Decision Support Tools for Smallholder Agriculture in Sub-Saharan Africa

T.E. Struif Bontkes and
M.C.S. Wopereis (editors)

Decision Support Tools for
Smallholder Agriculture in Sub-Saharan Africa
A Practical Guide

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Foreword

Agriculture remains the key to Africa's economic future. With approximately 200 million people chronically hungry, advances in African agricultural research and development (R&D) are urgently needed. This will require considerable investments and increased efficiency and effectiveness of agricultural R&D. Access to information and communication technology (ICT) is rapidly increasing in many African countries and provides tremendous opportunities to accelerate their economic growth and development through the enhanced efficiency and effectiveness of R&D.

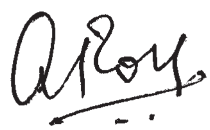
This trend offers scope for the use of decision support tools (DSTs) that can improve the efficiency and effectiveness of agricultural R&D in Africa. Such tools can, in principle, assist with the diagnosis of problems and opportunities in agricultural systems, the identification of options for alternative management, the analysis of experiments, and the diffusion of promising technologies/approaches. The use of DSTs to advance smallholder agriculture in these countries faces a number of specific constraints, however. These include lack of exposure of the development staff to DSTs, the complexity of African farming systems, and the lack of reliable data.

The COSTBOX project, financed by the Ecoregional Fund to Support Methodological Initiatives and carried out by IFDC and partner institutions in West Africa, was established to investigate opportunities for the use of DSTs in smallholder agriculture in sub-Saharan Africa with special reference to soil management issues. The COSTBOX experience shows that there is considerable interest among research and extension staff in Africa in applying these tools but also that access to appropriate tools, reliable data, and training in the application of such tools is essential.

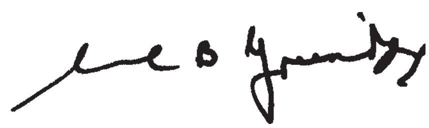
This guide provides a number of case studies that illustrate how combinations of DSTs can be used to address a specific situation.

Some case studies also show how the use of DSTs can be combined with farmer participatory learning and action research. The case studies served to develop a framework that will guide the user to decide what tool(s) to use in a particular stage of agricultural R&D.

We hope that this guide will contribute to increased knowledge and use of DSTs in sub-Saharan Africa leading to the increased efficiency and effectiveness of agricultural research and development in the region in general.



Amit H. Roy
President and CEO
IFDC



Carl B. Greenidge
Director
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Message from the Ecoregional Fund

African smallholder farmers are operating in a highly variable and complex environment; soil fertility levels may show considerable variations over short distances, and rainfall patterns are irregular. Blanket recommendations regarding fertilizer applications, choice of variety, sowing date, etc., are, therefore, unlikely to be effective. On the other hand, the cost and time required for the development of site-specific recommendations are prohibitive. In such situations, the use of generic decision support tools (DSTs) may allow cost and time savings and improve the quality of decision-making for the smallholder farmers.

Nevertheless, DSTs in research and extension are still rarely used in sub-Saharan agriculture. An important reason for this is that many research projects focus on the introduction of one single tool, whereas a systems approach is clearly needed to cover the diverse and sometimes contrasting demands of the farmer. Another problem is the limited availability and access to data that are required as inputs for the DSTs.

In 1999 the Africa Division of an International Center for Soil Fertility and Agricultural Development (IFDC) started to develop, evaluate, and promote a set of DSTs for soil fertility management in smallholder farming systems in sub-Saharan Africa. These efforts were implemented through a project entitled "A Client-Oriented Systems Toolbox for Technology Transfer Related to Soil Fertility Improvement and Sustainable Agriculture in West Africa (COSTBOX)," financed by the Ecoregional Fund to Support Methodological Initiatives and carried out in collaboration with a number of national agricultural research institutes and universities in West Africa. To promote the use of DSTs, the project organized several train-

ing courses and workshops at national research institutes and agricultural universities in Ghana, Benin, Togo, and Nigeria. Researchers applied the DSTs to problems and areas of interest to farmers in these countries. The number of DSTs gradually expanded because some problems could not be tackled by one particular DST alone. Contacts were, therefore, established with other groups that are developing and introducing DSTs in sub-Saharan Africa, thus contributing to learning experiences in a network context.

The present guide has been developed to provide potential users with a practical overview of existing DSTs and their applications. The guide includes a number of case studies with special reference to integrated soil fertility management (ISFM). In addition, a general overview is provided of the various stages in agricultural decision-making whereby, for each stage, tools are identified that can be used in that particular stage. Information is provided about ways to obtain each tool.

I consider this book to be an accessible and valuable guide that promotes the use of DSTs. I sincerely hope that it will increase the use of these tools and contribute to an accelerated and sustainable development of the agricultural sector in sub-Saharan Africa and the improvement of the well-being of farmer families in the region.

Prof. Dr. Johan Bouma
Chairman
International Scientific Advisory
Committee of the Ecoregional Fund
to Support Methodological Initiatives

Contents

Chapter 1

Opportunities for the Use of Decision Support Tools for Smallholder Agriculture in Sub-Saharan Africa

T.E. Struif Bontkes[1] and M.C.S. Wopereis[1]

Introduction

Africa's basic industry is agriculture, providing about 35% of the gross national product (GNP), 40% of exports, and 70% of employment. Given its size, agriculture should be the engine of economic growth. Nevertheless, living conditions are desperately poor; about 240 million citizens live on less than US $1 a day, primarily as smallholder farmers. This situation tends to be further aggravated by the fact that population growth is about 3% per year and exceeds growth in food production.[2]

Smallholder farmers in sub-Saharan Africa are facing difficult times as a result of production levels that are often far below what would be possible under improved circumstances. They are strongly dependent on, and constrained by, what is often one of their most important assets—soil fertility. Soil fertility, defined as a mixture of soil chemical, physical, and biological factors that affect land potential, is inherently low in sub-Saharan Africa. Furthermore, the often unfavorable climate and low soil fertility create intense pressure on land even at relatively low population densities (Breman, 1995). This situation leads to rapidly degrading soils in large parts of sub-Saharan Africa. Sanchez et al. (1997) stated, for instance, that, "soil fertility depletion in

1. IFDC–Africa Division, BP 4483, Lomé, Togo.
2. http://www.worldbank.org/afr/overview.htm

smallholder farms is the fundamental biophysical cause of declining per capita food production in sub-Saharan Africa."

Therefore, soil fertility management always needs to play a central role in interventions aimed at improving agricultural productivity. Options to improve soil fertility management should rely on soil nutrient-supplying capacity, available soil amendments, and judicious use of mineral fertilizers to achieve balanced nutrient-management systems. Such an approach is usually referred to as Integrated Soil Fertility Management (ISFM) and should be embedded in a framework that includes aspects such as: weather, the presence of weeds, pests and diseases, crop management, and socio-economic aspects such as input and output prices and labor availability.

It is important to consider the diversity and dynamics of farmer reality (Scoones, 2001). The diversity of farmer reality implies that solutions need to be site-specific, which requires much emphasis on farmer experimentation, participatory learning, and building of partnerships between soil fertility management stakeholders (farmers, credit providers, input dealers, research and extension agencies, and government) at the village, regional, and national levels. The dynamic environment in which the farmer operates implies that effective solutions of the past may not work in the present situation.

Under such conditions the traditional prescriptive approach does not work and needs to be replaced by an ability to analyze and understand the situation and to offer alternative options to solve problems or exploit opportunities in a sustainable manner (Bouma and Jones, 2001).

This situation calls for tools that can support decision making in smallholder agriculture in sub-Saharan Africa. Such decision support tools (DSTs) can assist with the diagnosis and analysis of problems and opportunities related to soil fertility and identify options for improved ISFM. Several DSTs have been developed over the past decade; they range from sophisticated computer models to simple tables that help provide answers to questions such as "What are best-bet options related to cultivar choice and use of mineral fertilizer for late sowing of maize during the main rainy season on a degraded sandy soil?" DSTs are very useful in developing site-specific ISFM recommendations that are flexible and respond to the diversity and dynamics of farmer reality. They are, therefore, very suitable to be used in participatory development and dissemination of ISFM options. In reality, however, DSTs are not widely used in sub-Saharan Africa.

Struif Bontkes et al. (2001), Matthews and Stephens (2002), and Walker (2000) summarized constraints to a widespread use of DSTs in agricultural research and development as follows:

1. DSTs often fail to capture sufficiently the complexity of smallholder agriculture of sub-Saharan Africa.
2. Some DSTs require much data that are often not available or are of poor quality.
3. Lack of knowledge to use DSTs has prevented widespread use.
4. Institutions promoting the use of DSTs in sub-Saharan Africa often emphasize the use of one particular tool. Nevertheless, the complexity and diversity in smallholder agriculture call for a more flexible, problem-oriented approach that requires a set of DSTs from which one or a combination of tools can be selected that can successfully address the problem.
5. The problem is not the handling of the tool but rather the whole process of problem identification, identification of the appropriate tool(s), data collection, application of the tool, and drawing conclusions from the results pertaining to the solution of the problem.

The objective of this guide is to help overcome some of these constraints, and in particular constraints 3 and 4 and to some extent constraint 5 by offering an overview of a variety of tools illustrated by a number of case studies.

In this chapter an overview of a number of DSTs is presented that can be used within the context of a participatory technology development approach to ISFM—an iterative learning cycle from diagnosis/analysis of the production environment, identification of ISFM options, experimentation and evaluation, to diffusion of successful technologies. Data requirements and potential users are briefly discussed with more details on the specificity of the tools in the appendixes. It should be noted that, although it is attempted to present a wide variety of DSTs, the list of tools discussed here is by no means exhaustive. The DSTs presented here are oriented toward improved understanding of biophysical processes and interactions between soil, climate, and animal and plant production systems. Some also allow the evaluation of the economic returns and the risks related to the options proposed. They, however, mainly deal with nutrient aspects of soil fertility and primarily ignore physical and biological aspects of ISFM. These non-nutritional effects are especially important when using organic amendments and, in combination with inorganic fertilizer use, they may lead to important gains in fertilizer use efficiency. Such synergies are not yet captured sufficiently in the DSTs that are available to date, and this is an important gap in our understanding of the potential of ISFM options in sub-Saharan Africa.

The case study chapters, which follow, demonstrate how these tools are used in practice and will show that they can be used at various spatial (farm, village, region) and temporal scales (days, growing season, years). The concluding chapter reflects on the links between the different case studies and how to promote the use of the tools.

Using Decision Support Tools Along the Research to Development Continuum

DSTs can be distinguished according to category or to the type of decision to be made. Some decision tools are very simple to use and require a very limited amount of data, whereas others are more complex and can only be used by trained researchers. The nature of the DSTs used in this guide cover the following categories:

- Decision trees that use rules of thumb or quantitative information that can be obtained from databases.
- Databases providing important information for decision making. Such databases may be separate, such as the ORD (Organic Resource Database) or the PRDSS (Phosphate Rock Decision Support System) or integrated in another tool; many tools have a database. In some cases these data, such as soil data, are geo-referenced.
- Cropping calendars that advise time of planting, fertilizer application, etc.
- Nutrient flow diagrams, showing the flows of the various nutrients, biomass, products, and money between different production units and entering/leaving the farm, such as NUTMON (Nutrient Monitoring Approach) or RFM (Resource Flow Mapping).
- Tools that help in quantifying, calculating, and visualizing these flows (NUTMON or ResourceKIT).
- Tools to calculate optimal fertilizer doses/ratios, e.g., NuMaSS (Nutrient Management Support System) or QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils).
- Dynamic models that mimic an important aspect of an agricultural system (e.g., a model that simulates the development of soil carbon over a number of years: the Rothamsted Carbon [RothC] model).
- Dynamic models that mimic the most important processes related to crop growth such as DSSAT (Decision-Support Sys-

tem for Agrotechnology Transfer), COTONS (a Windows-based model for simulation and growth development of cotton), APSIM (Agricultural Production Systems Simulator), and RIDEV (a model for Rice Development).

- Tools that relate climate and soil hydraulic properties to field-level water balance, and water balance to crop performance based on the SARRA (System for Regional Analysis of Agro-Climatic Risks) model.
- Tools that allow estimation of data required by the more sophisticated tools with more easily measurable parameters. This includes functions that use information on soil texture (easily measurable) to obtain estimates of soil hydraulic properties (e.g., SOILPAR). Such functions are usually referred to as "pedotransfer functions."

Table 1 provides an overview of the DSTs and their nature.

Decision making in agriculture can be categorized in different ways; for instance, decision making related to the time frame of the decision—short-term (when to apply fertilizer), medium-term (choice of crop variety), or long-term (decision to start agro-forestry).

In this chapter an overview of a number of DSTs will be provided related to the stage of the decision making process along the research to development continuum. Five phases are distinguished:

- **Strategic Site Selection Phase**—In this phase, zones are identified that are suitable for a particular technology; e.g., a zone that is suitable to promote the cultivation of cotton. Such zones should satisfy a number of criteria.
- **Diagnosis/Analysis Phase**—In this phase, problems are identified and analyzed. For example, actual production levels may be far below what is expected, given soil and weather conditions (observation), and this is caused by nutrient leakages in the system (analysis).

Table 1. Decision Support Tools (DSTs) Used in This Guide and Their Level of Complexity (for each DST, relevant case study chapters, and appendixes are indicated)

Decision Support Tool	Type / Complexity	Case Study Chapter	Appendix
Soil maps	Database / simple	2, 6	
Cropping calendars	Calendar / simple	7, 8	
RFM	Nutrient flow diagram / simple	2	5
ResourceKIT	Quantification of nutrient flows / medium	2	6
DST Legumes	Decision tree / simple		15
ORD	Database / simple		12
QUEFTS	Optimal fertilizer doses / medium	5	1
NUTMON	Quantification of nutrient flows / medium	3	7
NuMaSS	Optimal fertilizer doses, database / medium	4	9
PRDSS	Database / simple		11
RIDEV	Dynamic rice model / medium	8	10
DSSAT	Dynamic crop growth model / complex	7	2
APSIM	Dynamic crop growth model / complex	6	3
COTONS	Dynamic crop growth model / complex		8
RothC	Dynamic carbon model / medium	10	4
SOILPAR	Pedotransfer functions / complex		13
Soil-Water characteristics	Pedotransfer functions / simple		14
SARRA	Dynamic water balance model / medium	9	16

- **Options Identification Phase**—Options for improvement are identified and compared, and ex-ante evaluations are conducted (including financial consequences and risk analysis). For example, "What is the maize yield response to alternative soil fertility management options?" or "What is the risk related to a particular choice of maize cultivar x fertilizer dose x sowing period combination?"
- **Evaluation Phase**—In this phase, results obtained in the field are evaluated and interpreted. This phase can also be used to evaluate and improve the tool itself.
- **Technology Diffusion Phase**—When several viable technologies have been developed for a particular set of conditions, it is necessary to explore the likelihood of success of a technology for a different set of conditions by matching the "technology profile" with environmental characteristics of those conditions.

Below, the use of DSTs for each phase is explained in more detail.

Strategic Site Selection Phase

Careful selection of intervention zones and key sites is a prerequisite for successful technology development and diffusion. DSTs may play a role in this phase as exploratory tools, especially if combined with a Geographic Information System (GIS). Depending on the objectives, intervention zones may need to satisfy criteria pertaining to, e.g., population density, soil fertility, weather, and distances to markets and yield gaps (differences between actual yields and potential yields given soil and weather conditions). A GIS allows combining these different layers and selecting regions that satisfy all or most of the selection criteria, e.g., all areas with total rainfall between 900 and 1,100 mm, a soil depth of at least 0.6 m, and distance to the nearest town with more than 25,000 inhabitants not exceeding 15 km. To calculate yield gaps, the GIS may be combined with a crop growth simulation model. This combination permits the estimation of irrigated or rainfed potential yields for any site x sowing date x cultivar combination with varied historical weather data, and the comparison of simulated potential yields with actual farmer yields to indicate range for improvement. An example of the combined use of GIS and a crop growth simulation model (DSSAT) for an exploratory study is given in Chapter 7.

Besides the outcome of DSTs, many other factors will influence strategic site selection, such as the presence of information and communication networks, and the opportunity for partnership building between agricultural development stakeholders, etc.

