 1: Muzavazi 1998/99 cropping season

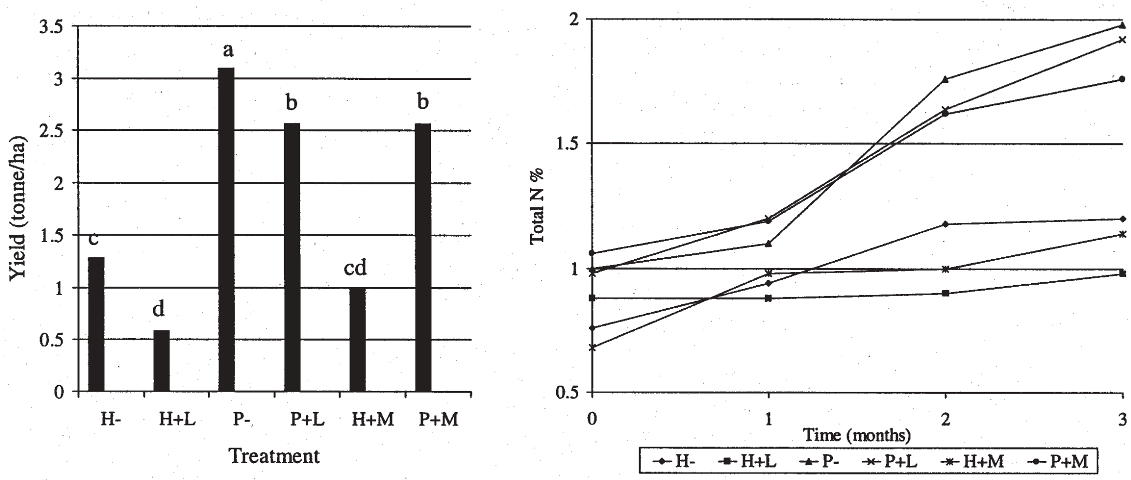


LSD 1%=0.83. Means followed by the same letter are not significantly different (P<0.01)

H-= Heaped manure without straw
H+L= Heaped manure with straw incorporated in layers
H+M= Heaped manure mixed with straw
P-= Pit manure without straw
P+L= Pit manure with straw incorporated in layers
P+M= Pit manure mixed with straw

Figure 12. Effect of Manure From Different Storage Systems on (a) Maize Yield and (b) Change in Total N During Storage.

Site 2: Manyanii 1998/99 cropping season



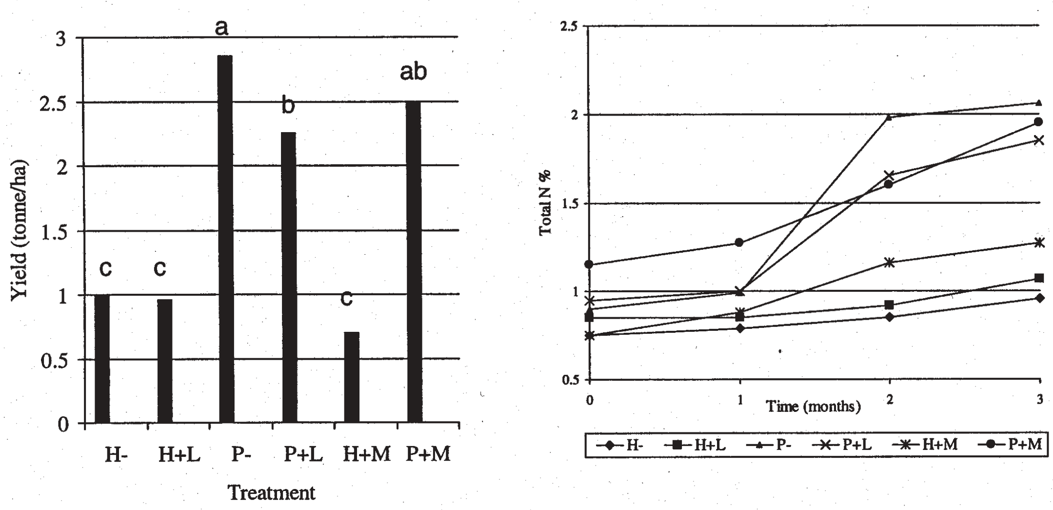
LSD 1%=0.44. Means followed by the same letter are not significantly different (P<0.01)

H-= Heaped manure without straw
H+L= Heaped manure with straw incorporated in layers
H+M= Heaped manure mixed with straw

P-= Pit manure without straw
P+L= Pit manure with straw incorporated layers
P+M= Pit manure mixed with straw

Figure 13. Changes in Manure N During Storage and Subsequent Effects on Maize Yield.

Site 3: Musegedii 1998/99 cropping season



LSD 1%=0.47. Means followed by the same letter are not significantly different (P<0.01)

H-= Heaped manure without straw
H+L= Heaped manure with straw incorporated in layers
H+M= Heaped manure mixed with straw

P-= Pit manure without straw
P+L= Pit manure with straw incorporated in layers
P+M= Pit manure mixed with straw

Figure 14. Effect of Manure From Different Storage Systems on (a) Maize Yield and (b) Change in Total N During Storage

incorporating straw particularly in pits. For heaps, the only significant effects of method of incorporation were at Muzavazi (Figure 12).

Residual Effects of Manure From Different Storage Systems

The residual effects of manure applied at the sites in Figures 10 and 11 were evaluated in the 1998/99 season (Tables 28, 29, and 30). Pit manure without straw gave significantly higher yields in the first season compared with the residual year. However, the opposite was observed for heap-stored manure, with yields higher in the residual year than in the first season of application. When added over the 2-year period, yields were significantly higher ($P<0.05$) from pit than heap-stored manure.

Other On-Farm Trials

Combining Organic and Inorganic Plant Nutrient Sources: Zimbabwe—The aims of this work were to find the fertilizer value of different cattle manures, the extent to which low quality manure immobilized, and the amount required to overcome the negative effects of these manures. The efficacy of manure-inorganic N combinations in improving maize yields was also assessed. Two hypotheses were tested: (1) that low quality manure (high lignin, low N content) immobilize N resulting in reduced maize yield and (2) combinations of high quality manure (low lignin, high N content) and inorganic N perform better than sole applications. The study was carried out in the Murewa communal area. This was done in two parts: (1) using low-N manure from farmers in Murewa and (2) manure from a commercial feed lot was used (Table 31). The trials were conducted on N-limiting granitic sandy soils with maize as the test crop. A normalized-manure effect was also calculated for each site using the formula: (net treatment effect/control).

Table 28. Effect of Different Types of Manure on Maize Yields in the Year of Application and Its Residual Effects at Chipunza, Zimbabwe

Storage System	Maize Yield 1997/98 (tonne/ha)	Residual Effects 1998/99
Heap - straw, July	1.50	3.07
Heap + straw, July	1.06	2.79
Pit - straw, July	4.04	1.85
Pit + straw, July	3.08	2.00
Heap - straw, April	0.78	2.25
Heap + straw, April	0.52	2.15
Pit - straw, April	2.35	1.45
Pit + straw, April	2.02	2.02

Table 29. Effect of Different Types of Manure on Maize Yields in the Year of Application and Its Residual Effects at Mukudu, Zimbabwe

Storage System	Maize Yield 1997/98 (tonne/ha)	Residual Effects 1998/99
Heap - straw, July	1.94	2.38
Heap + straw, July	1.19	1.98
Pit - straw, July	4.31	0.87
Pit + straw, July	3.39	0.96
Heap - straw, April	1.66	2.05
Heap + straw, April	0.91	2.76
Pit - straw, April	3.01	1.10
Pit + straw, April	2.48	0.97

Table 30. Effect of Different Types of Manure on Maize Yields in the Year of Application and Its Residual Effects at Musegedi, Zimbabwe

Storage System	Maize Yield 1997/98 (tonne/ha)	Residual Effects 1998/99
Heap - straw, July	1.29	1.89
Heap + straw, July	0.94	2.27
Pit - straw, July	4.20	1.57
Pit + straw, July	3.27	1.25
Heap - straw, April	1.05	2.35
Heap + straw, April	0.62	2.64
Pit - straw, April	2.64	1.05
Pit + straw, April	1.97	0.89

Table 31. Chemical Characteristics of Cattle Manure Applied

Site	% N	% C	C/N	% Lignin	% Polyphenol	% Ash
Mapira	0.56	8.10	14.5	6.07	0.054	82.15
Chisunga	0.60	6.90	11.5	6.46	0.040	84.21
Chinonda	0.47	9.90	21.1	6.07	0.074	82.79
Manjoro	0.89	12.90	14.5	21.14	0.135	56.42
Mukudu	0.89	18.00	20.2	13.82	0.067	68.36
Commercial feed lot	2.70	19.20	8.35	8.75	na	26.64

na = not available.

To determine the extent of immobilization caused by different manures, the amount of inorganic N required to overcome the negative effects and the fertilizer values of the manures was used. The amount of cattle manure applied was kept constant at 5,000 kg/ha while incremental amounts of inorganic N (0, 20, 40, 80, 100 kg N) from ammonium nitrate were added to the manured plots. Ammonium nitrate was applied in two splits, one at 6 weeks and the other at 10 weeks after planting. A blanket P (as SSP) and K (as muriate of potash) of 40 kg P and 30 kg K was applied, respectively.

To assess the effects of manure-inorganic N combinations relative to both manure and inorganic N sole treatments, manure with 2.7% N was used in this experiment. The amount of N applied in all the different treatment combinations was constant at 100 kg N. The treatments were 100% from manure, 75% from manure, 25% inorganic N, 50% from manure 50% inorganic N, 25% from manure, 75% inorganic N, and 100% inorganic N. Manure was incorporated at planting and fertilizer was split applied at 6 and 10 weeks after planting. A randomized complete block design was used in both experiments. A least significant difference (LSD) test was used in comparing the means of different treatments.