Diagnosis/Analysis Phase

Problem Identification and Awareness Creation—Once key sites have been identified, the first step at the community level will be to develop a common understanding of the local landscape; i.e., how it has been transformed over time and how this has affected soil fertility. Farmers may be asked what changes have occurred over the past 10-20 years, whether there are differences between farmers or between different parts of the village territory or with other villages they know.

In this guide, ISFM is our focal point but many issues are related to that. The implication is that one should enter the farmer discussions with a broad view. To capture the interest of the farmers, it is important to encourage them to discuss their problems related to agricultural production. The discussion should go beyond direct causes of low soil productivity because there may be other constraints that prevent them from taking appropriate actions to overcome those problems. At this stage it is useful to ask farmers to draw a map of their village territory and indicate different soil types, water availability, crops grown, and road infrastructure. Transect walks can greatly facilitate this process and can also be used to diagnose the problems.

A village map can become an important information and communication tool in discussions with farmers. This approach is part of several DSTs discussed in this guide, such as NUTMON and RFM. Farmers should be encouraged to estimate the suitability of each soil type for different crops. It is important at this stage to analyze what indicators farmers use for soil fertility. This may include color and texture of the soil, nutrient deficiency symptoms, and the growth of certain weed species when fallow. NuMaSS is a useful tool to help diagnose nutrient deficiency symptoms in a large number of crops.

Analysis of Yield Gaps—Farmers often achieve far less than 50% of the climatic and genetic yield potential for a given sowing date, cultivar choice, and site. Figure 1 illustrates factors that define yield gaps at different levels. The potential yield or maximum yield (Y_{max}) is limited by climate and crop cultivar only; all other factors are optimal. Under irrigated conditions water is assumed to be plentiful, but under rainfed conditions this assumption is often not true. Y_{max} is not constant but fluctuates from year to year and with sowing date because of climatic variability. The

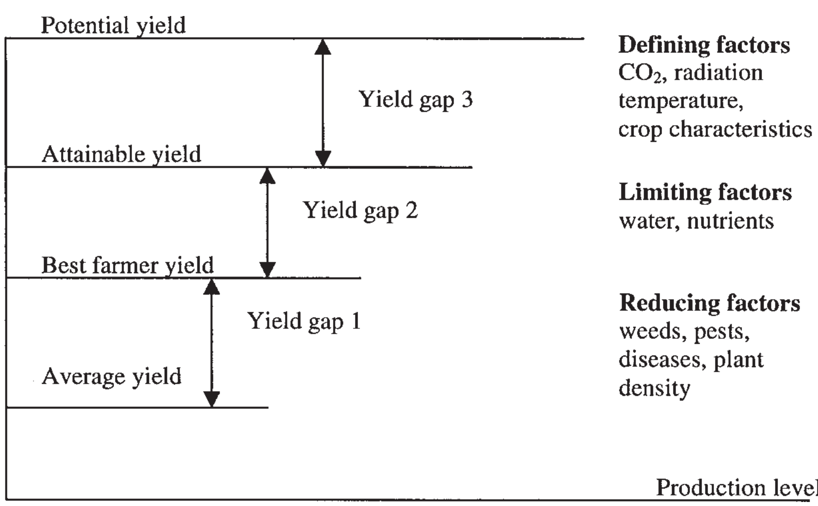

Figure 1. Effect of Crop Management on Potential or Maximum Yield, Attainable Yield, Best Farmer Yield, and Actual Average Farmer Yield

attainable yield (Y_a) is the "nutrient-limited" yield that farmers can achieve with current soil fertility management practices but with optimal water and crop management. The maximum Y_a is often about 80% of Y_{max}. This is often referred to as the economic yield target (Y_{target}) because it is often not economical to close the remaining gap of about 20% of Y_{max} (Fairhurst and Witt, 2002). In reality, actual farmer yields (Y_f) are much lower because of a range of constraints to crop growth, including weed pressure, pests and diseases, sub-optimal soil fertility, and water management practices.

A first approach to understand causes of low yields is to compare average yields in the village with the yields the best farmers obtain. Discussions with farmers may give hints about what "best farmers" do differently. This approach will help to identify the causes of the differences, e.g., weeds, pests, or diseases (reducing factors), and will also provide the scope for short-term improvement (yield gap 1 = best farmer yield – average yield).

Simulation models (DSSAT, APSIM, COTONS, SARRA) can be applied to determine the attainable yield ceiling under given growth conditions (yield gap 2 = attainable yield ceiling – best farmer yield). This ceiling is limited by nutrients and/or water (the limiting factors). Finally, these models can also be used to determine potential yield; i.e., when sufficient water and nutrients are available. It should be realized that these yield gaps give indications about what is agronomically possible, not what would be economically optimal.

Crop growth simulation models may also be helpful to analyze farmer management practices and identify areas for improvement.

When analyzing growth-reducing and limiting factors, soil fertility will often be one of them. It should be realized, however, that crop growth in farmers' fields may also suffer from other factors, such as drought or excessive flooding or from incidence of pests, diseases, and weeds. Current management practices may prevent the farmer from obtaining better yields, such as choice of variety, plant population, sowing date, and the type of fertilizer applied. In the latter case, crop response to fertilizer application may be disappointing due to the fact that the type of fertilizer applied does not match the requirements of the soil; e.g., crops grown on soils that are low in potassium (K) will not respond to large doses of nitrogen (N) or phosphorus (P).

Several tools exist to better understand nutrient limitations. QUEFTS is a simple tool to analyze the effectiveness of the N, P, and K ratios used when applying mineral fertilizers; it requires a limited number of soil fertility parameters. NuMaSS can help to diagnose soil fertility problems related to N, P, and soil acidity. Although NuMaSS requires more data than QUEFTS, it includes an extensive database, including pictures of crops suffering from nutritional disorders, nutrient contents of crops, and soil data.

Crop response to phosphate rock (PR) can be analyzed for different soil types and crops with the PRDSS. PRDSS is a database that includes a large number of PR types from within sub-Saharan Africa and allows matching these types with a particular combination of soil, climate, and crop. PRDSS estimates P uptake from PR in the first year and compares the outcome with P uptake from mineral fertilizer, e.g., triple superphosphate (TSP).

A poor response to fertilizer may also be due to other causes, such as shallow soil depth, the production potential of the crop/variety, weed competition, or the wrong combination of planting date and variety. Crop simulation tools such as DSSAT, APSIM, COTONS, SARRA, or RIDEV are particularly helpful for this type of analysis.

Labor shortages may seriously reduce yields, because they may delay sowing, weeding, or harvesting. The extent to which timeliness of operations is the cause of low productivity can be determined by comparing actual cropping calendars of farmers with optimal cropping calendars derived with crop simulation tools.

An interesting way to understand the role of soil fertility management is to map resource flows and analyze the nutrient flows. Soil fertility management implies transport and transformation of nutrients. Farmers transport material that contains nutrients in the form of harvested products, manure, fertilizer, or straw used for thatching roofs. Some processes may lead to a loss of nutrients; e.g., burning of straw will result in an almost complete loss of carbon and nitrogen. It is important to realize that such analyses try to model a complex reality and should, therefore, be used with care. Boundaries of the farming system that are analyzed and boundaries of its subsystems (e.g., rice production system, vegetable production system, animal production system, and household system) should be clearly defined. A first qualitative DST that can be used is RFM. Farmers are asked to indicate flows of material entering and leaving their fields or their farm as a whole. Such an analysis may give first indications of soil fertility management practices that are unbalanced; i.e., nutrients are leaving the field, but no nutrients are added.

To compare flows, there is a need to express them in the same unit; e.g., kilograms (kg) of N, P, or K. This means that one needs to know the concentration of N in, e.g., manure, millet grains, and millet straw, etc., and the amount of dry matter (at 0% moisture) that is produced, transformed, or transported. NUTMON and ResourceKIT may be used to help quantify the resource flows at the field and farm level. One of the problems in quantifying these flows is often the lack of data on nutrient contents. NUTMON includes databases not only on nutrient contents of crops, manures, etc., but also it provides estimates of the production of animal manure, household waste, human excreta, and feed intake of the animals. NUTMON also permits quantifying flows that are invisible to the farmers such as volatilization and leaching of N.

Table 2 gives an overview of DSTs that can be employed during this diagnostic phase of the participatory technology development cycle. Such tools are usually re-employed during the identification of options addressing the problem and/or opportunities identified during this phase.

Options Identification Phase

At the end of the diagnostic phase, a number of problem or opportunity areas will have been identified. The next challenge is to identify potential solutions that may help to solve the problem or exploit the opportunity. The search for such ISFM options may include the use of DSTs. Nevertheless, it should be stressed here that as people discuss the results of the diagnostic studies, options certainly will already become apparent. Field visits among participating farmers and to other areas may also be organized. Researchers and extension personnel may contribute to these discussions through the use of a number of qualitative and quantitative DSTs. This may help to screen the options generated and retain the most promising ones for further testing. It may be useful to develop a list of criteria that should be satisfied for the solution of the problem. This action may help to avoid only including aspects that can be addressed by the DST, as other aspects may be more important bottlenecks.

Options related to ISFM can be grouped as follows:

- Adding organic or inorganic fertilizer.
- Better management of available resources.
- Improving external input use efficiency.

Adding Organic or Inorganic Fertilizer—One of the options is to focus on building nutrient capital in the long term through fallowing, application of organic resources, or application of one-time high doses of inorganic P or PR.

Table 2. DSTs for the Diagnostic Phase of Participatory Technology Development

Goal	Tools	Data Requirements	Potential Users
Common understanding of the landscape	Discussions with farmers (current land use and history) Transect walks	Very limited	Farmers, extension, research
Spatial variability in soil fertility	Transect walks Mapping (soils, land suitability) Pictures (nutrient deficiency symptoms)	Very limited	Farmers, extension, research
Identification of yield gaps	Comparing yields among farmers and fields	Very limited	Farmers, extension, research
	DSSAT, APSIM, COTONS, SARRA	High	Research
Identification of factors limiting or reducing crop growth	Cropping calendars, field observations, yield records	Limited	Farmers, extension, research
	QUEFTS, NuMaSS, PRDSS	Medium	Research
	DSSAT, APSIM, COTONS, RIDEV, SARRA	High	Research
Identification of leaks, losses, untapped resources	RFM	Limited	Farmers, extension, research
	NUTMON, ResourceKIT	Medium	Research

Management of organic resources to improve soil-organic matter requires a long-term view. The RothC model has been developed to estimate the effect of organic amendments on different types of soil-organic carbon over a longer time frame. To be able to differentiate between the decomposability of organic amendments, the Organic Resource Database (ORD) may be useful. ORD provides data on N, lignin, and polyphenol content of organic resources. High quality materials (high N, low lignin, low polyphenol) release a large proportion of N very rapidly in advance of the main period of N-uptake by the crop and contribute little to soil organic matter buildup. In principle, they are a good substitute for mineral fertilizers; however, large quantities will still be required because of the relatively low N content (rarely above 4%). Materials of lower quality (high lignin or high polyphenol) release a smaller total proportion of their N at a low continuous rate and contribute more to soil organic matter buildup. Such materials can be used as mulch for erosion control and to conserve water or be mixed with fertilizer or added to compost. ORD provides average N, P, lignin, and polyphenol contents of a large range of organic resources.

APSIM and the newest version of DSSAT (Gijsman et al., 2002) allow simulating the buildup of organic matter over a longer period as a function of organic resources management. The buildup of P stocks in the soil proves to be difficult to simulate although developers of the APSIM and DSSAT models are currently attempting to incorporate this process. Although PR is usually applied to build up P stocks in the soil, the present version of the PRDSS does not calculate residual effects of PR application on P soil reserves.

In addition to building soil nutrient capital, fertilizers are used to achieve short-term gains; e.g., higher yields. Balanced nutrient management strategies require that nutrients recovered from mineral fertilizer application and nutrients supplied by the soil match crop requirements. QUEFTS and NuMaSS can be used to determine balanced fertilizer strategies: QUEFTS for N, P, and K and NuMaSS for N, P, and lime. QUEFTS takes interactions between N, P, and K into account and allows determination of optimal N, P, and K ratios. The dynamic crop simulation models presented in this guide can only handle N-limiting growth environments, while assuming that P and K are in ample supply.

Combined use of organic and inorganic fertilizers may result in synergistic effects and increased fertilizer use efficiency. For example, green manures or crop residues may serve as mulch to suppress weeds and may greatly improve soil-water availability in the root zone. Increases in soil-organic matter content improve soil structure, cation exchange capacity (CEC), pH, and water-holding capacity. However, this type of interaction is hardly captured in DSTs available to date.

Crop rotation may also contribute to soil fertility improvement such as the rotation of cereals with legumes. A decision support tool for the use of legumes has been developed to estimate the feasibility of their use.

Better Management of Available Resources—Resource flow diagrams may be helpful to identify resources that are not used in the best possible way but that are not lost from the system. An example would be the potential to use human excreta deposited in latrine pits or composting of organic residues available on the farm. The ORD decision support tool may be used to identify organic resources most suitable for composting or direct application as mulch or nutrient provider. Some organic resources that have high decomposition rates should mainly be considered as suppliers of nutrients; the slow decomposers can be used for the buildup of soil organic matter. ORD provides information on different types of organic resources and best use in terms of ISFM.

Increasing External Input Use Efficiency—Nitrogen and phosphorus are nutrients that limit crop growth more frequently in sub-Saharan Africa. N is highly dynamic and will be easily lost from the system. Crops may not immediately take up P, but it will rarely be lost from the root zone. Nevertheless, some soils may fix large amounts of P resulting in largely unavailable P stocks in the soil.

Increasing input use efficiency in terms of nutrients is, therefore, especially important for N. Two factors are very important—the recovery of applied N in the crop, and the use of plant N to produce harvestable dry matter; i.e., the physiological N use efficiency. The product of N recovery (ΔN uptake by the crop / kg N applied) and the physiological N use efficiency (Δ yield / ΔN uptake by the crop) is the agronomic efficiency (Δ yield / kg N applied).

N recovery may be enhanced through improved crop management and crop choice. Synchronization of plant demand for nutrients and fertilizer application may greatly enhance recovery. DSSAT, APSIM, COTONS, and RIDEV may help identify optimal intervals for fertilizer application as a function of cultivar choice and sowing date.

Local varieties may perform better without inputs than improved varieties although improved varieties perform better in a favorable environment with inputs. Similarly sowing time and sowing density affect yield potential and hence fertilizer requirement. Crop growth simulation models may be used to determine yield potential and corresponding nutrient demand of the cultivar.

Weeds, pests, and diseases may constitute bottlenecks, and it may be better to spend the available money on weeding or prevention of pests and diseases than on fertilizer. Some DSTs such as APSIM include the effect of weed competition on crop growth, and APSIM may be used to set threshold dates for weeding. Frequent field observations, discussions among farmers, and placing the timing of farmer management interventions on a cropping calendar will, however, usually be the best way to identify important growth-reducing factors and alternative management strategies.

Profitability and Risk Analyses—Risk is a very important factor for farmers. Farmers who are prone to risk will not be ready to make investments in external inputs, other than those that will reduce such risks. APSIM, DSSAT, RIDEV, SARRA, and COTONS can be used to assess the risk due to climate variability of sowing date, fertilizer applications, plant densities, introduction of new crops and varieties, etc. Profitability of a crop is, however, also influenced by other factors, such as input and output prices, marketability of the product, storage facilities, value of secondary products, labor requirement, labor availability, and wages. The socioeconomic/institutional environment may be important as well—taxation, access to credit, access to input (and output) markets, land ownership (farmers who do not own the land they cultivate may be reluctant to invest in soil fertility), and poverty level of the farmer (poor farmers are likely to be more averse to risk than rich farmers). Such factors are, however, not dealt with in the DSTs presented in this guide.

Table 3 gives an overview of the DSTs that can be used in the identification of ISFM options as outlined above.

Evaluation Phase

After ISFM options have been identified, DSTs are useful to help narrow down the range of feasible solutions for further on-farm or on-station testing. The role of models is much smaller during this phase since models are rarely sufficiently reliable to replace practical testing. DSTs can be used, however, to evaluate and interpret experimental results; e.g., to estimate the effect of erratic rainfall during the growing season on crop growth and establishment (e.g., with DSSAT, COTONS, SARRA, or APSIM). Experimental results can also be used to improve DSTs if key observations that allow validating and improving (parts of) the tool have been made during the growing season.

Table 3. DSTs Especially Useful During the Identification of Suitable ISFM Options

Identification of ISFM Options			Time Span
Adding organic or inorganic fertilizer	Better management of available resources	Improving external input use efficiency	
QUEFTS NuMaSS		QUEFTS NuMaSS	Medium term
	RFM, NUTMON		Medium term
PRDSS			Medium to long term
ORD	ORD		Medium to long term
RIDEV, DSSAT, APSIM, COTONS		RIDEV, DSSAT, APSIM, COTONS	Variable
RothC			Long term
DST Legumes			Medium term

Technology Diffusion Phase

Technologies that show good promise may be considered for large-scale diffusion. During this phase, DSTs in combination with GIS may again be used as exploratory tools; the requirements of the technology are matched with environmental characteristics of target regions to get a first indication of the likelihood of success of the technology. For example, the analysis of the requirements of a technology may indicate that the technology works well on poor soils, in a climate with a bi-modal rainfall distribution, with relatively low population pressure, and where external input use is minimal because of a large distance to input markets. Combining the appropriate DST with geo-referenced data on soils, climate, population density, and road and market infrastructure in a GIS may help to identify extrapolation domains where the technology may show a plausible promise of being adopted.

Using the Tools

Who are the users of these tools? The tools are meant to help improve the lives of the smallholder farmer and his/her family in sub-Saharan Africa. The direct users, however, are likely to be scientists and for the simpler tools—planners and extension staff. DSTs should, therefore, be used in close interaction with the target population to ensure their relevancy.

It is important to review the following points when selecting DSTs to address a given constraint or opportunity:

- Does the tool address the question? All tools are specialized; thus, it is necessary to select the right tool (or combination of tools). This requires a proper definition of the question and the prospective user of the tool.
- Is the tool (and the necessary equipment to use it) available? Some tools can be obtained free of charge or can be downloaded immediately from the Internet, whereas others have to be purchased.
- What does it take to be able to use the tool? Some tools are very simple but others are difficult to use without formal training or access to an Internet help site.
- What are the (minimum) data requirements of the tool and are these data available? Data requirement constitutes an important bottleneck for the use of tools, even for the simplest tool.

Use of DSTs in sub-Saharan Africa is far from common practice. This is partly due to the fact that few African scientists have been exposed to them. But there is also the problem of tools not being tuned to the problem at hand and the lack of reliable data. This is a serious limitation for the application of the more sophisticated tools. This implies that efforts should continue to: (1) expose agricultural scientists to the use of DSTs, (2) integrate systems analysis and modeling in university curricula, (3) develop geo-referenced soil and weather databases, and (4) validate and fine tune DSTs to most important agro-ecological regions. Such efforts are already underway in various countries, and an increasing number of scientists are becoming enthusiastic about using such tools.

Nevertheless, in view of the existing limitations, DSTs should be used with caution and are only a support to, not a replacement for, sound decision making. DSTs are, for example, usually quite good in the ranking of options but not in predicting the actual performance of such options.

As discussed, DSTs can play an important role all along the research to development continuum for agriculture in sub-Saharan Africa. If DSTs are actively used, experimental data will certainly be more purposefully collected and analyzed, which will help reduce research costs. DSTs are particularly useful in discovering inconsistencies in datasets. And finally, the more DSTs are used, the more frequent the opportunity to improve them.

References

Bouma, J., and J. W. Jones. 2001. "An International Collaborative Network for Agricultural Systems Applications—ICASA," *Agricultural Systems,* 70:355-368.

Breman, H. 1995. "Sustainable Agriculture in the Sahel? (Integrated Farming, Perennials and Fertilizers)," IN *Eco-Regional Approaches for Sustainable Land Use and Food Production*, pp. 213-235, J. Bouma et al. (Eds.), Kluwer Academic Publishers, Netherlands.

Fairhurst, T., and C. Witt. 2002. *Rice: A Practical Guide to Nutrient Management,* Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC), and the International Rice Research Institute (IRRI), 89 p. + Appendixes.

Gijsman, A. J., G. Hoogenboom, W. J. Parton, and P. C. Kerridge. 2002. "Modifying DSSAT Crop Models for Low-Input Agricultural Systems Using a Soil Organic Matter-Residue Module from Century," *Agronomy Journal,* 94:462-474.

Matthews, R. B., and W. Stephens (Eds.). 2002. *Crop-Soil Simulation Models: Applications in Developing Countries*, Cranfield University, United Kingdom, 304 p.

Sanchez, P. A., K. D. Shepherd, M. J. Soule, F. M. Place, R. J. Buresh, A. N. Izac, A. U. Mokwunye, F. R. Kwesiga, C. G. Ndiritu, and P. L. Woomer. 1997. "Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital," IN *Replenishing Soil Fertility in Africa,* R. Buresh et al. (Eds.), Soil Sci. Soc. Am., Madison, Wisconsin.

Scoones, I. 2001. *Dynamics and Diversity. Soil Fertility and Farming Livelihoods in Africa*, Earthscan Publications Ltd., London and Sterling, Virginia, 244 p.

Struif Bontkes, T.E., U. Singh, and V. Chude. 2001. "Problems and Opportunities in Adopting System Tools for Decision-Making Related to Soil Fertility Improvement in Africa," Paper presented at the 2001 Integrated Natural Resource Management (INRM) Workshop, Cali, Colombia.

Walker, D. H. 2000. "Decision Support, Learning and Rural Resource Management," *Agricultural Systems,* 73:113-127.

Chapter 2

Assessing Changes in Soil Fertility Management in Southern Mali Using Resource Flow Mapping and ResourceKIT[1]

T. Defoer[2]

More information on Resource Flow Mapping and ResourceKIT can be found in Appendixes 5 and 6

Introduction

Farming systems of southern Mali are traditionally based on cereal crops, such as sorghum, millet and maize, used as staple food. Later on, cotton was introduced and became the most important cash crop, grown in rotation with cereals; minor crops are cowpea and groundnut. With growing population pressure, land is increasingly permanently cropped. Mineral and organic fertilizer use on cotton is widespread but less common for cereals, which suffer from a poorly developed marketing system and relatively low returns.

A large part of the income from cotton is invested in livestock, especially in cattle that constitute the core of the southern Malian livestock system. Cattle graze during the day and return in the

1. This case is a revised version of a case study made by Defoer, T., Kanté, S., and Sanogo, J. L. (2000). *Cotton Farming in Southern Mali*. IN: A. Budelman and T. Defoer (Eds.). *PLAR and Resource Flow Analysis in Practice*: Case Studies From Benin, Ethiopia, Kenya, Mali, and Tanzania; IN: T. Defoer and A. Budelman (Eds.). *Managing Soil Fertility in the Tropics: A Resource Guide for Participatory Learning and Action Research*. Amsterdam, Netherlands: Royal Tropical Institute.
2. WARDA, The Africa Rice Center, BP 320, Bamako, Mali.

evening to the "kraal" near the homestead. During the cropping season, cattle mainly graze on fallow land. Shortly after harvesting, cattle are allowed to graze the crop residues left in the fields. During the dry season, cattle mainly graze on common pastures. Cattle manure produced in the kraal constitutes an increasingly important source of organic fertilizer.

It has been widely reported that soil fertility in southern Mali is at risk and diagnostic studies indicate that low productivity threatens the sustainability of agricultural development in the region. One of the main factors contributing to the decline in soil fertility is the depletion of the soil's nutrient reserves, a process known as soil nutrient mining. The overall nutrient balances for southern Mali as a whole are negative, especially for nitrogen (N) and potassium (K) (Pieri, 1989; Stoorvogel and Smaling, 1990; van der Pol, 1992).

Without denying the seriousness of soil mining in southern Mali, the story is much more complex. Farming systems and soil fertility management practices in the area show a great degree of heterogeneity and complexity due to a wide range of socio-economic conditions and differences in access to resources. There is also considerable environmental variation because soils tend to differ in quality from one place to another. This implies that the farmer has to deal with multiple stocks, sources, and flows of nutrients of different natures and origins. As a result, patterns of soil fertility can vary considerably in space, and soil nutrient balances will vary between farms and fields (Scoones and Toulmin, 1999; Scoones, 2001).

Such variability and complexity have important consequences for agricultural research and development services. Farmers should not only be seen as end-users of new technologies that are developed by researchers and promoted by extension workers. Farmers need to play an active role in the process of fine-tuning and adapting practices and methods to the specific conditions in which they have to produce to ensure their livelihoods. Moreover, as farmers work in such diverse situations, they need a wide choice of alternative options. Researchers and development workers should act as catalysts or facilitators of the processes of self-discovery and learning by farmers and information exchange between farmers. Collaborative learning and on-farm testing by farmers themselves become essential elements of an action-research process (Defoer, 2002).

This is the background of the work done by the Production Systems and Natural Resources Management Team (ESPGRN) of the Malian Agricultural Research Institute (IER) based in southern Mali to develop a process of Participatory Learning and Action Research (PLAR). The case study reported here is situated in the village of Noyaradougou (located about 35 km northwest of Sikasso, the regional capital of southern Mali), where the PLAR process for ISFM has been implemented during five consecutive years, from 1994 to 1999. This case study does not look at the PLAR process as a whole but gives specific attention to nutrient flows and balances. The evolutions of the flows and balances are used as indicators of the impact of the actions undertaken by the farmers who were involved in the PLAR process.

Resource Flow Mapping Within the PLAR Context

The PLAR approach implemented in Noyaradougou consisted of an initial diagnostic phase, followed by an annual cycle of planning-implementation-evaluation of improvements. An important tool used during the diagnostic phase was the diagnostic RFM tool.

Prior to the mapping exercise, farmers classified the farms of the village into three classes: Class 1 – good soil fertility managers, Class 2 – average soil fertility managers, and Class 3 – poor soil fertility managers. They did this on the basis of criteria for good soil fertility management, such as recycling of crop residues, managing crop and livestock in an integrated way, using organic and mineral fertilizer, and applying anti-erosion measures. The farmers also indicated several underlying factors for these differences in management. Access to productive resources such as labor, cattle, and carts plays a significant role in soil fertility management.

Within each farm class, test farmers were selected with whom in-depth analyses of farmers' soil fertility management strategies were carried out, using the diagnostic-RFM technique. Following the diagnostic phase, test farmers developed planning-RFMs before the beginning of the growing season. At the end of the growing season, the test farmers evaluated their achievements, thereby turning the planning-RFM into an RFM of implemented activities. Test farmers continued making planning-RFMs and RFMs of implemented activities over the 5-year period considered here (1994-99). Test farmers adopted a number of improved soil fertility management practices as a result of their active involvement in the PLAR process (Table 1).

Nutrient Flows and Balances

Information contained in each of the RFMs (the diagnostic-RFM and the RFMs of implemented activities from 1994 to 1999) drawn by the test farmers was transferred on recording forms (available in ResourceKIT) and subsequently entered into computer databases. The data were recorded in different forms: (1) farm-level data, (2) cropping field-level data, (3) flows of resources leaving the fields: produce and crop residues, (4) resources entering the fields (fertilizers), (5) resources leaving the household and animal production system, and (6) resources entering the household and animal production system. The resource flow databases include variables such as the type of flow, its origin and destination, and the amount involved each year. The quantities of organic fertilizers and crop residues transported around the farm are expressed in local units (as indicated on the farm

Table 1. Overview of Types of Activities Planned as a Function of Year and Farm Class Over a 5-Year Period

Activity/Experiment	Year of Planning	Farm Class 1	Farm Class 2	Farm Class 3
Increase Organic Fertilizer Production				
▪ Use litter in kraal	Yr1; Yr2; Yr3; Yr4; Yr5		✓	✓
▪ Compost crop residues	Yr1; Yr2; Yr3; Yr4; Yr5		✓	✓
Improve Quality of Organic Fertilizer				
▪ Apply rock phosphate	Yr1; Yr2; Yr3; Yr4; Yr5	✓	✓	
▪ Store in pit	Yr1; Yr2; Yr3; Yr4; Yr5	✓	✓	
Limit Transportation				
▪ Purchase cart	Yr1; Yr2			✓
▪ Compost near the field	Yr1; Yr2; Yr3; Yr4; Yr5		✓	✓
▪ Build cattle pen near fields	Yr1	✓	✓	
Improve Cattle Feeding in Kraal				
▪ Increase storage before grazing	Yr1; Yr2; Yr3; Yr4; Yr5	✓	✓	
▪ Improve fodder storage	Yr1; Yr2	✓	✓	
▪ Use chaff cutter and salt block	Yr1; Yr2	✓	✓	
▪ Grow fodder crop: maize/dolichos	Yr1; Yr2; Yr3; Yr4	✓	✓	
Improve Erosion Control				
▪ Cultivate along the contour lines	Yr1; Yr2; Yr3; Yr4	✓	✓	✓
Improve Fertilizer Efficiency on Cotton				
▪ Test different fertilizer dosages	Yr3; Yr4; Yr5	✓	✓	✓
Increase Biological Nitrogen Fixation				
▪ Plant Acacia on bunds of contour lines	Yr4, Yr5	✓	✓	✓

maps) and subsequently transformed into kilograms, using conversion factors. Data were then used to calculate nutrient flows and balances using the ResourceKIT. To facilitate this analysis, a picture was made of the system and flows recorded in the database. The farm system was used as the unit of analysis. This is part of the village land use system, which consists not only of farms but also of communally used resources. Three sub-systems were distinguished within the farm system: the crop production system (cps), the animal production system (aps), and the household system (hhs), see Figure 1.

For each of the sub-systems the flows entering the farm from outside are presented as "IN," and flows leaving the farm are designated as "OUT." Links between the sub-systems of the farm are designated as "INT" (internal).

The list below shows all possible types of flows; the system that each type belongs to (*cps*, *aps* or *hhs*) is indicated. For the

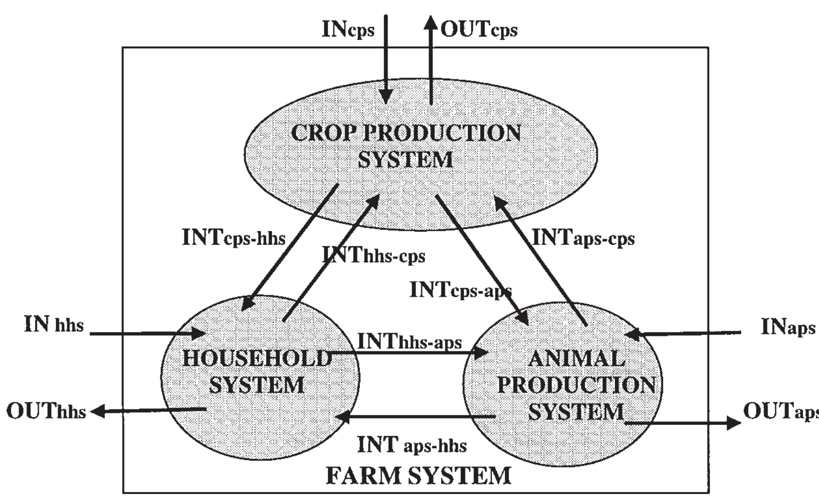

Figure 1. Nutrient Flows Within the Farming System

internal flows, the link between the two sub-systems of the farm is indicated.

INcps	Flows entering the crop production system from outside the farm system
OUTcps	Flows leaving the crop production system and farm system
INaps	Flows entering the animal production system from outside the farm system
OUTaps	Flows leaving the animal production system and farm system
INhhs	Flows entering the household system from outside the farm system
OUThhs	Flows leaving the household system and farm system
INTcps-aps	Flows from the crop production system to the animal production system
INTaps-cps	Flows from the animal production system to the crop production system
INTcps-hhs	Flows from the crop production system to the household system
INThhs-cps	Flows from the household system to the crop production system
INTaps-hhs	Flows from the animal production system to the household system
INThhs-aps	Flows from the household system to the animal production system

Annual nutrient flows and balances were determined for typical farms of Class 1 and Class 3 over a period of 4 years. As an example the potassium (K) balances are presented. Although trends are similar for N and P, the case of K is used to emphasize the effect of changes in livestock management and the use of crop residues.[3]

3. Crop residues and grass have a relatively high percentage of potassium.

Example of a Class 1 Farmer

Table 2 presents the K balances for a Class 1 farm, operated by a farmer who is considered a good soil fertility manager. This farmer grows cotton on about one-half of the total cultivated area, which increased from 13 to 17 ha over the period of 4 years. The farmer generally grows maize in rotation with cotton and cultivates sorghum, groundnut, and sweet potatoes on smaller patches of land. He sells all cotton and about 20% of the cereals, groundnuts, and sweet potatoes. In the first 2 years of the PLAR process, the farmer owned 15 head of cattle but 7 died of a disease that swept through the village in Years 3 and 4. The cattle owned by the farmer spent about 3 months feeding on crop residues left in the field, along with 210 head of cattle belonging to other farmers of the village (non-farm cattle). His cattle therefore ingested about 7% of the crop residues of his field. The farmer's cattle also graze on crop residues left on fields that do not belong to him (so-called non-farm fields). Cattle graze during 9 months of the year on common pastures and fallow land. While they graze, cattle excrete and deposit nutrients on the fields and pastures. If they digest about 50% and graze for 12 hours a day, the cattle leave about 25% of the ingested feed on the fields and pastures as dung and urine.