Negative Effects of Low-Quality Manure—Treatments in this experiment were arranged in a factorial manner, two manure levels (0 and 5,000 kg/ha) and five inorganic N levels (0, 20, 40, 80, and 100 kg N/ha). Four sites were used in this study (Manjoro, Chinonda, Chisunga, and Mapira) in the first season and five in the second (Chitemerere, Mudonhi, Mukudu, Chigariro, and Makunzva). The inorganic-only curve was used to calculate the amount of N required in overcoming immobilization effects or the N fertilizer value of manure at each site.

At Chisunga and Mapira manure immobilized N with 90 kg N and 100 kg N required to overcome the negative effects, respectively. It is only after these levels that the manure-fertilizer combinations begin to give the added beneficial effects. Thus, the fertilizer values for the Chisunga and Mapira manures are -90 and -100 kg N, respectively. Chinonda and Manjoro manures did not immobilize N in the soil. The fertilizer N value of both Chinonda and Manjoro manure was found to be 30 kg N.

The yield depression after using low-quality manure at Chisunga and Mapira demonstrates the immobilization phenomenon. Manures from these two sites immobilized some substantial amounts of N (90 and 100 kg N), showing how serious this process can affect soil N supply. A C/N ratio greater than 23 is often associated with immobilization, however, this study shows that immobilization could occur at lower C/N ratios, e.g., Chisunga manure (C/N = 12) and Mapira manure (C/N = 15) immobilized leading to yield reduction. The critical values for immobilization of manures obtained in this study were 1.2% N and a C/N ratio of 12. These critical values need to be verified using a larger sample size. Hence, C/N ratio cannot be reliably used as the only index of mineralization in manure. Lignin content and % ash also described the observed N fertilizer values of low-quality manure. However, the relationships were inverted, as it was not expected that fertilizer equivalency values would be larger for manure with higher polyphenol and lignin content.

Relative manure effects for the different sites were calculated and neither linear nor quadratic regressions could be used to relate it to the manure indices measured.

A general linear relationship was observed between the fertilizer values and the initial N content of the manures (Figures 15 and 16). The N fertilizer values obtained in the second season (Figure16) ranged from 10% to 35% with most between 10% and 20%. While the figures obtained are on the low side, this can be due to the low N content in manure (most had less than 1% N). The positive N fertilizer value obtained show that there was no overall reduction in the yield after applying sole manure to the maize crops. Results obtained in the two seasons show the typical scenarios in which manures with an almost equal amount of N content behave differently. This would support the hypothesis that, while % N in manure is a good indicator of quality, it is not the only index of its fertilizer value. The results also show that except for two samples with % N>1 there would have been no clear trend in the relationship (Figure16).

Efficacy of High-Quality Manure and Inorganic N Combinations—Four sites at Manjoro,

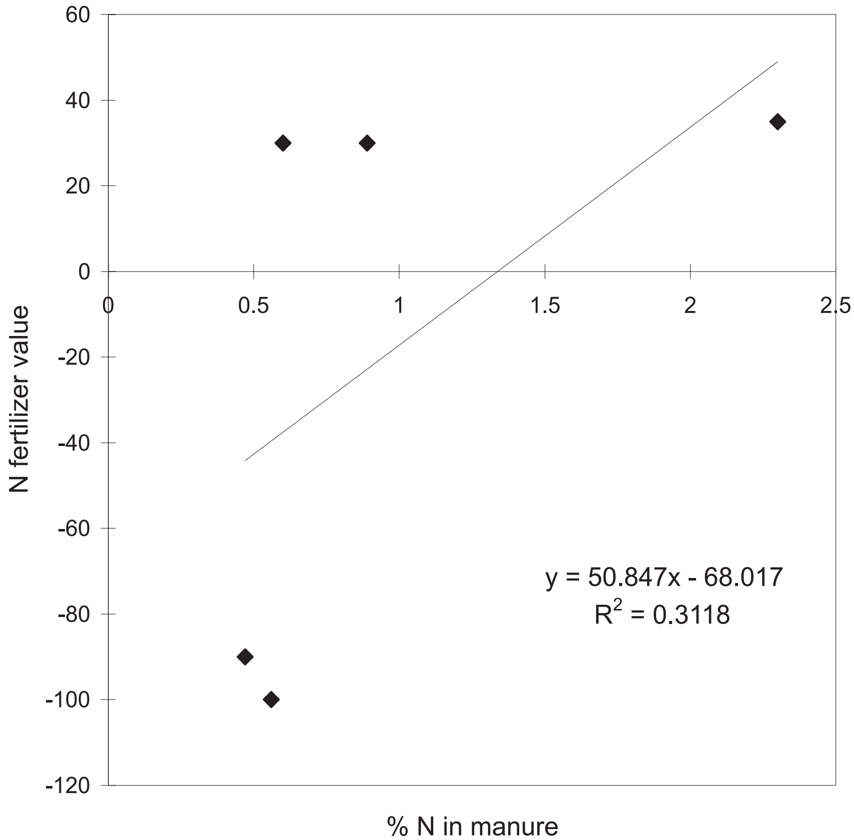


Figure 15. Regression of the N Fertilizer Value Against % N in Manure (1997/98 Season).

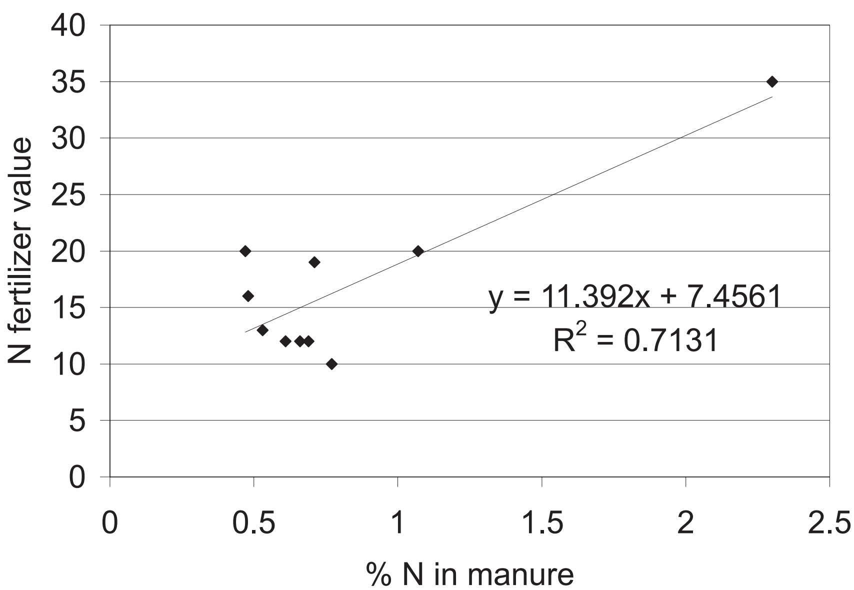


Figure 16. Regression of the N Fertilizer Value Against % N in Manure (1998/99 Season).

Mapira, Chinonda, and Chisunga were used for the study on high-quality manure in the 1997/98 season (Figure 17). At Chisunga, sole inorganic N produced significantly ($P<0.05$) higher yields than sole manure. Though the overall treatment effects were not significant, the 50% manure 50% inorganic N had the highest yield at Mapira. However, at all the other three sites the 75% inorganic 25% manure treatment produced the highest yield. Results from three of the four sites (Chisunga, Mapira, and Chinonda) show that combinations produced better yields than their soles.

At Manjoro, use of high-quality manure and sole inorganic treatment resulted in comparable yield results with no statistical difference among the combinations suggesting that the two materials relate in a substitutive manner.

In 1998/99 season at Chinonda there was no overall statistical significant differences between combinations and soles (Figure18). The treatment with 25% inorganic and 75% organic had the highest yield. At Sunhwa both the 50% inorganic 50% organic and the sole manure treatment were significantly higher yielding relative to the sole inorganic treatment. Sole organic and the 25% inorganic and 75% organic treatments were significantly better ($P<0.05$) than the sole inorganic treatment at Mangena site. At Chimombe the 100% inorganic and the 75% inorganic 25% organic significantly had higher yields than the sole manure treatment. There was no significant difference between the other combinations and the 100% organic treatment. Though there was no statistical difference among treatments, the combinations performed better than their soles at Kaitano. Grain yields obtained from the residual effects of 100 kg N applied in different proportions of manure and inorganic fertilizers (1998/99 season) Zivhu combinations had yields

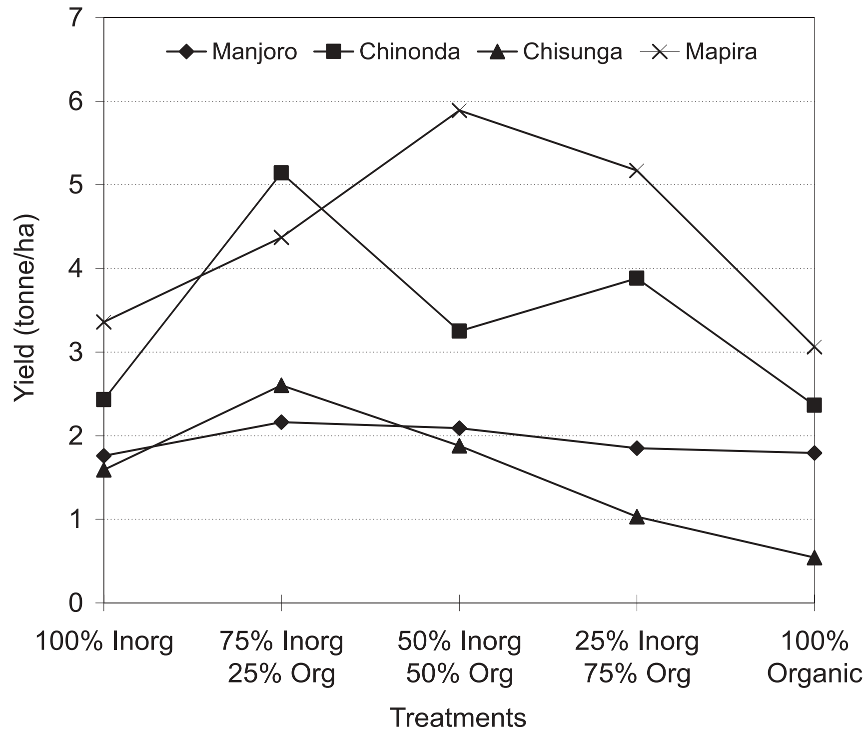


Figure 17. Grain Yields Obtained From 100 kg N Applied in Different Proportions of Manure and Inorganic Fertilizers for the 1997/98 Season.