Looking at the K flows, Table 2 shows that cattle grazing on communal pastures (INaps) represents the largest K input into the farm system. From Year 2 onward, however, this source of K decreases considerably—from 387 to 255 kg K. To compensate for this, the farmer recycled crop residues as feed for cattle, equivalent to 200 kg K (INTcps-aps). He left fewer crop residues for non-farm cattle, which is equivalent to a decrease from 148 to 59 kg K (OUTcps). Because there were fewer cattle in Years 3 and 4, less K was imported through cattle grazing on communal pastures. The same is true for K import by cattle grazing on crop residues of non-farm fields. At the same time a decrease in K recycled through crop residues for feed (INTcps-aps) and an increase of K exported in crop residues grazed by non-farm cattle

Table 2. Nutrient Flows and Partial Balances for a Typical Class 1 Farm ("Good Soil Fertility Manager")

Level	Type of Flow	Type of Produce	Potassium Displaces (kg/year) Year 1	Year 2	Year 3	Year 4
CPS	*IN cps*	Mineral fertilizers purchased	144	170	194	166
		Dung/urine from non-farm grazing cattle	17	9	10	12
	OUT cps	Cotton sold	138	134	171	198
		Other produce sold	3	4	2	0
		Crop residues burned	3	0	0	0
		Crop residues grazed by non-farm cattle	148	59	74	98
APS	*IN aps*	Feed for cattle purchased	28	29	16	6
		Grazing on commons	387	255	136	136
		Grazing crop residues on other fields	122	122	85	56
	OUT aps	Dung/urine left by grazing on commons	57	38	20	20
		Dung/urine left by grazing on other fields	18	18	13	8
HHS	*IN hhs*	Grass from commons for compost	4	8	46	26
	OUT hhs	Produce sold	9	12	16	18
CPS-APS	*INT cps-aps*	Crop residues grazed by own cattle	13	5	6	7
		Crop residues for kraal bedding	56	53	47	90
		Crop residues for feed	0	200	107	39
	INT aps-cps	Dung/urine from grazing cattle (own)	2	1	1	1
		Manure applied on fields	41	69	57	143
CPS-HHS	*INT cps-hhs*	Crop residues for compost/ash	228	300	129	114
		Produce stored	45	34	65	33
	INT hhs-cps	Household waste applied on fields	17	51	50	69
		Compost applied on fields	0	29	0	130
Partial farm balance: $IN_{cps}+IN_{aps}+IN_{hhs}-OUT_{cps}-OUT_{aps}-OUT_{hhs}$			**326**	**328**	**191**	**60**
Partial cps balance: $IN_{cps}+INT_{aps\text{-}cps}+INT_{hhs\text{-}cps}-OUT_{cps}-INT_{cps\text{-}aps}-INT_{cps\text{-}hhs}$			**-413**	**-460**	**-289**	**-58**
Partial cps balance per hectare field			**-32**	**-33**	**-18**	**-3**
Area cultivated (hectare)			13	14	16	17
Number of cattle heads			15	15	10	7

(OUTcps) are observed. Despite the high animal mortality, the amount of K recycled through crop residues used as kraal bedding (INTcps-aps) increased considerably and more K was recycled in the crop residues used for composting (INTcps-hhs).

Mineral fertilizers are another important source of K coming (INcps) into the farm system. Despite the increase in cultivated area (from 13 to 17 ha), K input from mineral fertilizers has only slightly increased. On the other hand, organic fertilizers have become an increasingly important source of K for the crop production system. This is true for both manure from the animal production system (INTaps-cps) and household waste and compost from the household system (INThhs-cps).

Table 2 shows that the partial K balances at the farm level are positive. This means that K input, mainly from mineral fertilizers (INcps) and cattle grazing on the commons and other (non-farm) fields (INaps) compensates for K output, which consists mainly of sold cotton and crop residues grazed by non-farm cattle (OUTcps). During the project activities, the partial K balance at the farm level tends towards an equilibrium. K input from cattle grazing on the commons decreased from about 400 kg to less than 150 g; this decrease explains the change in overall farm-level balance between Years 1 and 4.

Looking at the crop production system, a different picture emerges. K balances are negative; thus, K imports (mainly from mineral fertilizers: INcps and organic fertilizers (INTaps-cps, INThhs-cps)) do not compensate for K exports (mainly sold cotton: OUTcps, and recycled crop residues: OUTcps, INTcps-aps, INTcps-hhs and stored produce: INTcps-hhs). Nevertheless, after 4 years the partial K balance of the crop production system became about 8 times less negative than it was at the start of the process. The partial K balance per hectare was almost zero in Year 4. This positive trend is largely due to the decrease in crop residues grazed by non-farm cattle (OUTcps) and better management of organic fertilizer; as a result the use of animal manure (INTaps-cps) and household waste (INThhs-cps) increases.

Example of a Class 3 Farmer

Table 3 presents the same type of information as Table 2 but now for a typical Class 3 farmer, a so-called poor soil fertility manager. Compared with his counterpart of Class 1, the farm of the Class 3 farmer is slightly more than half the size. He also grows cotton, maize, sorghum, and groundnuts. As in the case of the Class 1 farmer, the total cultivated area increased over the 4 year period. The cropping pattern and rotations are quite similar to those of the Class 1 farmer; however, this farmer sells very little crop produce except cotton. In the beginning of PLAR, the farmer owned five head of cattle but had only two left in Year 3. Table 3 shows that 1 year later (Year 4) the farmer has almost recovered from this calamity since the number of cattle increased again up to 4. The livestock management of this farm is similar to that of the Class 1 farm; the cattle spent 9 months on the common pastures and fallow land and about 3 months grazing crop residues left on the field. Because the fields are open to all animals, the farmer's cattle theoretically only consume about 2% of the crop residues left on his fields (five head of the farmer's own cattle/210 village cattle).

As with the Class 1 farm, grazing of cattle on communal pastures and crop residues represent significant K inputs into the farm system (INaps). Mineral fertilizer is another important K flow entering the farm system (INaps). There are two primary K sources leaving the farm system: cotton sale and crop residues grazed by non-farm cattle (OUTcps). Since the farmer has a relatively small herd, crop residue grazing on other fields (INaps) brings in only about 50% of the amount of K lost by village cattle grazing on the farmer's own crop residues (OUTcps). To reduce such losses, the farmer recycled considerable amounts of crop residues for kraal bedding (INTcps-aps). In year 3, however, due to the severe loss of animals, he did not recycle crop residues for

Table 3. Nutrient Flows and Partial Balances for a Typical Class 3 Farm ("Poor Soil Fertility Manager")

Level	Type of Flow	Type of Produce	Potassium Displaces (kg/year) Year 1	Year 2	Year 3	Year 4
CPS	*IN cps*	Mineral fertilizers purchased	42	69	46	58
		Dung/urine from non-farm grazing cattle	10	10	7	11
	OUT cps	Cotton sold	44	56	65	62
		Other produce sold	0	2	1	0
		Crop residues burned	6	4	0	9
		Crop residues grazed by non-farm cattle	79	79	47	78
APS	*IN aps*	Feed for cattle purchased	6	8	3	2
		Grazing on commons	128	128	55	112
		Grazing crop residues on other fields	44	44	17	34
	OUT aps	Dung/urine left by grazing on commons	19	19	8	16
		Dung/urine left by grazing on other fields	7	7	3	5
HHS	*IN hhs*	Grass from commons for compost	3	0	17	14
	OUT hhs	Produce sold	1	0	2	3
CPS-APS	*INT cps-aps*	Crop residues grazed by own cattle	2	2	1	2
		Crop residues for kraal bedding	37	38	0	28
		Crop residues for feed	16	0	0	0
	INT aps-cps	Dung/urine from grazing cattle (own)	0	0	0	0
		Manure applied on fields	8	10	65	65
CPS-HHS	*INT cps-hhs*	Crop residues for compost/ash	17	14	124	46
		Produce stored	24	19	12	21
	INT hhs-cps	Household waste applied on fields	40	40	22	33
		Compost applied on fields	0	0	11	63
Partial farm balance: $IN_{cps}+IN_{aps}+IN_{hhs}-OUT_{cps}-OUT_{aps}-OUT_{hhs}$			**77**	**93**	**19**	**59**
Partial cps balance: $IN_{cps}+INT_{aps\text{-}cps}+INT_{hhs\text{-}cps}-OUT_{cps}-INT_{cps\text{-}aps}-INT_{cps\text{-}hhs}$			**-125**	**-84**	**-99**	**-16**
Partial cps balance per hectare field			**-17**	**-11**	**-12**	**-2**
Area cultivated (hectare)			7.5	8	8.5	9
Number of cattle			5	5	2	4

litter. Table 3 shows that the farmer compensated for this by recycling more crop residues for composting (INTcps-hhs). As with the Class 1 farm, the K input into the crop production system has considerably increased during the 4 years of PLAR. This is the case for both animal manure (INTaps-cps) and compost (INThhs-cps).

The K balances at the farm level are positive for all years as shown in Table 3; however, in year 1, the Class 3 farm K balance was about 4 times lower than the Class 1 farm K balance. Contrary to what happened for the Class 1 farm, the values of the Class 3 farm K balances did not change dramatically over time. Only in year 3, the Class 3 farm K balance was substantially lower due to the reduction of cattle grazing on the commons. In year 4, the partial K balances at the farm level were almost the same for both farmers.

The situation is different for the K balance at the crop production level. As for the Class 1 farm, all balances are negative, although there is a clear movement toward equilibrium. This positive trend is principally caused by a substantial increase in the use of manure and compost. Another similarity between the two farms is that on a per-hectare basis the partial K balance has become almost zero in Year 4.

The above analysis of K flows indicates that the Class 1 farm performed better than the Class 3 farm at the start of PLAR, considering the entire farm system. The main reason for the substantially higher Class 1 farm K balance was that this particular farmer owned more cattle that harvested K when they grazed on the commons. Four years later, the distinction between Class 1 (a "good soil fertility manager") and Class 3 (a "poor soil fertility manager") seems no longer valid, as livestock have become a less important component of the farm K balance.

When the partial balances of the crop production system are examined, the distinction between Class 1 and Class 3 also disappears in the course of PLAR. In Year 1 neither farm seemed sustainable, particularly the Class 1 farm, but the situation clearly improved after 4 years of PLAR. In Year 1, large K inputs into the animal production system (INaps + INTcps-aps) resulted in small returns from manure applied to fields (INTaps-cps). Four years later, the ratio between manure K (INTaps-cps) and K inputs into the animal production system (INaps + INTcps-aps) increased from 3% to 37% for the Class 3 farm and from 7% to 43% for the Class 1 farm. Using PLAR for 4 years helped farmers to substantially improve their production and management of organic fertilizers and to re-dress the negative K balance. The partial K balances suggest that the distinction between Class 1 and Class 3 farmers no longer holds true.

Conclusions

Farmers develop and evaluate resource flow maps by visualizing the activities effectively implemented; this activity constitutes the primary tool used during the planning-implementing-evaluating continuum of the PLAR approach. During the 4 years of implementation, farmers gradually adopted the RFM tool and slightly adapted it to their needs. Farmers liked the tool because it helps them to select techniques and solutions that are appropriate for their available resources. They also said that the RFMs allow them to set targets more effectively, based on past experiences, which they systematically evaluate using the maps of implemented activities. Farmers use the maps as a management instrument, which guides them during the growing season. The mapping tool was not only used individually by farm households. During sessions organized for all farmers of the village at the beginning and end of the growing seasons, the maps were used to facilitate exchange of information among farmers and stimulate farmers to take action.

This case study illustrates that farmer-drawn maps can be used to collect and interpret data on resource flows within the farm. If these data are stored, transformed, and analyzed systematically, useful information can be obtained to help farmers move toward more productive and sustainable soil fertility management. Nutrient flows and balances are a useful input within the interactive process of learning and action research. This type of quantitative information provides a common ground for creative interaction between farmers and facilitators from research and/or extension agencies.

References

Defoer, T. 2002. "Learning About Methodology Development for Integrated Soil Fertility Management," *Agricultural Systems,* 73:57-81.

Defoer, T., and A. Budelman (Eds.). 2000. *Managing Soil Fertility in the Tropics: A Resource Guide for Participatory Learning and Action Research*, Amsterdam, Netherlands: Royal Tropical Institute (KIT).

Pieri, C. 1989. *Fertilité des Terres de Savanne: Bilan de Trente ans de Recherche et de Développement Agricole au Sud du Sahara*, Paris, France: Ministère de la Coopération, Centre International de Recherche Agricole et Développement/ Institut de Recherche Agronomique Tropicale (CIRAD/IRAT).

Pol, F., van der. 1992. *Soil Mining: An Unseen Contributor to Farm Income in Southern Mali*, KIT Bulletin No 325. Amsterdam, Netherlands: Royal Tropical Institute (KIT).

Scoones, I. (Ed.). 2001. *Dynamics and Diversity: Soil Fertility Management and Farming Livelihoods in Africa*, London, United Kingdom: Earthscan.

Scoones, I., and C. Toulmin. 1999. *Policies for Soil Fertility Management in Africa*, Issues Document, Department for International Development (DFID), Nottingham, United Kingdom: Russel Press.

Stoorvogel, J. J., and E.M.A. Smaling. 1990. *Assessment of Soil Nutrient Depletion in Sub-Saharan Africa, 1983-2000,* vol. I-IV, Wageningen, Netherlands: The Winand Staring Center.

Chapter 3

Using NUTMON to Evaluate Conventional and Low External Input Farming Practices in Kenya and Uganda

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More information on NUTMON can be found in Appendix 7

Introduction

Soil degradation is a serious threat to food security in sub-Saharan Africa, which is, among other factors, related to a very low use of mineral fertilizer (average of 8 kg/ha according to Henao and Baanante [1999]). This is attributed to, e.g., lack of farmer purchasing power, low or insecure returns on fertilizer, and poorly developed distribution networks and has given rise to a call for low external input agriculture (LEIA) as opposed to high external input agriculture (HEIA).

The effectiveness and impacts of LEIA versus HEIA technologies have been the subject of much debate. Some advocate combining elements of both schools of thought by using organic resources and mineral fertilizer. This would reduce investment costs and increase the efficiency of mineral fertilizer (Smaling et al., 1996; Pretty, 1995). This approach, in combination with im-

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proved agricultural practices and better access to input and output markets (ISFM), is thought to effectively address nutrient depletion of African soils. The appropriate balance between the use of organic resources and mineral fertilizer depends on many factors, including soil characteristics, accessibility of input and output markets, and agricultural potential of the areas concerned.

To shed light on this issue, two different soil fertility management approaches were compared in low-potential (low soil fertility and low and unreliable rainfall) and high-potential areas (high soil fertility and high and reliable rainfall) in Kenya and Uganda (Table 1).

In each agro-ecological zone, two farm management groups were distinguished and compared:

Table 1. Characteristics of the Four Sites

	Kenya		Uganda	
	Nyeri	Machakos	Kabarole	Palissa
Agricultural potential	High	Medium-low	High	Medium-low
Altitude (m)	1,100–2,400	500–1,300	1,500–1,800	1,000–1,100
Rainfall (mm)	1,200–2,000	500–900	1,300–1,500	800–1,200
Soil type following FAO (FAO, 1990) classification	Andosols, Nitisols (clay)	Luvisols (loamy-sand)	Andosols	Ferrasols
Average slope (%)	21	17	20	1
Population density (people km^{-2})	250	100	400	220
Average size of holding (ha)	0.9	2.5	1.6	2.6
Main crops	Tea, coffee, maize	Maize, beans, sorghum	Banana, tea, maize, coffee	Maize, cotton, beans
Livestock	Dairy cattle (zero-grazing)	Cattle (corralled at night)	Cattle (zero-grazing)	Cattle (free-range)

- The LEIA management group—farm households trained by the Kenyan Institute of Organic Farming (KIOF) in low-external input technologies (composting, application of liquid manure, etc.) and having applied at least three of these techniques on more than 50% of the cultivated area over a minimum of three consecutive years.
- The conventional management group—farm households with production resources similar to those of the LEIA management group but not practicing any of the defined LEIA techniques and acting as representative for the farming systems used in the area concerned.

Approximately 14-18 households were selected and divided into two groups according to the criteria selected for LEIA and conventional management. The performance of these farms was assessed using the nutrient monitoring approach (NUTMON), as described by De Jager et al. (1998; 2001) and by Vlaming et al. (2001). The approach distinguishes two phases—a diagnostic phase and a development phase. In the diagnostic phase, natural resources management at the farm level and its impact on resource flows, economic performance, and the socioeconomic environment are assessed. In the development phase, promising technologies are identified and evaluated on farms with farmers. Subsequently policies and measures are formulated at the district level; farmers are thus enabled to apply these technologies.

The diagnostic phase consisted of the following activities: (1) assessment of natural resources and their management at the farm household level, (2) soil sampling, (3) monthly monitoring of farm activities, and (4) data analysis. These activities are explained more in detail below.

Soil fertility management practices were identified through interviews, transect walks, and soil and nutrient flow maps, and developed with farmers (Figure 1). Primary soil types distin-

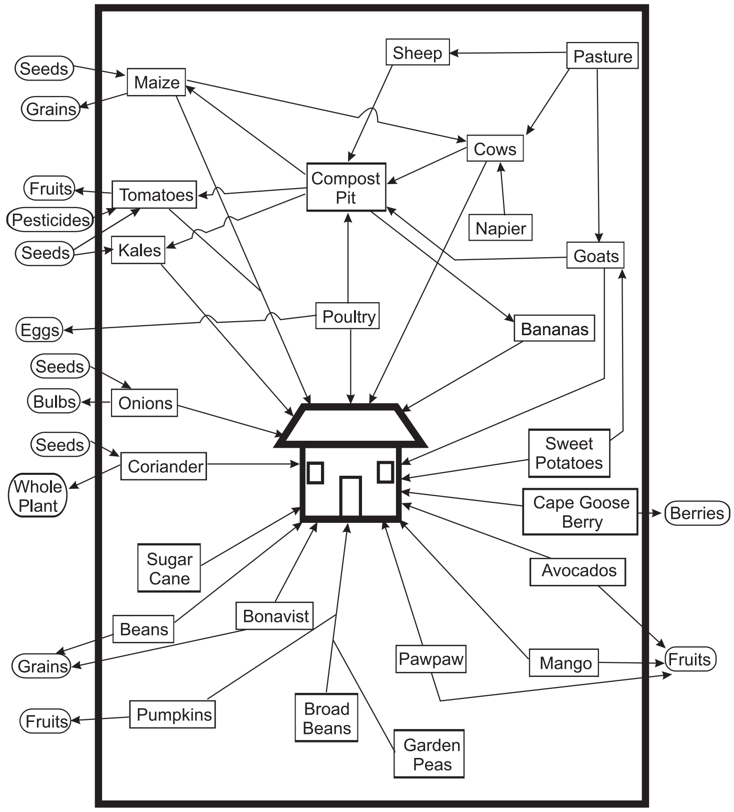

Figure 1. Example of a Qualitative Product Flow Diagram Drawn by Farmers During the Diagnosis Phase

guished on the farmer soil maps were analyzed for total N, plant-available P, exchangeable K, and organic matter content following standard laboratory methodologies.

Farm management practices were monitored using structured questionnaires. Input and output flows at the farm level were quantified and nutrient contents (N, P, K) of significant flows (Table 2) were determined. Transfer functions were used to calculate "hidden" nutrient flows, such as atmospheric deposition,

Table 2. Average Farm Level N Flows Per Site and Management-Type (Conventional Versus LEIA)

Country	Kenya				Uganda			
Site	Machakos		Nyeri		Palissa		Kabarole	
Agricultural Potential	Medium-Low		High		Medium-Low		High	
Management Type	Conv.	LEIA	Conv.	LEIA	Conv.	LEIA	Conv.	LEIA
Mineral fertilizer (kg/ha)	5	2	64	68	0	1	0	0
Organic fertilizer (kg/ha)	3	1	28	70	1	2	1	2
Grazing (kg/ha)	2	8	4	4	4	5	19	15
Atmospheric deposition (kg/ha)	4	4	6	6	4	4	5	5
Biological N fixation (kg/ha)	8	10	7	7	1	1	15	12
N in crop/livestock products (kg/ha)	-2	-2	-38	-30	-1	-2	-3	-3
Crop residues (kg/ha)	0	0	-6	-2	0	0	0	0
Manure (kg/ha)	-2	-5	-2	-4	-2	-2	-9	-7
Leaching (kg/ha)	-20	-27	-56	-58	-7	-7	-85	-78
Gaseous losses (kg/ha)	-7	-10	-44	-48	0	-1	-18	-21
Erosion (kg/ha)	-8	-5	-55	-94	0	0	-67	-19
Human excreta (kg/ha)	-4	-2	-8	-9	-2	-4	-5	-4
Net Balance	**-21**	**-26**	**-100**	**-90**	**-2**	**-3**	**-147**	**-98**

biological N-fixation, leaching, and gaseous losses. To feed these transfer functions, additional data had to be collected such as annual precipitation and clay content of the soil. In addition, data were collected on items such as prices, harvesting indexes, manure production of animals, etc., to feed the background database of the NUTMON software (Vlaming et al., 2001).

The data consisted of (1) analysis of the largely qualitative farmers' assessment of natural resource management, (2) analysis of the quantitative nutrient flows using the NUTMON methodology and soil analyses, and (3) integration of the two previous steps and discussing the results with participating farmers.

In the development phase, LEIA techniques were jointly identified and selected for further testing by researchers and farmers using the participatory technology development (PTD) process (Reijntjes et al., 1992). This process includes the following steps: (1) problem identification, (2) identification of alternative options to evaluate, (3) determination of farmers' criteria and indicators to evaluate LEIA technologies, and (4) implementation and evaluation of on-farm trials. Simple record sheets were designed for data collection by farmers in addition to quantitative data collected by the research staff.

Results were evaluated at three levels—individual farmer's evaluation, communal evaluation among farmers during field days, and joint evaluation during group meetings involving farmers, extension staff, and researchers. The results of both the farmers' qualitative and the researchers' quantitative evaluation indicators were analyzed using parametric and non-parametric statistical methods for all study seasons.

Based upon the participative diagnosis, the results of the on-farm testing program, an inventory of historic developments in the district, and an inventory of existing and relevant policies in the research sites, draft scenarios for future developments in the areas were formulated focusing on farm-level soil fertility management. In district workshops, including each research area, all relevant stakeholders discussed the draft scenarios and produced a final version of the development scenarios and a prioritized action plan.

Results

Diagnosis of Soil Fertility Status and Management Practices

For all farms, soil maps and nutrient flow maps were produced jointly by farmers and project staff. These maps enabled farmers to visualize nutrient flows on their farms and to provide insight in farmers' perceptions of soil nutrient status and flows. In addition, the maps and quantitative analysis contributed to the overall problem analysis of soil nutrient depletion. The farmers' nutrient flow maps showed, for instance, that conventional farms had a slightly higher number of different in-flows than the LEIA farms. On the other hand, the internal and out-flows were considerably more numerous for the LEIA farms because of a higher diversification of crops cultivated and the fact that manure was more often used on LEIA farms than on conventional farms. Application of the NUTMON model resulted in a quantitative assessment of soil nutrient status and flows and of economic performance indicators of the current farming systems. Only marginal differences were observed between the conventional and LEIA farm management systems.

The differences between the districts were much more profound. The high potential areas, although different in each farming system, showed not only a relatively high N, P, K nutrient content of the soil (Table 3) but also a more negative nutrient balance at the farm level, especially for N (90 to 147 kg/ha/year, representing an annual 0.7% to 1.8% loss of the stock). The latter was mainly due to erosion, leaching and gaseous losses, which were not sufficiently compensated by the high use of mineral and organic fertilizers (Table 2).

In the low potential areas, differences between farming systems were clearly reflected in the soil nutrient flows. In the Machakos district (Kenya), intensive crop farming on relatively poor soils resulted in negative nutrient balances and an annual

Table 3. Stocks and Net Balances of N, P, and K

	Machakos		Nyeri		Palissa		Kabarole	
	Conv.	LEIA	Conv.	LEIA	Conv.	LEIA	Conv.	LEIA
N-stock (kg/ha)	3,900	6,400	12,200	12,300	3,100	3,000	6,800	3,800
N-balance (kg/ha/year)	-21	-26	-100	-90	-2	-3	-147	-98
P-stock (kg/ha)	2,000	1,700	7,900	8,000	1,000	2,500	10,300	9,000
P-balance (kg/ha/year)	2	1	-23	-27	0	0	-70	-57
K-stock (kg/ha)	7,800	10,200	10,400	15,300	6,100	6,300	7,800	8,400
K-balance (kg/ha/year)	-9	2	-23	18	2	1	-55	-7

decline in N-stock of 0.5% at the farm level, mainly due to very low levels of external inputs applied. The low potential area in the Pallisa district (Uganda) is characterized by a much more extensive farming system with comparatively large numbers of free-ranging livestock. The domination of free-ranging livestock in the subsistence-oriented farming system resulted in nutrient accumulation on the cropped fields due to the manure of cattle that graze the communal lands. At the farm level this resulted in a nearly balanced situation of nutrient flows. However, this situation can only remain stable as long as sufficient common grazing land in the district remains available.

Tables 2 and 3 show that all N-balances and most P-balances are negative, especially in the more fertile areas. Nutrient losses are slightly lower for the LEIA farms, notably K for which these farms often show a positive balance.

The economic performance indicators showed no clear differences between the management systems (Table 4). However,

Table 4. Net Farm Income Per Hectare, Replacement Costs Per Hectare, and Labor Requirements Per Hectare for Conventional and LEIA Farms

	Machakos		Nyeri		Palissa		Kabarole	
	Conv.	LEIA	Conv.	LEIA	Conv.	LEIA	Conv.	LEIA
Net farm income (US $/ha/year)	95	194	955	310	57	102	254	238
Replacement costs (US $/ha/year)	43	60	155	163	5	3	363	235
Labor requirement (days/ha/year)	193	253	485	648	75	120	255	215

analysis of labor data showed that LEIA management requires more total farm labor than conventional management.

The farms in high potential areas realized, on average, higher net farm income levels per hectare per year.

Huge differences between districts exist if depleted nutrients are valuated against replacement costs. The replacement costs were calculated by multiplying the net nutrient losses by the price of fertilizer. This was required to compensate for losses. In Pallisa the replacement costs constitute only 5% of the net farm income per hectare while these costs are also relatively low in Nyeri for the conventional farms. In Machakos and Kabarole, a considerable proportion of the net income per hectare was based upon nutrient mining with respective figures of 30%-45% and more than 100%.

Identification, Testing, and Evaluation of Low-External Input Technologies

The technology identification and experimental design exercise resulted in a research plan for on-farm testing in each research district. All experiments focused on adding nutrients through composting and liquid manure, while hardly any nutrient-saving techniques were selected. In general, the results show that significant increases in yield and economic returns can be realized with relatively high application levels of compost, but availability of material and labor inputs soon become limiting factors. Substantial and sustained yield increases can therefore only be realized through smart combinations of mineral fertilizers and locally available organic resources.

Formulation of Enabling Policies and Measures at the District Level

Four workshops were held and attended by a total of 150 stakeholders including district policymakers from various ministries, researchers, extension workers, non-governmental organization (NGO) personnel, staff from development projects and others. During these workshops, development scenarios and a prioritized action plan were developed. The scenarios indicated the consequence of continuing the existing farming practices, applying LEIA techniques, and introducing ISFM technology. The action plans stressed the need for improving aspects such as:

- Information flows to farmers about improved soil fertility management methods.
- Credit availability.
- Input and output markets.
- Infrastructure.

Conclusions

This case study revealed that all N balances and most of the P balances were negative at the farm level, especially in the high potential areas. Most sites were adequately supplied with K. This constitutes a serious threat for future agricultural productivity. Causes of N and P depletion differ considerably between the sites. Soil nutrient analysis revealed that no differences in soil nutrient status could be observed between LEIA and conventional management. Apparently application of low-external input techniques such as compost, liquid manure, etc., does not result in a significantly better soil fertility status (measured in N, P, K, and carbon [C] content) compared with conventional practices such as application of farmyard manure, mineral fertilizers, etc. In general, the nutrient status was considerably higher in the high potential areas compared with the low potential areas. Overall, soils were adequately supplied with K and deficient in P. Large variations were observed in soil fertility management, soil nutrient flows, nutrient balances and economic performance indicators between farms within one management group in a particular research area.

In general, rather low and erratic economic returns to agricultural production activities were observed. Moreover a considerable part of these returns was based upon nutrient mining. Net farm income levels per hectare were slightly higher for LEIA farms in low potential areas and higher for conventional farms in high potential areas.

Low-external input technologies alone offer limited opportunities to address the observed problems of soil nutrient depletion in the region. Significant increases in yield and economic returns could be realized with relatively high application levels of compost, but availability of material and labor inputs then become limiting factors. On the other hand, an increased application of external inputs alone is not a realistic solution either. For most of the smallholders, this option is not economically feasible because the required infrastructure is lacking. Appropriate combinations of external inputs and LEIA techniques appear to be the most appropriate alternative strategy—maximal use of locally available nutrients combined with an (environmental-economic) optimal use of external nutrients is one example. More emphasis should be paid to the reduction of nutrient losses when using locally available organic resources.

Changes in agricultural policies are required to provide sufficient incentives for farmers to undertake short-term and long-term investment in soil fertility and soil nutrients. Policymakers need to be involved in monitoring and research activities geared toward soil nutrient improvement.

The project revealed the need for a systematic economic and ecological evaluation of soil fertility management and its impact on sustainability in various farming systems. The approach has made considerable contributions to methodologies for participatory assessment of nutrient flows and economic performance indicators as a basis for further development of appropriate, condition-specific ISFM technologies. All partners have acquired additional insights in the dynamics of smallholder farming systems, in addition to knowledge and skills in participatory technology development and assessment of the sustainability of technologies and farming systems.

The diagnostic phase of the methodology proved to be a rather time-consuming activity with intensive participative assessment and detailed gathering of primary data during a monthly monitoring process. Although a very clear and accurate picture of the current constraints in the soil management system was obtained and farmers entered into a successful process of learning and observation, a faster and less resource-demanding methodology needs to be developed for successful large-scale adoption of this approach. For instance, data collection only once during a growing season, reduction of the different types of participative tools used, and organized meetings are possible options to be explored.

The involvement of district-level policymakers in the project appeared to be extremely valuable in placing the technical results of the project in a larger perspective. Although regular involvement was planned, district-level stakeholder workshops could be organized only at a late stage of the project. This resulted in interesting observations and action plans, but without an adequate follow-up. In future activities, interactions with policymakers at an early stage of the project should be given priority to ensure full integration of facilitating policies and technical options.

References

De Jager, A., D. Onduru, M. S. Van Wijk, J. Vlaming, and G. N. Gachini. 2001. "Assessing Sustainability of Low-External-Input Farm Management Systems With the Nutrient Monitoring Approach: A Case Study in Kenya," *Agricultural Systems*, 69:99-118.

De Jager, A., S. M. Nandwa, and P. F. Okoth. 1998. "Monitoring Nutrient Flows and Economic Performance in African Farming Systems (NUTMON). I. Concepts and Methods," IN *Nutrient Flows and Balances as Indicators of Productivity and Sustainability in Sub-Saharan African Agro-Ecosystems*, 71(1-3):37-48, E.M.A. Smaling (Ed.), Agric. Ecosyst. Environ.

FAO. 1990. *FAO-Unesco Soil Map of the World*, Revised Legend, Soils Bulletin 60, Food and Agriculture Organization of the United Nations, Rome, 119 p.

Henao, J., and C. A. Baanante. 1999. *Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa*, IFDC T-48, International Fertilizer Development Center, Muscle Shoals, Alabama.