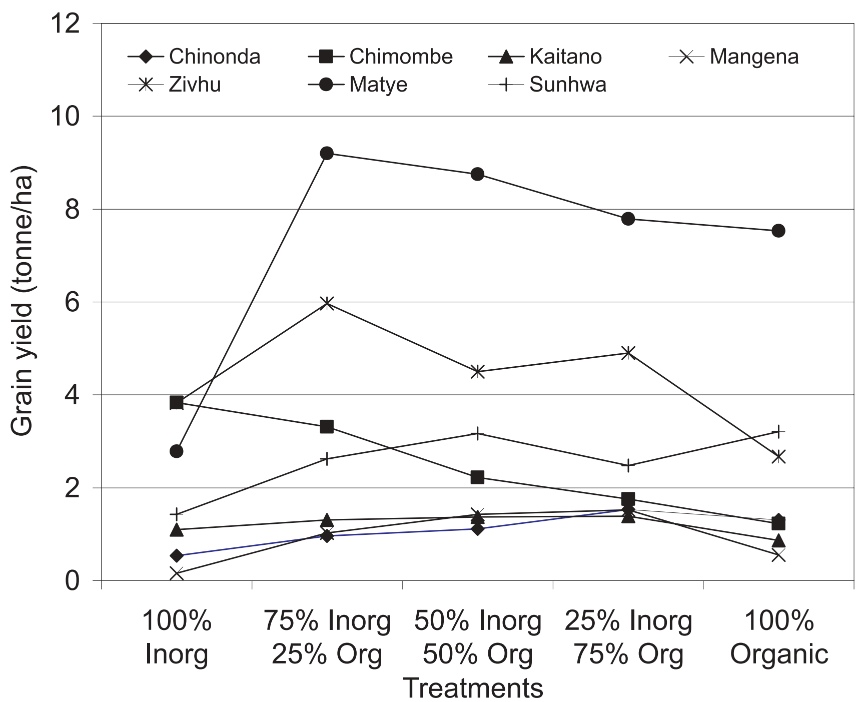


Figure 18. Grain Yields Obtained From 100 kg N Applied in Different Proportions of Manure and Inorganic Fertilizers for the 1998/99 Season.

that were statistically higher than the sole manure treatment. There was also no significant difference between the soles. There was no significant difference among treatments at the Matye site, but combinations and 100% manure had much higher yields than the 100% inorganic.

Residual effects of the combinations of high N manure and inorganic N were assessed after applying the treatments for one season at three sites (Figure19). At Mapira and Mukudu sites, there was no clear trend of yield responses observed in the residual effects of the treatments. There was no significant difference among treatments. However, at Mangena, there was a clear increase in yield with increase in proportion of manure added in the previous season. Little residual effects are expected from inorganic fertilizer applied at low rates. It also shows that even manure of high N content continues to mineralize nutrients in the second season of application.

Detailed measurements on N uptake were taken on two sites. The uptake efficiency was higher in the combination treatments at both sites (Figure 20). This implies that there was better synchrony between nutrient release and uptake when combinations of organic and inorganic inputs are used. Though the differences were not statistically significant, at Mapira the 100% manure treatment had a higher efficiency compared with 100% N, whereas at Chinonda the opposite was true.

Optimal Combinations of Organic and Inorganic N Sources: Zambia

The objectives were to investigate yields and nutrient use efficiencies from the combined use of organic and inorganic sources and to determine the fertilizer equivalency values of high-quality organic resources. The research study was conducted on a sandy loam soil classified as fine, mixed, isohyperthermic, Oxic Rhodic

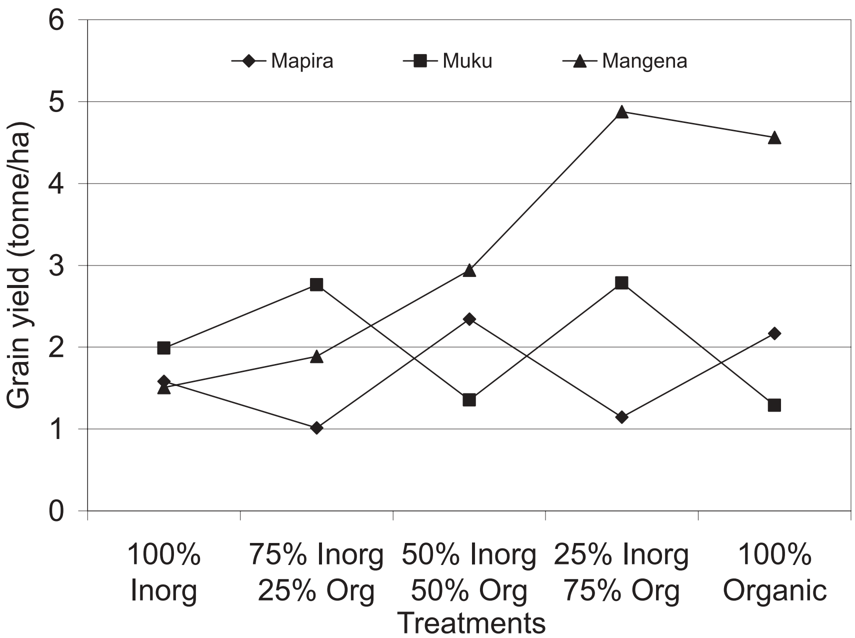


Figure 19. Residual Effects of the Combinations of High N Manure and Inorganic N.

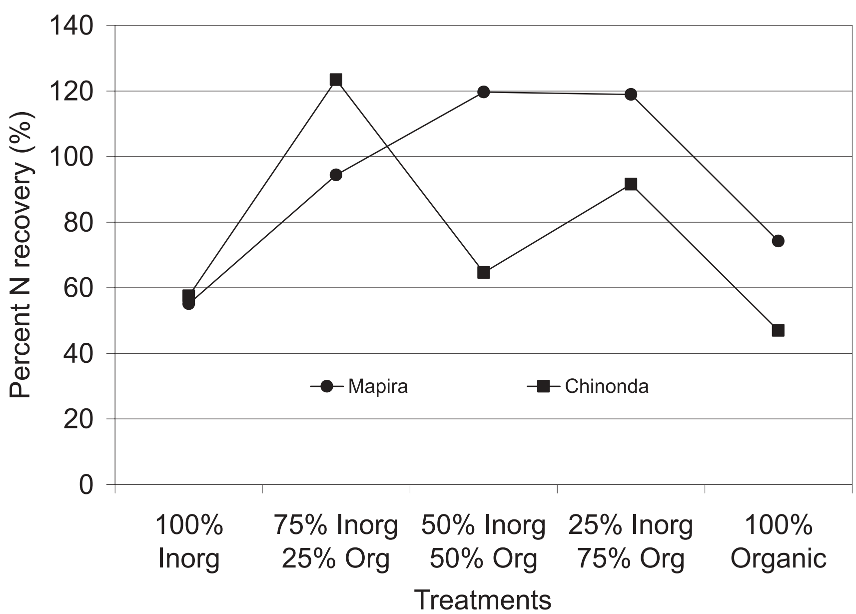


Figure 20. Amount of N Recovered (%) in Grain and Non-Grain Biomass From the 100 kg N Treatments Applied in Different Proportions of Manure and Inorganic Fertilizers.

Paleustalf at Chalimbana Research Station (Table 32). An application rate of 100 kg N ha^{-1} was used. The inorganic source was urea while the organic source was sesbania sesban tree prunings. Sesbania sesban was chosen because of its availability and acceptance by farmers especially in the eastern part of Zambia. It is also a high-quality organic resource. Chemical characteristics of the sesbania sesban used in the study are shown in Table 33. It was applied just before planting at rates as shown in Table 34. The sesbania sesban (leaves and twigs less than 2 mm in diameter) was spread on the plot and mixed with a hoe.

The main plots were 4.5 m by 5 m. To quantify the N use efficiency of the maize and determine the residue N recovered, 2% atom excess ^{15}N was applied in micro plots (dimensions 3 m by 1 m) within the main plots at rates shown in Table 34. The treatment plots were arranged in randomized complete blocks with 4 replications. The inorganic fertilizer (both labelled and unlabelled) was applied as topdressing. All plots received a blanket application of phosphorus (40 kg/ha) as TSP and potassium (20 kg/ha) as potassium chloride.

Treatment combinations of inorganic and organic were: 100:0; 77:25; 50:50; 25:75; 0:100 kg N/ha. Inorganic N was also applied at 30, 60, 90, and 120 kg N/ha. Maize (Zea mays L, var. MM601) was the test crop.