Pretty, J. N. 1995. *Regenerating Agriculture; Policies and Practice for Sustainability and Self-Reliance*, Earthscan, London, United Kingdom.

Reijntjes, C., B. Haverkort, and A. Waters-Bayer. 1992. *Farming for the Future. An Introduction to Low-External-Input and Sustainable Agriculture*, ILEIA, Leusden, Netherlands.

Smaling, E.M.A., L. O. Fresco, and A. De Jager. 1996. "Classifying and Monitoring Soil Nutrient Stocks and Flows in African Agriculture," *Ambio*, 25:492-496.

Vlaming, J., H. Van den Bosch, M. S. Van Wijk, A. De Jager, A. Bannink, and H. Van Keulen. 2001. *Monitoring Nutrient Flows and Economic Performance in Tropical Farming Systems; Part 1: Manual for the NUTMON Toolbox*, Wageningen, Netherlands.

Chapter 4

On-Farm Testing of NuMaSS in the Philippines

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More information on NuMaSS can be found in Appendix 9

Introduction

In the Philippines, acid uplands, primarily Ultisols (FAO, 1990), comprise close to 9 million ha of underused, deforested land (information obtained from the Bureau of Soils and Water Management, Philippines). To explore the potential of this area for a more diversified and higher value crop production, the nutrient management support system (NuMaSS) is expected to be a useful tool.

Since 1987 the International Rice Research Institute (IRRI) and the Philippine Rice Research Institute (PhilRice) as partners in the Soil Management Collaborative Research Support Program (SM-CRSP) were involved with NuMaSS development in the testing, evaluation, and refinement of fertilizer and lime recommendations in the Asian uplands.

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Within this framework, IRRI and PhilRice have collaborated with U.S. universities for on-farm testing of NuMaSS in Ilagan, Isabela, and Arakan Valley, North Cotabato in the Philippines.

An on-farm evaluation of NuMaSS was undertaken with the following objectives:

- Testing the NuMaSS nutrient decision aids to determine whether they optimally diagnose and detect nutrient-responsive conditions on farms.
- Using on-farm evaluation data to improve diagnosis and prediction by NuMaSS.

Methodology

The on-farm evaluation involved superimposition of various fertilizer practices on the farmers' crops of upland rice or maize. These treatments were:

1. Check (no fertilizer).
2. Farmer practice (farmers' choice of N, P, K fertilizers).
3. Regional blanket recommendation (134 kg N/ha, 18 kg P/ha, and 35 kg K/ha for maize and 90 kg N/ha, 9 kg P/ha, and 18 kg K/ha for upland rice).
4. NuMaSS recommendation (N, P, and lime application based on field-specific soil data and NuMaSS predictions, and K as treatment 3).
5. NuMaSS recommendation + high K (N, P and lime applications based on field-specific soil data and NuMaSS predictions, and high K levels if K level in treatment 3 was deemed inadequate).

Farms and farmers were selected to represent a diversity of production situations including farmers with and without off-farm income, farms with gentle (0%-8%) to moderate slopes (8%-16%), low to high pH, and small to large farms. Farmers were identified based on their intention to grow upland rice or maize. All operations other than NuMaSS recommendations were as per farmer practice. After conducting a diagnostic discussion with the farmer about his/her farming, soil samples of 0.15 m depth were collected and analyzed for organic matter content, pH, aluminum (Al), exchangeable bases, clay percentage, and Mehlich 1 P.

Based on soil analyses and "intended yield" levels, NuMaSS diagnoses and NuMaSS recommendations were made and implemented for treatments 4 and 5. "Intended yields" were determined locally, usually by agronomists or field staff with knowledge of the crop, and tended to be rather optimistic yield levels that might occur in 2 out of 5 years.

Fertilizer application varied in the two crops. For rice one-sixth of N and all of P and K were incorporated into the soil at planting time. The remaining N was applied as split at maximum tillering (one-third), 5-7 days before panicle initiation (one-third), and at flowering (1/6). For maize, one-third of N and all of P and K were incorporated into the soil at planting. The remaining N fertilizer was applied at 15-20 days after planting (dap) (one-third) and at 30-35 dap (one-third). Lime was incorporated into the soil at least 3 weeks before planting at 0.15 m depth. Grain yield and stover or straw were sampled at harvest. After recording fresh weight of bulk and sub-samples, sub-samples were oven dried for 48 h at 70^{o}C and analyzed for N, P, and K.

On-farm plots were established in 7 upland rice farms in Ilagan in 1998, 13 upland rice farms and 15 maize farms in Ilagan in 1999, 13 maize farms and 4 upland rice farms in Ilagan, and 17 upland rice farms in Arakan Valley in 2000 (Table 1).

NuMaSS Diagnosis and Assessment of Its Accuracy

Although most Ilagan soils were severely acidic (pH_{KCl} less than 4.5 in 62% of farms across upland rice and maize fields) and extremely low in exchangeable bases, soils in all farms in Arakan

Table 1. Number of On-Farm Trials Established

Location	1998		1999		2000	
	Rice	Maize	Rice	Maize	Rice	Maize
Ilagan	7	0	13	15	4	13
Arakan	0	0	0	0	17	0
Total	7	0	13	15	21	13

recorded pH_{KCl} exceeding 4.5 and contained high amounts of calcium (Ca) and magnesium (Mg); this resulted in moderately high effective CEC (Table 2). While Ilagan and Arakan soils varied substantially in soil acidity and Ca and Mg contents, most of both soils were extremely deficient in Mehlich 1 extractable P. Across all farms, soils in 89% of farms were below 5 mg/kg soil in Mehlich 1 P. The percentage of farms reporting P deficiency

Table 2. Summary of Soil Acidity, Extractable P, and Exchangeable Bases (Ca, Mg) Across Rice and Maize Testing Sites

		Rice		Maize
		Ilagan, 1999	Arakan, 2000	Ilagan, 1999
		(% of farms)		
pH_{KCl}	<4.5	62	0	60
	>4.5	38	100	40
Mehlich 1 P (mg/kg)	<5	100	76	93
	>5	0	24	7
Ca ($cmol_c$/kg)	<2	99	0	100
	2-10	1	1	0
	>10	0	99	0
Mg ($cmol_c$/kg)	<2	99	0	100
	2-10	1	49	0
	>10	0	51	0

for both upland rice and maize increased to 94% when only Ilagan farms were considered and increased to 100% when only rice soils in Ilagan were included.

Thus, upland rice tends to be grown in soils that are extremely deficient in P. Soils in Ilagan, which were less acidic and higher in bases compared with the remaining soils, were on farms located on the river plains that benefited from flood-derived alluvial deposits and were frequently used to produce maize.

Thus, for all crops and at both sites, NuMaSS diagnosed P deficiency in most of the farms and acidity as a constraint in only some farms.

Diagnosing N deficiency was not as straightforward as acidity and P diagnoses, which were based on soil tests calibrated against soil critical levels. According to the NuMaSS algorithm, the native N uptake was estimated by the N uptake of an N-unfertilized crop.

A deficiency was diagnosed when estimated native N uptake was lower than the N uptake required to achieve the target yield. The native N uptake estimated both in Ilagan and Arakan ranged only from 20 to 30 kg N/ha, hardly sufficient for 1 t/ha of upland rice yield and 1.5 t/ha of maize yield. Given this low yield level, the NuMaSS estimation of N fertilizer requirement would be heavily influenced by the selected target yields unlike estimates of P and lime, which are independent of target yields in NuMaSS. Given the low native N levels, an average native N estimate was used across all farms to calculate the N requirement. Furthermore, since there is no provision in NuMaSS to vary target yields between farms within the same general location, target yields were assumed to be the same on all farms. Based on these assumptions, N deficiency was diagnosed in all farms across Arakan and Ilagan for upland rice or maize.

NuMaSS diagnoses and observed responses for the various crops and sites are summarized in Table 3.

Given that there were no replications for observed responses in each farm, a minimum 0.5 t/ha increase in grain yield of upland rice and 1 t/ha increase in grain yield of maize in the NuMaSS treatment compared with the check treatment of zero input was recorded as a positive response. Note that while diagnoses were done for individual nutrient constraints, responses were measured for the combined application of the deficient nutrients. Kappa statistics were calculated to determine the agreement between the diagnoses and field observed responses.

A Kappa value of 1 indicates that diagnoses and field-observed responses always matched. A Kappa value of 0 indicates that there were an equal number of correct and incorrect diagnoses.

The Kappa values for the various crops and sites varied from 0.85 to 1 indicating high accuracy in NuMaSS diagnoses; for

Table 3. Assessing the Accuracy of the NuMaSS Diagnosis for Maize and Upland Rice in Ilagan and Arakan

Diagnosis		Input	Ilagan						Arakan	
			Upland Rice 1999#		Maize 1999#		Maize 2000#		Upland Rice 2000#	
			+	-	+	-	+	-	+	-
Response	Pred.	N	13	0	15	0	8	0	17	0
		P	13	0	12	3	8	0	16	1
		Lime	8	5	9	6	0	8	0	17
	Obs.*	NPLime	11	2	15	0	8	0	17	0
Kappa coefficient			0.85		1		1		1	

*Observed response is to any or all of the deficiencies diagnosed.
#An increase in grain yield of at least 0.5 t/ha in the NuMaSS treatment compared with the zero input control is arbitrarily set as a positive response.

instance, there was almost always an agreement between responses to combined application of N, P, and lime when any one or all of them were diagnosed to be deficient.

NuMaSS Prediction and On-Farm Testing of Prediction

Evaluation of Upland Rice Response in Acid Upland Soil, Ilagan, Isabela, 1999 Wet Season

The farmer practice in the Ilagan 1999 upland rice trial varied widely in NPK use ranging from 0 to 134 kg/ha N, 0 to18 kg/ha P, and 0 to 35 kg/ha K; thus, some farmers exceeded the NPK rates of both regional and NuMaSS recommendations.

The range of application based on the NuMaSS recommendation was as follows: N = 132 kg/ha, P = 0-36 kg/ha, lime = 0-2 t/ha (Table 6). Because of the observed wide variation in NPK rates across treatments, the NPK applications were grouped in increasing bands of amounts and were assigned new NPK treatment designations (Table 4).

The new dataset with the new NPK level designations was then subjected to cluster analysis. The data clustered only with respect to N and indicated that K was not a significant factor influencing the yield. N clusters were N1 = 9 to 40 kg/ha and N2

Table 4. Range of NPK Applied to Upland Rice in On-Farm Trials at Ilagan, Isabela, 1999

Nutrient	Range of Amounts Applied (kg/ha)			
	None	Low	Medium	High
N	0	9-40	60-90	120-138
P	0	4-12	17-29	36
K	0	8-23	35	60-100

= 60 to 138 kg/ha. Analysis of variance using these two levels of N as treatments showed that yield was significantly different between these two clusters (p-value = 0.0001) and about 78% of the variation in yield was accounted for by these groupings of N levels (Table 5). Uptake of N, P, and K was also significantly different between these N clusters.

Given that K was not identified as a significant factor in the 1999 Ilagan upland rice trial, an analysis of variance was performed with NuMaSS and NuMaSS+K data combined. NuMaSS and regional recommendations produced similar yields of 1.2 t/ha, which was significantly superior to the farmer practice and control treatments (Table 6).

Table 5. Grain Yield and Nutrient Uptake by Upland Rice, 1999, Ilagan, Isabela, Philippines. Data Analyzed After Separating into Two N Clusters

N Cluster	Grain Yield	N uptake	P uptake	K uptake
(kg/ha)				
9–40	633b*	40b	4.8b	40.4b
60–138	1,160a	86a	9.3a	66.8a

* Values in columns with the same letters are not significantly different at 5% level by least significant difference (LSD).

Similar differences were observed for NPK uptake.

Evaluation of Maize Response Across Acid Upland and Less-Acid River Plain Soils, Ilagan, Isabela, 1999 and 2000

In 1999 analyses of variance indicated no significant maize yield differences between regional and NuMaSS recommendations; only NuMaSS was superior to farmer practice (Table 7). It

Table 6. Grain Yield and Nutrient Uptake by Upland Rice Subjected to Various Nutrient Inputs, 1999, Ilagan, Isabela, Philippines

Treatments	Inputs			Lime	Grain Yield	Nutrient Uptake		
	N	P	K			N	P	K
	(kg/ha)			(t/ha)		(kg/ha)		
Control	0	0	0	0	0.59c*	37.6c	4.2d	38.2c
Farmer practice	0-134	0-18	0-35	0	0.93b	58.3b	6.8c	53.8b
Regional recommendation	90	9	18	0	1.21a	84.4a	8.8b	61.1ab
NuMaSS and NuMaSS + K	132	0-36	60-100	0-2	1.21 a	94.7a	10.5a	73.1a

*Values in columns with the same letters are not significantly different at 5% level by LSD.

Table 7. Grain Yield of Maize in Response to Nutrient Inputs, 1999 Wet Season, Ilagan, Isabela, Philippines

Treatments	**N**	**P**	**K**	**Lime**	**Grain Yield**
	(kg/ha)			(t/ha)	
Control	0	0	0	0	1.25c
Farmer practice	0-274	0-20	0-50	0	3.86b
Regional	134	18	35	0	4.82ab
NuMaSS	210	0-60	60	0-2	4.95a

*Values in columns with the same letters are not significantly different at 5% level by LSD.

was found that K was not a significant factor in increasing yields; hence, data for NuMaSS+ K (regional recommendation) and NuMaSS + high K were combined in Table 7.

In 2000 there were no significant differences in yield among all treatments except the control receiving no inputs (Table 8).

Evaluation of Upland Rice Response in Less-Acid Upland Soils, Arakan Valley, 2000

Analysis of variance of grain yield data showed very large coefficients of variance (CV) and low regression coefficients (R^2) with no model significance. This was attributed to the fact that N applied under farmer practice varied widely and overlapped with N levels in the regional and NuMaSS treatments. The CV was significantly reduced (20%), and R^2 improved to 91% when the farmer practice N levels were grouped into 16 to 45, 90 and 113 to 180 kg/ha and re-analyzed. The results indicated that grain yield under NuMaSS (with regional or high K), regional recom-

Table 8. Grain Yield of Maize in Response to Nutrient Inputs, 2000 Wet Season, Ilagan, Isabela, Philippines (Lime was not included in the comparison as it was not commercially available at the time.)

Treatments	Nutrients Applied			Grain Yield
	N	P	K	
	(kg/ha)			(t/ha)
Control	0	0	0	1.36b
Farmer practice	90-120	12-25	12-23	2.52a
Regional	134	18	35	2.90a
NuMaSS +regional K	225	30-51	35	3.13a
NuMaSS + high K	225	30-51	80	3.10a

*Values in columns with the same letters are not significantly different at 5% level by LSD.

mendation, and farmer practice with 90 kg N/ha were similar but significantly higher than the control and farmer practice of low and high N (Table 9). It should be noted that farmer practice did not include any K application and except under low N, no P application either.

Discussion

The on-farm trials collectively indicated that there is a high degree of accuracy in diagnosing constraints of N, P and acidity by NuMaSS. However, the yields achieved for both upland rice and maize were substantially lower than the target yields for which NuMaSS diagnoses and recommendations were made.

In general, NuMaSS recommendations resulted in similar yields as the regional recommendation both at the more acid upland site in Ilagan, Isabela and at the less acid site in Arakan Valley and for

Table 9. Grain Yield of Upland Rice in Response to Nutrient Inputs, 2000 Wet Season, Arakan Valley, Philippines (Lime was not included in the comparison as it was not commercially available at the time.)

Treatment	Nutrients Applied			Grain Yield
	N	P	K	
	(kg/ha)			(t/ha)
Control	0	0	0	0.99c
Farmer practice high N	113-180	0	0	1.34c
Medium N	90	0	0	1.77b
Low N	16-45	0-22	0	1.20c
Regional	90	26	25	2.07ab
NuMaSS +regional K	132	0-12	25	2.20a
NuMaSS + high K	132	0-12	67	2.05ab

*Values in columns with the same letters are not significantly different at 5% level by LSD.

both upland rice and maize crops. Thus, NuMaSS performed as well as the regional recommendation. It should be noted, however, that K, which is routinely included in the regional recommendation, is not currently addressed in NuMaSS. It should also be noted that there were instances when farmer practice yielded the same as the regional and NuMaSS recommendations, and often with no P and K and never any lime applied. A cluster analysis on 1999 upland rice yield in Ilagan indicated that there was a yield response to N but not to P, K, or lime. The overall results confirm N but not P, K, or acidity as a limitation to yield of upland rice and maize. It cannot be concluded, however, that P, K, or acidity was not limiting yields since the response to NuMaSS recommendation was observed collectively for N, P, and lime. For example, George et al. (2001) demonstrated that upland rice response to P application occurred (such as increased straw production in traditional varieties and increased grain yield in improved varieties) when constraints other than P were generally absent. In the present trials, it is likely that the soil P and K supplies were sufficient to support the relatively low yields achieved.

We could conclude from our results that NuMaSS performs as well as the regional recommendation in the initial years, but it cannot be ascertained whether there would be a saving in the long term when NuMaSS was followed because this can only be assessed when accounting for residual effects of P and lime inputs.

Although the collaborating farmers were requested to repeat the trials on the same plots, very few farmers did so for various reasons, including lack of timely rainfall and fallowing the land.

It should be realized that NuMaSS does not predict yields but provides recommendations to achieve a target yield. Although the NuMaSS target yields were reasonable for the regions, none of the trials produced such yields. This is particularly true for N diagnosis and recommendation for maize. The target yield of 6 t/ha used in the on-farm testing is indeed possible with hybrid maize as was demonstrated by Aragon et al. (2003). They reported hybrid maize yields obtained in the field experiments of 5.8 t/ha in 2000 and 6.2 t/ha in 2001. However, none of the farmer fields produced 6 t/ha although the amount of N fertilizer applied was supposed to be sufficient for a yield of 6 t/ha. There are several reasons for this. The target yield was based on the assumption in NuMaSS that all factors other than N, P, and acidity are not limiting the yield, which in fact is not true. Unlike alleviation of acidity and P deficiency, N uptake is demand driven and this implies that other growth-limiting factors may determine target yield and, hence, N demand.

In the current implementation of NuMaSS, the N uptake from the soil is estimated by N uptake of the unfertilized check. Nevertheless, actual N-uptake from the soil may also be constrained by other limiting factors and may therefore be different from the potential N-uptake from the soil. The potential N-uptake could be estimated by a treatment where all other factors are optimized so that N could be considered as the only limiting factor. These two estimates would vary substantially, given that in the absence of other nutrient limitations all of the initial and in-season mineralized N would be taken up by the crop.

It is therefore important to define realistic target yields and then matching input recommendations for those yield goals rather than solely basing them on soil nutrient levels. For the definition of such target yields, limiting factors such as the yield potential of genotype and time of planting in relation to drought events should be considered.

The treatment combinations used here did not permit testing whether there were responses to individual nutrient constraints such as N, P, or acidity. To test the success of diagnoses of such individual constraints, additional missing nutrient experiments may be considered in on-farm evaluation of NuMaSS; i.e.,

+N+P+lime, -N+P+lime, +N-P+lime and +N+P-lime experiments. A significant response to the complete treatment compared to, e.g., -N+P+lime would confirm the diagnosis of N deficiency.

References

Aragon, M. L., J. B. Lasquite, T. M. Corton, M. C. Casimero, S. T. Santiago, T. George, and R. S. Yost. 2003. “Intensive Testing of the NuMaSS Decision-Aids Tool in the Philippines,” IN *Field Testing of Integrated Nutrient Management Support System (NuMaSS) in Southeast Asia*: *Workshop Proceedings*, pp. 60-89. M. C. Casimero, S. Ma. Pablico, R. S. Yost, and M. L. Aragon (Eds.). PhilRice, Maligaya, Munoz, Nueva Ecija (in press).

FAO. 1990. *FAO-Unesco Soil Map of the World. Revised Legend*, Soils Bulletin 60, Food and Agriculture Organization of the United Nations, Rome, Italy. 119 p.

George, T., R. Magbanua, W. Roder, K. Van Keer, G. Trebuil, and V. Reoma. 2001. “Upland Rice Response to Phosphorus Fertilization in Asia,” *Agronomy Journal,* 93:1362-1370.

Chapter 5

The Use of QUEFTS in Search of Balanced Fertilizer Recommendations for Maize in Togo

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More information on QUEFTS can be found in Appendix 1

Introduction

Current fertilizer recommendations in Togo are mainly based on crop nutrient demand without considering the stock of available nutrients in the soil. Knowledge of this soil nutrient-supplying capacity is a great advantage because it permits a better match of fertilizer applications to crop nutrient demand.

Spatial and temporal variability of soil nutrient-supplying capacity occurs at different ranges—regional, village, and field. For example, in the southern part of Togo, mainly Ferralsols (FAO, 1990), locally known as "Terre de Barre," are found. These are deep soils, containing at least 90% sand and are often deficient in potassium (levels of exchangeable K as low as 0.2 mmol K/kg can be found). Acrisols dominate the remainder of the country. These soils are often rather shallow and potassium rarely constitutes a significant bottleneck for crop production with levels of 1.5-10 mmol/kg.

At the village level, concentric rings of varying soil fertility status may be found (Prudencio, 1983) with soil fertility gener-

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ally declining as distance increases from the village. In the first ring directly around the village, organic amendments such as household waste are used to increase soil fertility and offer good growing conditions for nutrient-demanding crops like maize. In the second ring, use of organic resources declines and some farmers may apply mineral fertilizer. In the third—outer ring—soil fertility is maintained through fallowing. Grazing cattle may actually mine nutrients from these areas and bring the nutrients to the first ring if the cattle are kept overnight at the homestead. Differences in soil fertility at the village level may also be caused by micro-topographic differences. Farmers are generally well aware of these differences and often have developed a local soil typology (Defoer and Budelman, 2000).

Table 1 provides some examples of the variability in soil fertility between and within regions in Togo. In this table, C-org is a measure for organic matter content, N-tot is related to N-supplying capacity, P-BrayI is a measure for plant available P, P-tot gives

Table 1. Example of Differences in Soil Chemical Properties Related to Indigenous Soil Nutrient-Supplying Capacity in Farmers' Fields in Four Villages in Togo (Two Fields per Village)

Village and Geographic Coordinates	Region in Togo	C-org	N-tot	P-BrayI	P-tot	K-exch
		(g/kg)	(g/kg)	(mg/kg)	(mg/kg)	(meq/kg)
Adjodogou 6.33N, 1.57E	South	9.0 4.8	1.1 0.7	3.5 6.3	416 340	1.6 0.2
Sevé Kpota 6.44N, 0.95E	South	19 9.0	1.6 1.2	3.3 2.6	331 205	4.1 2.1
Tsravekoe 6.53N, 1.01E	South	8.0 4.5	0.9 0.6	2.0 1.4	168 141	4.0 1.7
Mango 10.18N, 0.24E	North	7.5 7.0	0.8 0.9	2.6 3.4	283 357	1.9 1.6

an indication of P reserves in the soil, and K-exch is a measure for plant-available K. The two farmer fields in Mango have relatively similar chemical properties, but the two fields in Adjodogou are very different. One field is clearly degraded with very low N and K status and low organic matter content.

Ignoring the indigenous soil nutrient-supplying capacity may result in fertilizer applications that do not match crop nutrient requirements and, therefore, in a waste of nutrients and money, and may even contribute to environmental pollution. Figure 1 illustrates a situation where phosphorus (P) is the most limiting nutrient to crop growth.

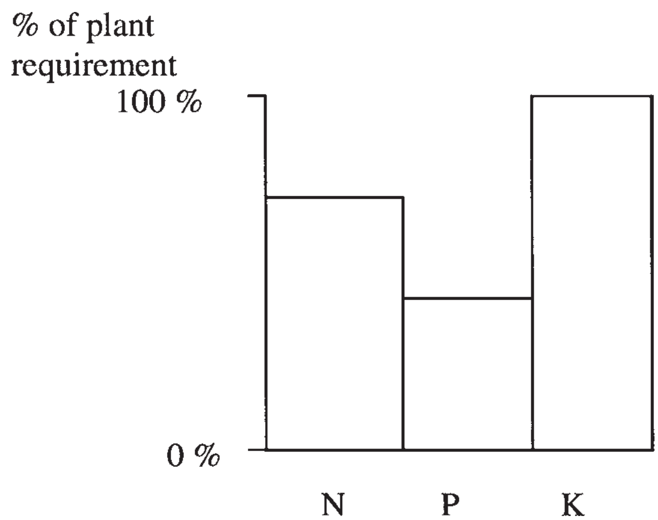

Figure 1. Ratio Between Actual Soil Nitrogen (N), Phosphorus (P), and Potassium (K) Supplying Capacity Over Required N, P, and K to Reach a Target Yield

Applying fertilizer containing a high percentage of K and a low percentage of P will not significantly improve yields and may even reduce economic returns (Figure 1). Application of mineral fertilizer should, therefore, consider the soil's indigenous nutrient-supplying capacity. Farmers are often aware of this, but the institutional environment in which they operate does not always allow for much flexibility. In Southern Togo, for instance, farmers can only buy urea if they also purchase NPK (15-15-15) usually at the rate of two bags of NPK for one bag of urea. Moreover, urea and NPK (15-15-15) are often the only two mineral fertilizers that are available, apart from another compound fertilizer that is specifically meant for cotton.

Ideally, fertilizer recommendations should be site-specific; i.e., specific for soil and weather conditions, crop management technology (choice of crop and variety, sowing date, crop establishment method, etc.), input and output prices, target yield, and the financial means of the farmer. It is clear that such recommendations cannot be obtained through field experimentation alone because associated costs would be prohibitive. A more promising approach may be the combined use of decision support tools (DSTs) and farmer-participatory approaches. This hypothesis was tested in three villages in southern Togo during the main rainy season of 2002 (April-August).

Approach

The QUEFTS model was adopted as the decision support tool in this study. QUEFTS was developed at the Wageningen Agricultural University using data from Kenya and Surinam (Janssen et al., 1990). This model is a very simple tool, which allows yield predictions based on a number of soil analyses (organic C, total N, total P, extractable P, exchangeable K, and pH-water). These data are used to derive estimates for the soil's nutrient-supplying capacity. Other inputs are maximum fertilizer recovery and the relationship between nutrient uptake and yield. To estimate this relationship, two linear boundaries are used to describe an envelope ranging from maximum accumulation to maximum dilution of a nutrient (often N, P, K) in the crop. If these envelope curves are known for different nutrients, they can be combined into curves that describe (balanced) nutrition, taking into account interaction between the nutrients. However, it should be noted that QUEFTS does not consider factors such as water supply, variety, pests, and diseases.

Three villages were selected in Southern Togo—Sevé Kpota, Adjodogou, and Kpétémé. Sévé Kpota (6.44N, 0.95E) is situated in the southwestern part of Togo, and Adjodogou (6.33N, 1.57E) and Kpétémé (6.30N, 1.54E) are located in the southeastern area of the country. Rainfall distribution is bi-modal. Rainfall in Sévé Kpota during the main rainy season from April to August is about 650 mm (20-year average for March 1 to August 31) and in Adjodogou and Kpétémé about 630 mm (20-year average from March 1 to August 31).

Sevé Kpota has a relatively low population pressure (95 persons/km) (DSEA, 1997); population pressure in Adjodogou and Kpétémé is much higher: 280 persons/km (DSEA, 1997). Soils in Sévé Kpota are mainly plinthic Acrisols (FAO, 1990). In Adjodogou and Kpétémé, soils are mainly Ferralsols (FAO, 1990) and generally less fertile than soils in Sevé Kpota. Maize (*Zea mays* L.) and cassava (*Manihot esculenta*) are the main crops grown.

The standard fertilizer recommendation for maize in Sevé Kpota, as recommended by the national extension authority, is 150 kg NPK (15-15-15)/ha and 50 kg urea/ha. In Kpétémé and Adjodogou, the local NGO recommends applying 200 kg NPK/ha and 150 kg urea/ha. In spite of that recommendation, less than one-half of the farmers in the villages studied actually use mineral fertilizer (Agboh-Noaméshie and Sedzro, 2002). Among the farmers who were using fertilizer, some were already adapting the fertilizer doses to soil type. They would apply only urea to the most fertile soils and a combination of NPK and urea to the soils that are less fertile.

A Participatory Learning and Action Research (PLAR) approach was used in all three villages (Defoer and Budelman, 2000) and resulted in village and soil maps. Farmers distinguished three soil types in Kpétémé and Sévé Kpota based mainly on color differences—red soils, black soils, and white soils. In Adjodogou, only red soils were distinguished. For each of these soil types, data on organic C, total N, total P, extractable P, exchangeable K, and pH-water were available from previous experimentation (Struif Bontkes, unpublished data). These data were used as an input for the standard version of QUEFTS to develop a range of alternatives to the standard fertilizer recommendations. Based on these preliminary results and discussions with farmers, fertilizer experiments were installed in each village and covered all soil types.

Each experiment consisted of five treatments (Tables 2 and 3): a control (1—no fertilizer), farmer's practice (2), the recommended practice (3), and two alternative fertilizer application strategies (4 and 5). One replication was installed per farmer. Composite soil samples were taken at 0-0.2 m depth in each plot for analysis of organic C, total N, total P, extractable P, exchangeable K, and pH-water, following standard laboratory methodologies (IITA, 1982).

The reason to include K_2SO_4 in Kpétéme and Adjodogou was the low exchangeable potassium level of Ferralsols. The number of bags in treatments 4 and 5 was reduced compared with the recommended practice (treatment 3) in all villages because farmers were generally reluctant to spend much money on fertilizer.

These alternative and standard fertilizer recommendations were evaluated on all soil types distinguished by farmers. Results were

Table 2. Mineral Fertilizer Application Strategies Evaluated With Farmers During the 2002 Main Wet Season on Ferralsols in Kpétémé and Adjodogou, South Togo (Numbers refer to bags of 50 kg)

Treatment	NPK	K_2SO_4	Urea (Basal Dressing)	Urea (Topdressing)	Total
1	0	0	0	0	0
2	Farmers' practice				
3	4	0	1.5	1.5	7
4	1	1	1.5	1.5	5
5	0	2	1.5	1.5	5

Table 3. Mineral Fertilizer Application Strategies Evaluated With Farmers During the 2002 Main Wet Season on Acrisols in Sévé Kpota, South Togo (Numbers refer to bags of 50 kg)

Treatment	NPK	K_2SO_4	Urea (Basal Dressing)	Urea (Topdressing)	Total
1	0	0	0	0	0
2	Farmers' practice				
3	3	0	0	1	4
4	1	0	1	1	3
5	0	0	1.5	1.5	3

discussed with farmers and compared with the results of a version of QUEFTS, which was calibrated for the two soil types based on a combination of a limited dataset on soils, yields, and nutrient uptakes from previous experiments in Sévé Kpota and Adjodogou (Struif Bontkes, unpublished data).

In this calibration the following parameters had been adjusted: the parameters governing nutrient uptake from soil, the maximum recovery rates (MRR) of fertilizers and the ratios between yield and nutrient uptake. This calibration was carried out by adjusting these parameters until the best (eye) fit was found between simulated and observed yields, and between simulated and observed yield-nutrient uptake ratios.

The calibrated QUEFTS version was subsequently used to develop site-specific fertilizer recommendations not only related to the soil nutrient-supplying capacity, but also to the capacity/willingness of the farmer to purchase fertilizer.

Results

The soil type specific parameters for the QUEFTS model that resulted from the calibration are as follows:

Parameters governing the soil nutrient-supplying capacity for N, P, and K:

SN	= (pH-3)*17*N-total	-1-
SP	= 0.028 * P-total + P-BrayI	-2-
SK(F)	= 400 * K-exch/ (2+0.9*C-org)	-3-
SK(A)	= 320 * K-exch/ (2+0.9*C-org)	-4-

Where:
SN = soil N-supplying capacity in kg/ha
SP = soil P-supplying capacity in kg/ha
SK(F) = soil K-supplying capacity in kg/ha on Ferralsols
SK(A) = soil K-supplying capacity in kg/ha on Acrisols

Parameters governing the yield–nutrient uptake ratios:

YNA = 30 * (SN – 5) -5-
YND = 60 * (SN – 5) -6-
YPA = 120 * (SP – 0.4) -7-
YPD = 300 * (SP – 0.4) -8-
YKA = 30 * (SK – 2) -9-
YKD = 120 * (SK –2) -10-

Where:

YNA = maize yield (kg/ha) at maximum N accumulation in the plant
YND = maize yield (kg/ha) at maximum N dilution in the plant
YPA = maize yield (kg/ha) at maximum P accumulation in the plant
YPD = maize yield (kg/ha) at maximum P dilution in the plant
YKA = maize yield (kg/ha) at maximum K accumulation in the plant
YKD = maize yield (kg/ha) at maximum K dilution in the plant

The MRR of fertilizers:

MRR (N) = 0.4 kg N uptake (kg N applied)$^{-1}$ for Ferralsols
MRR (N) = 0.5 kg N uptake (kg N applied)$^{-1}$ for Acrisols
MRR (P) = 0.3 kg P uptake (kg P applied)$^{-1}$ for Ferralsols
MRR (P) = 0.7 kg P uptake (kg P applied)$^{-1}$ for Acrisols
MRR (K) = 0.5 kg K uptake (kg K applied)$^{-1}$ for Ferralsols
MRR (K) = 0.5 kg K uptake (kg K applied)$^{-1}$ for Acrisols

Some results of the soil chemical analyses of samples taken before the start of the experiments are presented in Table 4.