The maize grain yield of the control treatment was significantly different from the rest of the treatments. Inorganic fertilizer applied at 90 kg N/ha had the highest mean yield of 3.2 tonnes/ha (Table 34); however, this was not statistically different with yields of inorganic 25/organic 75, inorganic 75/organic 25 or inorganic 50/organic 50 kg N/ha. The combination of inorganic and organic N could have caused some N immobili-

Table 32. Selected Chemical and Physical Properties of the Soil Used in the Experiment

Soil Characteristics Classification	Fine, mixed isohyperthermic, Oxic Rhodic Paleustalf
Soil pH ($CaCl_2$)	5.4
Ca ($cmol_c$/kg)	2.67
Mg ($cmol_c$/kg)	0.58
K ($cmol_c$/kg)	0.60
CEC ($cmol_c$/kg)	40.1
Available P (ppm)	10.0
Total N (%)	0.06
Organic C (%)	0.84
Clay (%)	18.0
Silt (%)	19.0
Sand (%)	63.0
Texture	Sandy loam

Table 33. Properties of the Sesbania Sesban Used in the Study

Moisture	N	P	K	Ca	Zn	Fe	Mn
(%)	(%)				(ppm)		
77.3	3.8	0.19	2.34	3.0	18.8	141	146

Table 34. Mean Grain Yield, Dry-Matter Yield, Number of Cobs and Total N Equivalency Values as Influenced by a Combination of Organic and Inorganic Fertilizer

Inorganic	Organic	Number of Cobs	Grain Yield[a]	Dry-Matter Yield	Total N Equivalency Values
(kg N/ha)			(kg/ha)		kg N/ha
0	0	19ab	1,813.2d[b]	2,454.1a	
100	0	22ab	2,724.7abc	2,078.5a	
25	75	18b	3,127.9ab	2,071.5a	95.0
50	50	21ab	2,929.1ab	2,252.8a	82.1
75	25	22a	2,986.3ab	2,200.1a	85.8
0	100	23a	2,297.6bcd	2,424.9a	41.4
30	0	19ab	1,968.7cd	1,780.4a	
60	0	21ab	2,420.9abcd	1,835.9a	
90	0	21ab	3,214.5a	1,975.9a	
120	0	21ab	2,693.3abc	2,650.3a	
LSD (0.05)			3.82	879	Ns
CV, %		12.7	19.4	30.0	

a. Means in each column followed by the same letter do not differ significantly (LSD = 0.05).
b. Means of 4 values.
Ns = not significant.

zation resulting in a slow release of N. There were no significant differences in the dry-matter yields between all the treatments (Table 34). A combination of inorganic 25/organic 75 gave a total equivalency value of 95 kg N/ha while inorganic 75/organic 25 and inorganic 50/organic 50 had total equivalency values of 86 and 82 kg N/ha, respectively. Inorganic 0/organic 100 had the lowest total N equivalency of 41 kg N/ha. The percent fertilizer N utilization values were 3.90% for inorganic 100, 6.27% for inorganic 25/organic 75, 4.0% for inorganic 75/organic 25 and 4.73% for inorganic 50/organic 50 kg N/ha (Table 35). The grey leaf spot and late planting could have contributed to the low yields and low fertilizer utilization values.

The N recovered from the residues were 16%, 11%, and 12% from inorganic 25/organic 75, inorganic 75/organic 25 and inorganic 50/organic 50 kg N/ha, respectively. These results indicate that 1 kg of urea supplies an equivalent amount of N as 14.5, 6.1, and 2.2 kg of residue at inorganic 75/organic 25, inorganic 50/organic 50 and inorganic 25/organic 75 kg N/ha, respectively. Under the current experimental conditions, the best combination was inorganic 25/organic 75 kg N/ha.

There were no significant differences in soil pH, P, K, Ca, Mg, CEC, total N, and organic carbon in all the treatments after experimentation. The rates used in this experiment were probably too low to influence changes in the levels of these parameters in the soil in the first season.

Effect of Timing of Application of Sesbania Sesban Prunings on Maize Yields

When crop residues are added to the soil as an organic source of nutrients, the nutrients may be lost because they may not be available for plant uptake. This is especially so for

Table 35. Percent N Utilization and Percent Residue N Recovered From the Plots Labeled With ^{15}N as Influenced by a Combination of Organic and Inorganic N

Inorganic	Organic	N[a]	^{15}N Atom Excess	Fertilizer N Utilization	Residue N Recovered	Residue Equivalent to 1 kg of Urea
- - - - (kg N/ha) - - - -		- - - - - - - - - - - - - - - (%)	- - - - - - - - - - - - - -			(kg)
100	0	1.11[b]	0.283	3.90a		
25	75	1.32	0.289	6.27a	16.16	2.2
75	25	1.11	0.221	4.00a	10.78	14.5
50	50	1.23	0.234	4.73a	12.17	6.1
LSD (0.05)				4.17		
CV, %				44.2		

a. Means of 4 values.
b. Means in each column followed by the same letter do not differ significantly (LSD = 0.05).

nitrogen which can be lost due to leaching and volatilization or denitrification. There is need, therefore, to synchronize nutrient availability with plant demand. One way of achieving this is to regulate the timing at which the organic material is added to the soil to maximize the nutrient use efficiency. The objective of this research project was to determine the effect of timing of application of sesbania sesban prunings on crop yields.

An equivalent of 100 kg N/ha was applied to plots with half (i.e., 50 kg N/ha) from sesbania sesban and the remainder as urea. No N fertilizer was applied in the control. Sesbania sesban was applied and incorporated either at planting, 1 week after planting (1 WAP), 2 WAP, or 3 WAP. Urea (50 kg N/ha) was applied to the plots 9 WAP. One of the treatments was 100 kg N/ha. Maize was the test crop. The experiment was replicated four times in a randomized complete block design.

The influence of the treatment effect on maize dry-matter and grain yield is shown in Table 36. Late application of OM produced more biomass but did not translate into more grain yield.

There were no significant differences in the dry-matter and grain yield between treatments except the control. The practical implication of this is that farmers have a choice as to when to apply the prunings, either at planting, 1, 2, or 3 WAP without fear of loss of yields. Farmers can time application of such high-quality organic resources when there is no critical demand for labor.

FARMER PARTICIPATORY TRIALS

These trials were meant to involve farmers in testing technologies jointly proposed as solutions to problems identified in the on-farm diagnostic surveys. They were targeted specifically at IFAD-supported rural development projects although they were also implemented at other sites. The first year of the project (1997/98) was very hectic and saw the establishment of farmer participatory trials in Zambia and Zimbabwe as part of action plans developed by the implementing partners. However, these efforts were hampered and progress slowed down in Zambia in 1998/99 due to operational problems and loss of key manpower within the implementing agencies. Trials are only being resuscitated now in Southern Zambia. The report will largely focus on the work in Zimbabwe.

In Zimbabwe, farmer participatory research trials were conducted in Chivi, Mangwende, and Shurugwi communal areas. The trials focused on use of organic and inorganic plant nutrient sources and manure from improved storage systems. The approach to farmer participatory research and to solving soil fertility constraints explicitly recognized that local knowledge provides the basis for problem-solving strategies for local

Table 36. Dry-Matter and Maize Grain Yield as Influenced by Time of Residue Application

Treatments	Dry Matter (Stover) Yield[a]	Grain
	- - - - - - - - - - - - - (kg/ha)	- - - - - - - - - - - -
3 WAP	3,840.3a[b]	3,179.8a
2 WAP	3,588.3a	3,528.6a
1 WAP	3,186.7ab	3,571.4a
At planting	3,549.7a	3,413.5a
100 kg N ha^{-1}	3,471.3a	3,683.3a
0 kg N ha^{-1}	2,212.6b	1,703.9b
LSD (0.05)	1,179.2	589.6
CV, %	23.6	12.3

a. Means of 4 values.
b. Means in each column followed by the same letter do not differ significantly (LSD = 0.05).

communities especially the poor. It is therefore essential to identify through technical and social analysis current practices and to assess their effectiveness, functionality and transferability relative to externally derived improved technologies. Technologies were tested in both farmer-led and researcher-designed experiments. Meetings were regularly held to facilitate exchange of knowledge between farmers and researchers and, in particular, build research capacity among farmers and farmer groups to share knowledge.

The aim of the on-farm farmer research activities was to demonstrate positive impact through participatory research. We consider impact to be significant if in the process innovative technologies are developed and the farmers have acquired additional research skills. This has important implications in encouraging farmer-led experimentation and suggests that research methods need to be developed that combine finding out about complex and dynamic situations with taking action to improve them in such a way that the actors and beneficiaries of the action research are intimately involved as participants in the whole process.

Impact can also be achieved through scaling up of the results from farmer participatory experiments. The main avenue through which this is achieved and which we have actively explored is encouraging group activities, field days, farmer-to-farmer visits, and field tours for farmers. At least 19 farmer groups were involved in the work on manure management in Chivi, Mangwende and Shurugwi. There were 9 groups in Mangwende, 6 groups in Chivi, and 4 groups in Shurugwi. Some of the results obtained from the farmer participatory trials are presented in Figures 21-24 and Table 37.

Preliminary Results of a Survey on the Adoption of Improved Manure Storage Systems, December 1999

The survey was conducted in five villages in Murewa randomly chosen to represent a cross-section of the study sites and zone of influence. One hundred households were interviewed using a structured questionnaire to determine the manure storage systems that the farmers were using and whether these practices have been influenced by the project in any way. Preliminary results are presented from only one village outside the villages in which trials were conducted by the project. The village, Muchagoneyi, is located about 10 km away from the nearest village in which on-farm trials on pit-stored manure were conducted.

Labor Availability

More than 90% of the households indicated that they have never hired any labor in the management and application of manure in the fields. This is surprising because farmers have commonly cited labor shortages as a constraint in the use of manure. Each household had on average three adults working full time on the farm. From the results there are indications that labor is not so much a constraint though it is necessary to see if this can be substantiated with the full sample results.

Management of Manure in the Kraal

Most farmers add grass and crop residues to the kraal as a way of managing their manure. Manure is removed from the kraal during the dry season from June to August each year. Manure is removed within that period because there will not be any competing labor demands as it will be in the off-season. More labor will be available from school children on holiday in August. Addition of crop residues and grass is done to increase manure quantities. This gives an indication that manure quantities are limited and farmers are doing much to increase quantities.

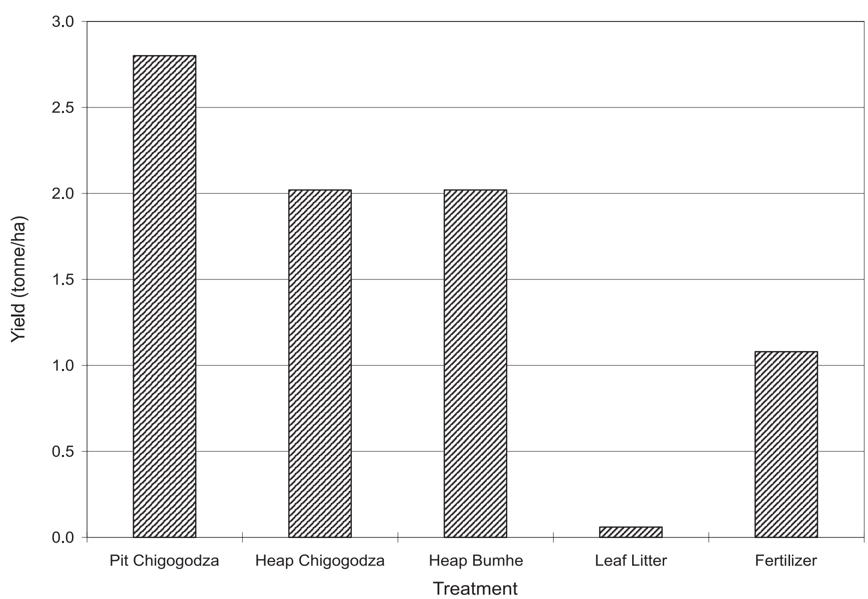


Figure 21. Effect of Manure Storage on Maize Yield (Site: Matemadombo Bumhe; Svinurai I Group).

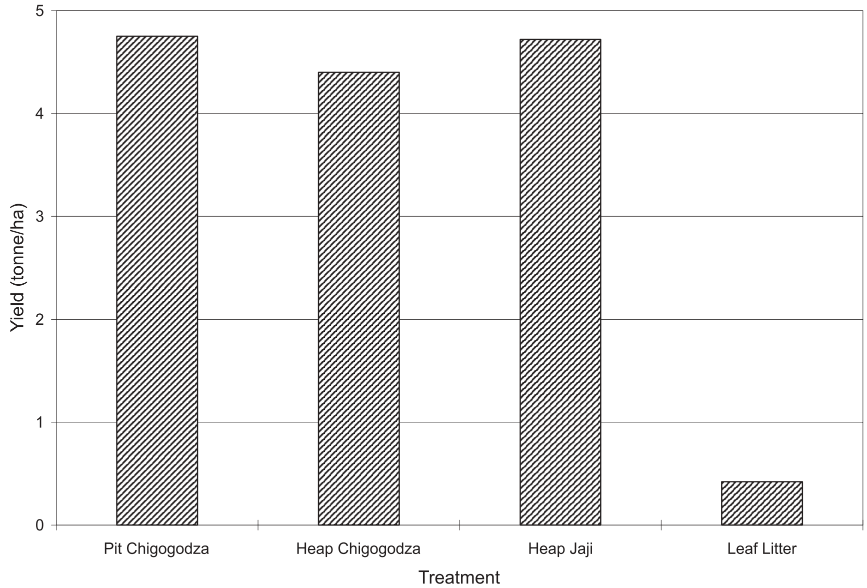


Figure 22. Effect of Manure Storage on Maize Yield (Site: Gezi Jaji; Svinurai II Group, Mangwende).

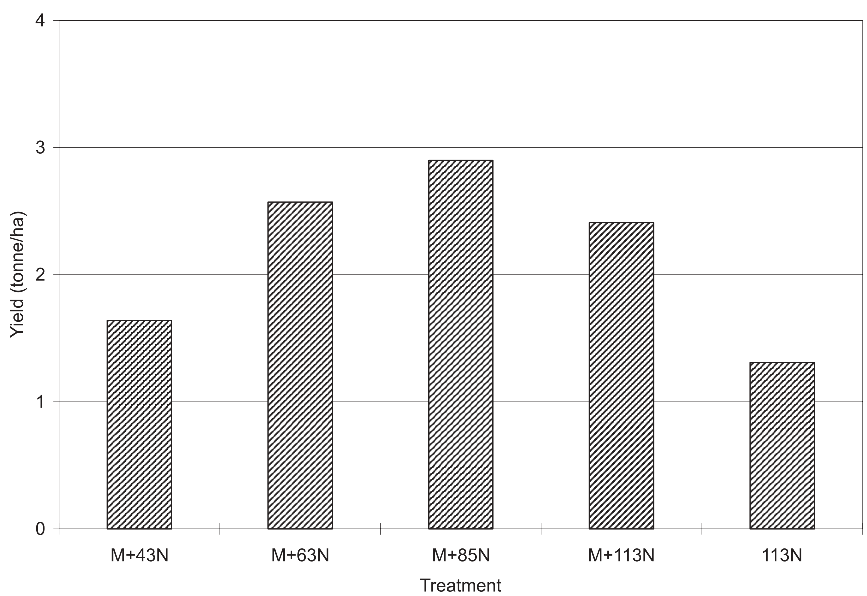


Figure 23. Effect of Manure (M) and Fertilizer N Combination on Maize Yield (Site: Matemadombo Bumhe; Svinurai I Group, Mangwende).

Manure Storage Systems

More than 80% of the farmers still store their manure on the heap outside the kraal. These farmers do not do anything to increase the quality of their manure. About 12% of farmers have adopted pit storing of manure as a way of improving manure quality. However, the village covered in the survey to date is far away from villages in which trials were done on the effectiveness of pit-stored manure. The adoption rate for the technology is likely to be more than 25% if all areas are covered. Farmers who have adopted it have made no modifications to the technology. This is a testimony of how effective the technology is, given the fact that the project only worked with a handful of farmers in testing the technology and for only 2 years.

Some 8% of farmers add inorganic fertilizer, compound D, and ammonium nitrate to the manure in an effort to increase the quality of available manure. Addition of crop residues and grass is also viewed by some farmers as a way of increasing manure quality and increasing the quantity of manure. Another farmer indicated that he controls runoff from the kraal to reduce the amount of nutrients leached away by rainfall.

Indicators of Manure Quality

The following indicators were given by farmers as indicators of good quality manure:

- No sand or soil in the manure.
- No sign of undecomposed crop residues.
- No sign of undecomposed grass.
- Complete breakdown of grass and residues.
- Brownish color.
- Dark color.
- Smaller particles almost like powder.
- Time manure spends in the kraal before removal, at least 2 years.
- A white mold.

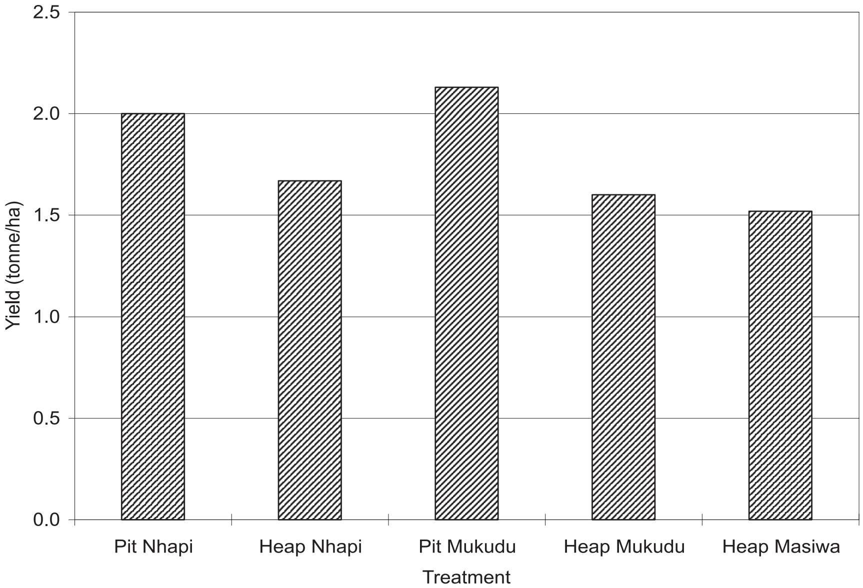


Figure 24. Effect of Manure Storage on Maize Yield (Site: Masiwa, Mangwende).

Table 37. Results From Farmer Participatory Research Using Improved Manures in Shurugwi (1998/99)

	Yield				
Type of Manure	Farmer Group 1	Farmer Group 2	Farmer Group 3	Farmer Group 4	Farmer Group 5
			(kg/ha)		
Nhapi heap	2,895	2,595	2,700	1,000	1,250
Nhapi pit	5,185	5,185	4,900	1,750	2,250
Mukudu heap	2,985	2,750	2,850	500	900
Mukudu pit	5,445	5,185	5,000	1,500	1,900
Farmer's manure banded	4,550	4,435	4,250	1,550	1,700
Farmer's manure broadcast	4,065	4,065	3,600	1,150	1,350
Fertilizer	2,595	3,248	2,650	1,200	1,450
Zero	2,965	3,335	2,750	400	600

The quality indicators seem to vary from one farmer to the other and from one village to the other. Once the survey is completed it will be important to determine how these indicators compare with laboratory indices on manure quality and also to link manure quality perceptions to use strategies.

Information on Manure

About 12% of the farmers who have adopted pit storage as a technology to improve the quality of manure received the information about the technology from research institutions working in the area, primarily the project and its partners in the Department of Research and Specialist Services, Zimbabwe. Extension was also cited as a potential source of information on manure storage systems. With the full sample it will be possible to clearly identify channels of information (farmer groups, extension, field days, mobile farmer training schools) that could be used to promote the technology.

The sample covered thus far is too small to generate substantive conclusions on the adoption rate of pit-stored manure technology. Most of the findings on manure management from the survey confirm the results that were obtained in several surveys that have been conducted in Murewa to date.

EVALUATING THE LONG TERM EFFECTS OF TILLAGE AND NUTRIENT MANAGEMENT ON SOIL ORGANIC MATTER FRACTIONS

One of the key goals of the project was to develop technology options for sustainable land management. Assessing sustainability requires studies of long-term impacts of technologies on key soil parameters for soil fertility improvement such as SOM. Since SOM plays an important role in determining the fertility and productivity of soils, it is necessary to understand more clearly the factors which control SOM dynamics as affected by land use management practices. The ability to quantitatively estimate SOM fractions is important for understanding SOM dynamics in intensively managed agricultural systems. SOM can be separated into a number of fractions based on their rate of turnover, each of which is differentially responsive to management practices.

Several chemical and physical methods have been developed to separate SOM fractions. Chemical separation methods have not proven to be particularly useful in following dynamics of organic matter in soils while physical fractionation yields functional SOM pools that differ in composition and biological function. SOM can be separated based on size and/or density of the fractions.

The effectiveness of soil dispersion is crucial for physical fractionation. Limited dispersion of soil may result in the recovery of the most easily dispersed part of the fraction, or the recovered fraction may consist of an unknown mixture of primary particles and microaggregates of the same size but belonging to different size classes.

In an attempt to follow SOM dynamics, measurements were carried out in some established long-term field experiments to determine the effects of tillage on SOM on a sandy soil in Domboshawa and on a red clayey soil at the Institute of Agricultural Engineering (IAE) in Hatcliffe Harare, Zimbabwe. Before following the dynamics of SOM in these soils, initial studies were conducted to test and establish methods for the fractionation of SOM. The methods tested are based on similar principles, but the dispersing agents used differed. The degree of dispersion of aggregates was used as the criterion to choose one method.

An experiment was established to assess the effectiveness of soil dispersion by using two dispersants, sodium resin bags and sodium hexametaphosphate (HMP). Two concentrations of sodium HMP were used. We hypothesized that higher dispersion would be achieved with the use of sodium resin bags than with sodium HMP while increasing the concentration of sodium HMP would increase the degree of dispersion.

Soil samples were collected from long-term tillage experiments in Zimbabwe at Domboshawa (a sandy soil) and Hatcliffe (a red clayey soil), both of which are close to Harare. The long-term experiments were established in 1988/89 on plots of 30 x 10-m planed at 4.5%. There are three treatment blocks consisting of six plots each with main treatments being randomly selected.

The treatments at Domboshawa are as follows:

- Rip-between-row into residues (tine into residues)—mulch ripping.
- Rip-between-row without residues (tine into bare soil)—clean ripping.
- Conventional annual ox plowing (single-furrow moldboard plow and spike harrow).
- No-till tied ridging (permanent crop ridges at 1 in 100 grades).
- Badza holing out without residues-hand hoeing.
- Bare fallow (tractor disc plow and disc harrow).

The treatments at IAE Hatcliffe are as follows:

- Rip-between-row into residues (tine into residues)—mulch ripping.
- Rip-between-row without residues (tine into bare soil)—clean ripping.
- Conventional annual ox plowing (single-furrow moldboard plow and spike harrow).
- No-till tied ridging (permanent crop ridges at 1 in 100 grades).
- Strip cropping

In all the treatments, except for the bare fallow, fertilizer is added at the rate of 150-200 kg ammonium nitrate and 300 kg compound D, and maize was planted continuously.

Treatments that were expected to yield the largest contrast were chosen. These are mulch ripping, conventional tillage, tied ridging, and clean ripping. Two dispersing agents were used to shake 50 g of soil in 200 mL water overnight (16 hours) before size separation of SOM. Dispersion was done in sodium HMP at two concentrations, 0.5% and 2%, and sodium resin bags, regenerated in 3M trisodium citrate. After shaking, the soil was wet sieved through two sieves, 212 and 53 µm to obtain three size fractions. For soil shaken in sodium resin bags, the fraction collected on the 53 µm sieve was shaken by hand for 1 hour in resin beads to allow for further disruption of aggregates. For the fractions collected on the 212-µm and 53-µm sieves, organic matter was separated from the mineral fractions by flotation in water. The mineral and organic fractions were allowed to dry in the oven at 55°C and weighed. The fractions were viewed under a binocular microscope to check for purity of the fractions and degree of dispersion of aggregates.

T-tests for paired observations using GENSTAT 5 Release 4.1 were done to test for differences in using the different dispersing agents.

For the sandy soil complete dispersion of aggregates was achieved for all dispersing agents used, and there were no significant differences for the amounts of fractions separated using the different dispersing agents except for the coarse OM fractions separated using resin bags. The use of the resin bags resulted in reduced recovery of the OM.

For the clayey soil all the dispersing agents used did not achieve complete dispersion. The use of resin bags increased dispersion of aggregates but reduced the amount of coarse OM recovered (Table 38). There were no significant differences in the amounts of fractions dispersed in 0.5% and 2% HMP. There were significant differences in the mineral fractions after soaking the soil for dispersions using 2% HMP, with soaking giving lower amounts of the mineral fraction with fewer aggregates than without soaking, but there were no significant differences for the organic matter fractions. There were significant differences in amounts of fractions dispersed in 2% HMP and resin bags with HMP giving higher amounts of the coarser fractions than resin bags (Table 38).

Although the use of resin bags led to an increase in the dispersion of aggregates, it also led to a significant decrease in the amount of OM recovered. The use of resin bags could have caused further breakdown of the coarse OM or solubilization of the OM. The material used to make the resin bags had a mesh size of about 150 µm so that some material could have them trapped inside the bags and was difficult to wash out, resulting in erroneous results and a reduc-

Table 38. A Comparison of Two Dispersing Agents on Soil Dispersion (2% Sodium Hexametaphosphate [HMP] Resin Bags)

	Weight of Size Fraction (g/50 g soil)									
	212-2000 µm OM		212-2000 µm Mineral		53-212 µm OM		53-212 µm Mineral		0-53 µm Mixed	
Conventional	HMP	Resin	HMP	Resin	HMP	Resin	HMP	Resin	HMP	Resin
Red Clayey										
Mulch	0.18	0.06	2.06	2.07	1.25	0.39	1.61	2.51	44.84	45.48
Ripping	0.15	0.06	1.89	1.71	0.94	0.26	2.07	3.12	44.74	44.86
Conventional	0.31	0.13	1.76	1.80	1.14	0.58	2.60	2.71	44.40	44.80
Tied ridging	0.15	0.06	1.93	1.96	0.89	0.33	2.32	3.52	44.11	44.20
Clean										
Ripping										
Sandy										
Mulch rip	0.18	0.07	29.69	23.81	0.21	0.23	11.08	13.01	8.80	12.88
Conventional	0.08	0.04	32.35	23.09	0.08	0.06	10.65	13.12	6.88	8.69
Tied ridging	0.20	0.07	30.80	27.34	0.08	0.12	10.20	11.90	8.59	10.58
Clean rip	0.16	0.05	29.57	22.87	0.11	0.11	12.43	13.80	7.74	13.12

tion in the effectiveness of the regeneration of the resin bags.

Soaking the soil before shaking led to an increase in the dispersion of aggregates. Soaking did not affect the coarse OM fraction as it is not found in close association with the soil and, hence, is easy to disperse. There was a decrease in the amount of the coarse mineral fraction after soaking the soil because more aggregates were disrupted as the bonds in the aggregates were weakened. The larger amounts of the mineral fractions that were obtained after dispersion without soaking was due to the inclusion of aggregates, many aggregate classes have the same size range as sand (0.05-2 mm). Increased dispersion after soaking led to an increase in the amount of the fraction less than 53 µm as the finer fractions that make up the aggregates were dispersed.

There was a slight but not significant increase in dispersion caused by increasing the concentration of the hexametaphosphate from 0.5 to 2%, suggesting that more effective dispersion might be achieved at higher concentrations of the salt. However, it is difficult to dissolve the hexametaphosphate, making it difficult to produce higher concentrations. In addition, the salt interacts with the fractions during mineralization, reducing the feasibility of using higher concentrations if incubation studies are to follow.

The reduced amount of coarse OM after using resin bags might have been a result of purer fractions being obtained. To determine if the reduction in the amount of OM recovered was a result of an increase in the purity of the OM fraction, we analyzed some of the fractions for organic carbon using an elemental analyzer.

Results in Table 39 suggest that the use of resin bags resulted in breakdown of OM into finer fractions, because there was more organic matter in the finer fractions separated using resin bags as compared to the HMP. For the clayey soil, the difference is not clearly seen for these fractions since their totals are almost the same for the two dispersing agents. How-

Table 39. A Comparison of Carbon Content in Fractions Obtained After Using Two Dispersing Agents

Sample Organic Matter for Tied Ridging		Mass of Fraction in 50 g Soil		% C in Fraction		% C in Fraction to Total C	
Tillage Practice	Total C	Resin	HMP	Resin	HMP	Resin	HMP
Red Clayey							
212-2000 µm	2.044	0.31		0.057	0.149	7.29	
53-212 µm	2.044	0.94		0.255	0.158	7.73	
Sandy							
212-2000 µm	0.477	0.20		0.028	0.980	20.55	
53-212 µm	0.477	0.12	0.08	0.081	0.045	16.98	9.43

ever the number of samples analyzed was small so that they cannot be used to make any inferences, thus, there is need to analyze more samples for organic carbon. There was a greater percentage of the organic carbon as a fraction to total organic carbon in the coarse OM fraction for the sandy soil than the clayey soil although the clayey soil had higher carbon contents (Table 39).

For the red clayey soil, clean ripping and conventional tillage had significantly lower amounts of very coarse organic matter fraction than mulch ripping and tied ridging, which were statistically different in their amounts in organic matter (Table 40). With finer fractions conventional tillage had the lowest amount of organic matter followed by clean ripping compared with mulch ripping whereas tied ridging had the largest amounts. Total organic carbon followed the same trend.

For the sandy soil bare fallow had the lowest amount of OM for all the fraction sizes (Table 41) and also had the lowest organic carbon content. Mulch tillage had the highest amount of OM in most of the size fractions and soil organic carbon followed by hand hoeing. Tied ridging, clean ripping, and conventional tillage had 0.48%, 0.46%, and 0.42% organic carbon, respectively, and almost the same pattern was followed by the amounts of OM in the size fractions.

Table 40. A Comparison of Tillage Effects on the Amount of Organic Matter on a Red Clayey Soil

Tillage Practice	Total Organic Carbon, %	Weight of Organic Matter Fraction (g/50 g soil) 212-2000 μm	53-212 μm	20-53 μm
Clean ripping	1.68	0.134a	0.262ab	0.449b
Conventional tillage	1.49	0.139a	0.182a	0.273a
Mulch ripping	1.72	0.174b	0.317b	0.509bc
Tied ridging	2.-4	0.304c	0.614c	0.568c
LSD		*0.027*	*0.114*	*0.106*

NB Values in the same column followed by the same letter are not significantly different.

Table 41. A Comparison of Tillage Effects on the Amount of Organic Matter on a Sandy Soil

Tillage Practice	Total Organic Carbon, %	Weight of Organic Matter Fraction (g/50 g soil) 212-2000 μm	53-212 μm	20-53 μm
Bare fallow	0.22	0.016a	0.030a	0.029a
Clean ripping	0.46	0.148c	0.113d	0.128cd
Conventional tillage	0.42	0.077b	0.074b	0.085b
Hand hoeing	0.60	0.234d	0.105cd	0.154d
Mulch ripping	0.68	0.170c	0.213e	0.158d
Tied ridging	0.48	0.189cd	0.077bc	0.106bc
LSD		*0.050*	*0.030*	*0.050*

NB Values in the same column followed by the same letter are not significantly different.

Most of the OM is associated with the finer fraction for the red clayey soil, whereas for the sandy soil the greater percentage of OM is associated with the coarser mineral particles. This can be explained by the higher amount of clay in the red clayey soil, which promotes OM protection within and between organo-mineral complexes. There is more OM buildup for the red clayey soil than for the sandy soil. The red clayey soil has high clay content (>30%) and contains iron oxides that protect OM from microbial decomposition hence promoting OM accumulation. This is unlike the sandy soil that has very low clay content (<6%) providing less protection of OM from microbial attack.

High amounts of OM accumulation with mulch ripping can be explained by residues left on the surface to enrich the soil and reduced tilling of the soil whereas with clean ripping residues are removed from the surface. Conventional tillage results in the mixing of upper and lower horizons of the soil profile and disrupts aggregates, thereby enhancing OM decomposition thus lowering OM content. Bare fallow is the most destructive of the tillage practices because it involves plowing the soil without planting any crop, thus exposing the soil to erosion.

Tied ridging had the highest amount of OM for the red clayey soil (Table 40) whereas mulch ripping had higher OM levels than tied ridging for the sandy soil (Table 41). From these results it can be concluded that tied ridging promotes high OM accumulation for the red clayey soil whereas mulch ridging would be the most appropriate practice for the sandy soil. However there is need to analyze the fractions for organic carbon and nitrogen to have an understanding of how they are distributed in the size fractions for the different tillage practices. There is also need to relate the size fractions to their functional roles, especially nutrient availability. The results reported are only preliminary since some of the work is ongoing. The work includes experiments designed to measure the effect of organic-inorganic input combinations and the quality of manure added on SOM and N fractions in sandy soils.

Tillage Effects on Soil Organic Matter Fractions Down the Profile of a Red Clayey Soil

Highest amounts of organic C and total N were observed for the weedy fallow followed by mulch ripping, and conventional tillage had the least amounts (Figure 25). This was because under the weedy fallow there is no loss of nutrients from the system because no crops are planted and hence no tillage. Under mulch ripping there was reduced tillage, and residues were left on the surface, whereas with conventional tillage there is maximum tillage with removal of residues from the surface.

Soil organic C % and total N decreased with depth for mulch ripping and weedy fallow which was mainly pronounced in the surface horizons (0-10 cm) (Figure 25). Weedy fallow and mulch tillage had higher C and N contents in the upper 20 cm depth than conventional tillage. This was probably due to faster decomposition and loss of SOM under conventional tillage enhanced by tillage and removal of residues. Mulch tillage on the other hand results in higher OM inputs and reduced tillage resulting in higher OM buildup and retention. Below the 20 cm there is little or no mixing of soil even for conventional tillage and, hence, there were no treatment differences beyond this depth. The C/N ratio did not change with depth for the treatments because as C content decreased down the profile, so did N altering the C/N ratio.

Conventional tillage resulted in a more or less uniform distribution of N among size fractions down the profile, especially in the sand size fractions (Figure 26a). This was because conventional tillage results in the mixing of upper and lower horizon soils. For mulch ripping there was an increase in total N in the clay size fractions going down the profile in the upper 30 cm followed by a decline in the depths below (Figure 26b). There was, however, a gradual decline in total N in the sand size fractions down the profile. Due to high organic inputs on the surface for the weedy fallow, there was high N contents in the surface horizon (0-2 cm) even in the sand size fractions (Figure 26c).

Nitrogen in the size fractions declined with depth for the weedy fallow with a more pronounced decline in the sand size fractions than in the silt and clay size fractions (Figure 26c). For all the treatments there were high amounts of N in the clay size fraction (0-2 μm) followed by the silt size (2-20 μm). The sand size fractions had significantly lower amounts of N than the silt and the clay size fractions (Figure 26). There was however no significant differences of N in the sand size fractions.

The results clearly showed that conventional tillage results in the faster decomposition and loss of OM than mulch ripping. Mulch ripping promotes physical protection and SOM accumulation in the plow layer compared with conventional tillage. Implications for future work are that soil fertility cannot be managed in

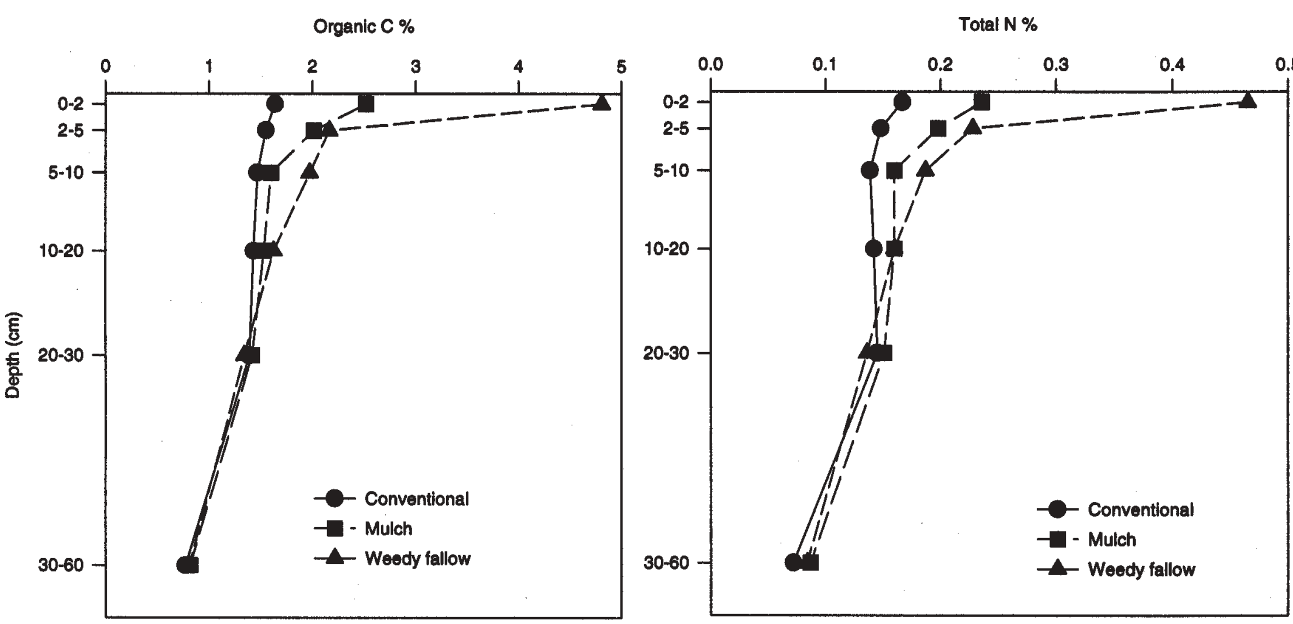


Figure 25. Tillage Effects on Organic C (a) and N (b) Distribution Down the Profile.

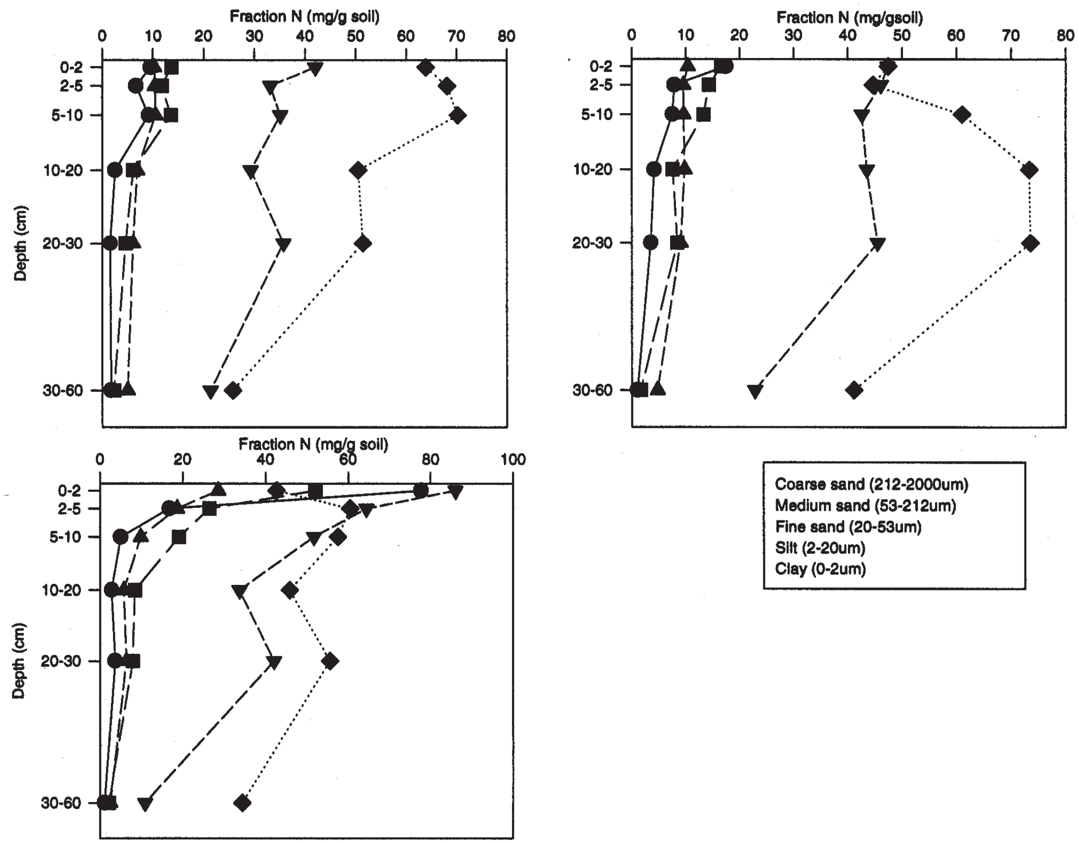


Figure 26. Effects of (a) Conventional Tillage, (b) Mulch Ripping, (c) Weedy Fallow, on the Distribution of N in Size Fractions Down the Profile of a Red Clayey Soil From Harare, Zimbabwe.

isolation of tillage practices. Farmers should move away from using tillage practices that do not build on soil fertility.

CONCLUSIONS FROM ON-FARM TRIALS

The main conclusions from the work on improving farmers' management of nutrient flows on-farm especially quality and effectiveness of manure were that:

- Pit storage of manure without residues gives better quality manure (total N) and higher yields than the conventional heaping system practiced by farmers.
- Storage of manure in pits should be in July and for not more than 3 months.
- Yields from pit-stored manure are higher than heaped manure in the first season but subsequent benefits are lower than from heaps. Total yield benefits over two seasons (including residual effects) are higher from pit than heaped manure.
- On the basis of these results and from Figure 26, a preliminary decision tree was developed (Figure 27) and is being tested with farmers as a management tool for manure use. The decision tree includes a link to a database listing manure with a wide range of quality characteristics.

Economic analysis of the OM management technologies developed in this study still needs to be done. The economic analysis should consider farmers' evaluation of organic resources and the criteria they use, in addition returns to labor and the value of the residual nutrient stocks in the experimental plots.

The work on combining organic and inorganic plant nutrient sources showed that N content, C/N ratio, and ash content in manure can be used as indices of the N fertilizer equivalency values. For most low N content manures the fertilizer equivalencies ranged between 10% and 35%. For the manures that had positive fertilizer values, no inorganic N fertilizer was required for them to mineralize N. For the manures, the amount of N required to overcome these negative effects, was as high as 100 kg N in some instances and less in others. Combining manure with inorganic N resulted in increased yield production relative to the individual application of either manure or inorganic N. However, at some sites, high-quality manure could be used in a substitutive manner with inorganic nitrogen. Combinations had better residual effects than indi-

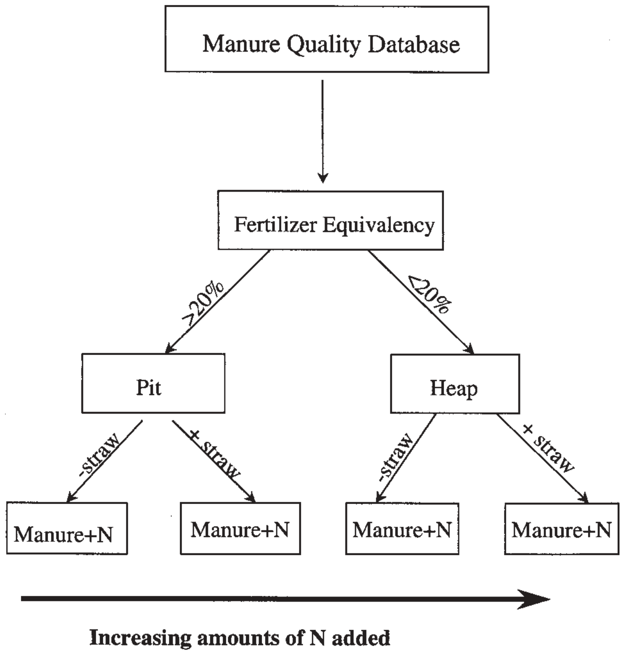


Figure 27. Decision Tree on the Use of Manure From Different Storage Systems.

vidual sources. Combinations of manure and N fertilizer had higher N use efficiency than the sole manure and inorganic N.

IMPLICATIONS FOR IFAD DEVELOPMENT PROJECTS

The project in Southern Africa focused on the processes that regulate nutrient availability and how they can be manipulated so as to optimize management of organic and inorganic plant nutrient sources. Advantages of such an approach were that it was possible to demonstrate the inter-relationships between organic resource quality and nutrient availability (e.g., pit vs. heaped manure) in both the short and long term. Linking process-level understanding with farmers' practice became key to linking 'science' with application at the farm level. This formed the basis of scaling up the adoption of successful technologies that have also been evaluated by farmers (Figure 28).

The results presented clearly show that there are potential benefits that can be obtained on-farm by utilizing the technologies that were tested. The technologies tested were not by themselves the complete panacea but added to the menu of options that are already available for dissemination. The project therefore made a deliberate attempt to disseminate the technologies in IFAD-supported rural development projects. Focus was both on the transfer of knowledge and of the technologies with an emphasis on the former. This is evidenced by the decision trees developed for use of manure of differing quality. These decision trees are not "recipes for action but sets of options which farmers can validate to suit their own individual circumstances."

There are obvious direct implications for IFAD-supported rural development projects of the approaches

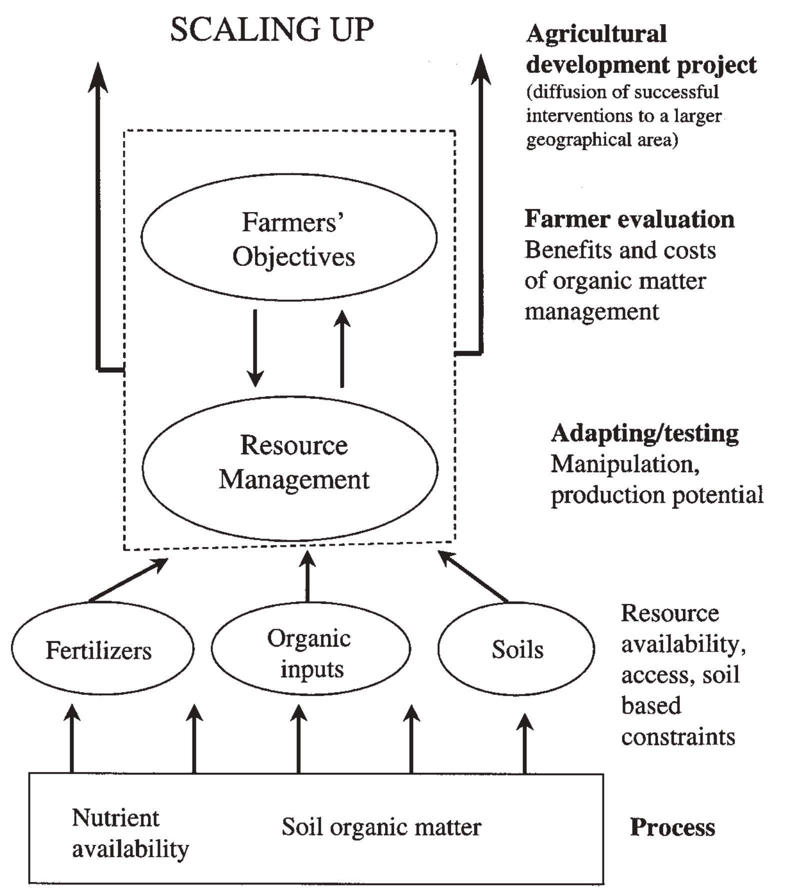


Figure 28. Linking Research Results Into the Development Process.

taken by the project. First, the need to understand local circumstances (constraints and opportunities) (Figure 28) and the knowledge/information gap should be recognized. Second, there is need to develop the necessary generic tools that can be used as a basis for dissemination of information/technologies.

The current status of soil fertility management on smallholder rural farms is still far from what would be desirable for sustainable agriculture. One of the underlying reasons for this scenario is that there has generally been a lack of intervention to the farming systems as far as soil management and indeed other aspects of agriculture are concerned. This was revealed particularly in the surveys in southern Zambia. Thus, there is a very large knowledge gap in most rural areas.

This scenario calls for systematic intervention. Interventions can be in the form of on-farm demonstrations of proven technologies such as green manures, logical rotations, contour ridges, and hedges against soil erosion. They can also be in the form of on-farm tests of technologies such as improved fallows that have been successful especially in the Eastern province of Zambia. Southern province lies in the same agroecological zone as Eastern province, and these technologies are likely to succeed in the Southern province also. In addition, there must be concerted efforts built up to enhance delivery of soil maintenance information to the rural farming communities through the extension services. The study sites could benefit from the production of a comprehensive manual for extension workers and farmers on soil fertility maintenance.

The removal of fertilizer subsidies upon the implementation of the SAPs has brought untold misery to farmers who cannot easily afford fertilizers anymore. Maize production has declined and, since it is the staple food, many households have become more food insecure. The liberalized market system has brought further misery in that supply and distribution of fertilizer has become haphazard. This is more so for outlying areas. This calls for innovative approaches to solving the problem of soil fertility decline.

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