Table 4 shows that black soils are generally more fertile than red and white soils in Sévé Kpota. Differences in soil fertility are less clear for Kpétémé.

Agreement between predicted yields and observed yields varied greatly. This can be attributed partly to the fact that field vari-

Table 4. Average Characteristics per Soil Type as Distinguished by the Farmers (The number of fields per soil type is indicated in parentheses)

	Sevé Kpota			Kpétémé			Adjodogou
	Black (8)	Red (8)	White (8)	Black (2)	Red (5)	White (1)	Red (6)
Clay (%)	26	19	13	8	6	4	8
Org. C (g/kg)	11	8	8	4	6	3	5
N-tot (g/kg)	1.7	1.2	1.2	0.5	0.6	0.5	0.6
P-BrayI (mg/kg)	8.4	3.6	4.5	3.5	4.9	4.6	6.6
P-tot (mg/kg)	636	238	205	193	187	187	346
K-exch (meq/kg)	6.7	3.0	2.0	1.0	0.8	0.7	0.5
pH-H_2O	7.3	7.1	6.9	6.4	6.5	6.8	6.9

ability was quite high due to the presence of trees (shading), heterogeneous plant density, delayed weeding, and (in the case of Adjodogou and Kpétémé) the presence of cassava as a relay crop, whereby cassava is planted in the maize field and allowed to develop fully after the maize harvest. This variability resulted in relatively low correlation coefficients as shown in Table 5. The large difference between observed and simulated yields for the Acrisols is due mainly to the black soils that are fertile but do not produce high yields because of the shallowness of these soils.

Table 5. Observed and QUEFTS-Simulated Average Maize Yield on Both Soil Types After Calibration

	Ferralsols	Acrisols
R^2	0.57	0.48
Average yield (t/ha)		
Observed	2.1	2.4
Simulated	2.3	3.1

A further adjustment of the QUEFTS parameters was not yet possible because nutrient uptake data were not yet available at the time of writing.

Fertilizer Recommendations

The adjusted version of QUEFTS was used to develop fertilizer recommendations for various soil conditions considering availability of fertilizer and the capacity of the farmer to purchase fertilizer.

We hypothesized that the farmer has access to four types of fertilizer—urea (7,500 FCFA per bag of 50 kg), NPK 15-15-15 (7,500 FCFA[2] per bag of 50 kg), K_2SO_4 (10,000 FCFA per bag of 50 kg), and TSP (15,000 FCFA per bag of 50 kg). It is assumed that farmers may be willing to purchase at least one and up to a maximum of four bags of fertilizer per hectare. At present it is difficult for farmers to obtain K_2SO_4, and TSP is not available at all. The price of TSP was therefore arbitrarily set at 15,000 FCFA per bag.

The sensitivity of a QUEFTS-derived fertilizer recommendation to soil K status was analyzed for Adjodogou. K-exch was set at 0.2, 0.3, and 0.4 meq K/kg. Such low values occur on very degraded soil (Table 1). Agronomic and financial performance of the different treatments as simulated by QUEFTS is presented in Tables 6 and 7.

In several cases, yields are similar but profitability differs significantly. This is due to large differences in yield without fertilizer.

These tables show that optimal doses of fertilizer vary between and within regions. It also indicates that on degraded Ferralsols, K is the limiting factor to maize production, whereas on Acrisols it is mainly N and P.

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2. The franc CFA (FCFA) is pegged to the euro, 656 FCFA = 1 euro.

Table 6. Agronomic and Financial Performance of Fertilizer Recommendations for Each of the Three Villages if the Farmer is Able to Purchase One Bag of Fertilizer (50 kg) as Predicted by QUEFTS

Village	Fertilizer	Yield	Yield Gain From Fertilizer	Net Benefit[a] From Fertilizer Use	Value/ Cost Ratio[b]
	(bags/ha)	(t/ha)	(kg/ha)	('000 CFA/ha)	(-)
Adjodogou					
0.2 meq K/kg	1 K_2SO_4	1.59	0.46	17.4	2.74
0.3 meq K/kg	1 NPK	1.66	0.17	2.7	1.36
0.4 meq K/kg	1 urea	1.82	0.19	4.0	1.53
Kpétémé					
Black soil	1 urea	1.65	0.33	12.3	2.63
Red soil	1 urea	1.68	0.25	7.5	2.00
White soil	1 urea	1.75	0.30	10.3	2.38
Sévé Kpota					
Black soil	1 urea	5.32	0.30	10.3	2.37
Red soil	1 TSP	3.34	0.82	34.1	3.27
White soil	1 TSP	3.13	0.73	29.1	2.92

a. Treatment net benefits: maize price * yield increase – costs of applied fertilizers.
b. Value/Cost ratios: (maize price * yield increase)/costs of applied fertilizers.

Both tables also show that the critical level for exchangeable K on the very degraded soils of Adjodogou is about 0.3-0.4 meq/kg soil as the recommended types of fertilizer change from K_2SO_4 to NPK and urea when exchangeable K increases from 0.2 to 0.4 meq K/ha.

These results suggest that it is important to (1) adapt fertilizer recommendations to specific field conditions, (2) provide farmers with a range of single component mineral fertilizers, and (3) allow farmers to purchase the fertilizer they prefer.

Table 7. Agronomic and Financial Performance of Fertilizer Recommendations for Each of the Three Villages if the Farmer is Able to Purchase Four Bags of Fertilizer (50 kg) as Predicted by QUEFTS

Village	Fertilizer	Yield	Yield Gain From Fertilizer	Net Benefit[a] From Fertilizer Use	Value/ Cost Ratio[b]
	(bags/ha)	(t/ha)	(kg/ha)	('000 CFA/ha)	(-)
Adjodogou					
0.2 meq K/kg	2 urea + 2 K_2SO_4	2.16	1.03	26.8	1.77
0.3 meq K/kg	2 urea + 1 NPK + 1 K_2SO_4	2.24	0.75	12.7	1.39
0.4 meq K/kg	2 urea + 2 NPK	2.35	0.72	11.1	1.44
Kpétémé					
Red soil	2 urea + 2 NPK	2.17	0.74	14.6	1.49
White soil	3 urea + 1 NPK	2.30	0.84	20.4	1.68
Black soil	2 urea + 2 NPK	2.20	0.88	22.8	1.76
Sévé Kpota					
Black soil	3 urea + 1 TSP	6.22	1.19	34.2	1.91
Red soil	2 urea + 2 TSP	4.32	1.80	62.9	2.40
White soil	2 urea + 2 TSP	4.01	1.62	52.0	2.15

a. Treatment net benefits: maize price * yield increase – costs of applied fertilizers.

b. Value/Cost ratios: (maize price * yield increase)/costs of applied fertilizers.

Results of this study were discussed with representatives of agricultural research institutes, extension services, farmers' organizations, and fertilizer distributors. All representatives agreed regarding the need for fertilizer recommendations that are adapted to the specific field conditions. This would imply more types of fertilizer that need to be distributed according to the need of the various regions. This requires knowledge of region-specific fertilizer requirements and a distribution system that can deliver the right quantities per fertilizer type at the appropriate time. In addition, part of the fertilizer is donated to the country, and it may be necessary to convince the donors to adjust the type of fertilizer donated.

Discussion

Average fertilizer use in sub-Saharan Africa is only about 8 kg/ha (Henao and Baanante, 1999). This is related to a number of factors such as climatic risks, poorly developed input and output markets, and the reluctance of farmers to acquire inputs against cash payment. Fertilizer recommendations should therefore be tailored to the need of the farmer, considering the soil fertility of the fields, other crop management factors such as varietal choice, sowing date, and the farmer's capacity to purchase inputs. The present practice of one general fertilizer recommendation for large regions does not stimulate farmers to use fertilizer. This is still aggravated by the restrictions on the types of fertilizer that can be purchased, as is the case in Togo.

QUEFTS can be useful in the formulation of fertilizer recommendations that consider these factors. An important advantage of QUEFTS is that it is a very simple tool, which requires only a few data (organic C, available P, exchangeable K and pH, yield potential, and the maximum fertilizer recovery rate), and it is easy to use. At the same time, this implies that many factors, such as water availability, varietal choice, plant population, weed infestation, and sowing time, are not considered, although they can partly be accounted for by adjusting maximum fertilizer recovery rates and yield potential.

Despite the fact that QUEFTS does not need many input data, such data may still not be easy to obtain and the quality may sometimes be questionable or difficult to interpret (e.g., if analytical methods used are not similar among laboratories). Moreover, conducting soil analyses requires time and money, which may seriously reduce the applicability of the QUEFTS tool.

There are several ways to overcome, or at least mitigate, that problem. Though soil fertility varies over short distances, it is likely that general statements can be made about individual soil types. For example, maize production on degraded Ferralsols, such as presented in this case study, is likely to be affected by the low K status of such soils. Nevertheless, within each particular soil type, significant differences may still occur, because of the history of land use and inherent spatial variability within the soil unit. Characterization of the variability within these soil types should be carried out in close collaboration with the farmers, using their method of soil classification. An alternative to the often expensive and time-consuming laboratory analyses may be the use of cheaper soil test kits that can be readily used in the field. Such test kits need, however, rigorous testing before they can be reliably used. A cheaper and more feasible approach may be to measure the soil nutrient-supplying capacity directly, using plant nutrient uptake as a proxy in nutrient omission trials at representative sites. In such trials the crop receives the full dose of fertilizer except for the element of interest. For example, maize N uptake in a plot that received an adequate dose of P and K but no N is a proxy for soil N-supplying capacity (SN).

Adopting such an approach would gradually lead to a shift from general to more site-specific fertilizer recommendations. To achieve this, researchers need to become familiar with the principles behind QUEFTS, interpretation of existing soil data, use of simple soil test kits, and/or nutrient omission trials. Researchers should also be able to estimate yield potential (related to varietal choice, sowing time, water availability) and to estimate maximum fertilizer recovery rates (related to, e.g., erosion and leaching, weed infestation, and water availability). To facilitate estimation of yield potentials under various conditions (variety x soil type x sowing time x rainfall patterns), crop growth simulation models can be used that incorporate these factors (e.g., DSSAT). The various combinations of soil fertility, variety, rainfall, and management practices need to be carefully evaluated in close collaboration with farmers and extension staff in their districts. QUEFTS can then be employed to develop fertilizer recommendations for the various combinations, including the capacity of a farmer to purchase fertilizer. A successful example of this approach was given by Haefele et al. (2003) for irrigated rice systems in the Sahel. Subsequently, agricultural extension staff and fertilizer dealers need to receive training to apply these recommendations in the field to their districts. Such an approach will put the responsibility for the formulation of fertilizer recommendations in the hands of those who are in direct contact with the farmer and will, therefore, stimulate the development of local knowledge and its feedback to researchers.

References

Agboh-Noaméshie, A., and K. M. Sedzro. 2002. *Amélioration de la Productivité du Maïs et Utilization des Modèles dans le Transfert des Technologies,* Rapport Technique. COSTBOX Project, IFDC/ITRA, Lomé, Togo.

Defoer, T., and A. Budelman (Eds.). 2000. *Managing Soil Fertility in the Tropics: A Resource Guide for Participatory Learning and Action Research,* Royal Tropical Institute (KIT), Amsterdam, Netherlands.

DSEA. 1997. *Rapport Annuel*, Directorate of Statistics and Information, Lomé, Togo.

FAO. 1990. “FAO-Unesco Soil Map of the World, Revised Legend,” *Soils Bulletin* 60, Food and Agriculture Organization of the United Nations, Rome, Italy, 119 p.

Haefele, S. M., M.C.S. Wopereis, M. K. Ndiaye, and M. J. Kropff. 2003. “A Framework to Improve Fertilizer Recommendations for Irrigated Rice in West Africa,” *Agricultural Systems,* 76(1):313-335.

Henao, J., and C. A. Baanante. 1999. *Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa,* Tech. Bull. No. 48, International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, U.S.A.

IITA. 1982. *Automated and Semi-Automated Methods for Soil and Plant Analysis,* Manual series 7, International Institute for Tropical Agriculture, Ibadan, Nigeria.

Janssen, B. H., F.C.T. Guiking, D. Van der Eijk, E.M.A. Smaling, J. Wolf, and H. Van Reuler. 1990. "A System for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS)," *Geoderma,* 46:299-318.

Prudencio, Y. C. 1983. "A Village Study of Soil Fertility Management and Food Crop Production in Upper Volta: Technical and Economic Analysis," Ph.D. thesis, University of Arizona, U.S.A.

Chapter 6

Application of APSIM in Smallholder Farming Systems in the Semi-Arid Tropics

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More information on APSIM can be found in Appendix 3

Introduction

Despite decades of research, smallholder farmers in the semi-arid regions of southern and eastern Africa invest little in soil fertility management; crop yields and water use efficiencies remain despairingly low (Ryan and Spencer, 2001; Mapfumo and Giller, 2001). To tackle the problem of continuing food insecurity, scientists from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and their partners from the National Agricultural Research and Extension Services (NARES) have conducted research that combines farmer participatory research (FPR) and cropping systems modeling to identify improvements in fertility management technologies for drought-prone regions. On-farm, participatory research approaches can help to ensure relevance and will capture farmer preferences and adaptations of the soil fertility technologies being tested. The expectation is an increased adoption and adaptation of fertility technologies in smallholder farming.

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FPR generally explores technology and management options through interactive discussion and shared experimentation between farmers and researchers (Ashby and Sperling, 1994). An often overlooked limitation of the participatory experimentation process is the site and season specificity of the on-farm experiments. These are the same constraints that on-station experimentation faces and that crop simulation modeling has long claimed to overcome (Keating et al., 1991). In drought-prone regions, in particular, the risk associated with seasonal rainfall variations is a key determinant of whether or not, or at least in what form, a technology is likely to be adopted by farmers (Marra et al., 2003, Stewart, 1988). For this reason, simulation models were introduced into the ICRISAT research programs to capture more effectively the effects of seasonal rainfall variability and to help quantify climatic risk associated with a given technology and environment. Nevertheless, a simulation capability offers other benefits, such as improved research efficiency, by helping to identify "best bet" options for testing with farmers (Dimes et al., 2002) and provides a framework to extrapolate research findings to other sites and management situations (Gowing and Young, 1997), particularly when accompanied by sound economic analysis (Rose and Adiku, 2001).

Previous work in the fields of FPR and computer-based simulation modeling in both Australia (FARMSCAPE—McCown et al., 1998) and South America suggest that synergistic effects might be achieved from using the two very different approaches in a complementary way (Engel et al., 2001; Robertson et al., 2000; Carberry et al., 2002). Skeptics from both research and farming communities, however, do question whether or not the poorly resourced smallholder farmers of southern Africa are ready for such synergies. This chapter reviews the experiences of ICRISAT scientists, in association with NARES partners, in linking system simulation models with FPR in smallholder farming systems in Zimbabwe.

Combining Participatory Research Methods and APSIM

In October 2001 a workshop was organized in Zimbabwe; this activity was specifically designed to allow farmer input in setting scenario analysis and evaluating model output using local experience. The aims of the workshop were not only to help focus research activities, but also to build capacity in simulation modeling within NARES partners and explore approaches for coupling simulation with participatory research techniques (Braun, 2001; Dimes, 2001).

Interdisciplinary teams, consisting of agronomists, economists, and social scientists, visited the villages of Zimuto Communal Land Area, Masvingo (19.823°S 30.910°E) and Tsholotsho Communal Land Area, Matebeleland (19.165°S 27.578°E), in southern Zimbabwe. A useful approach for engaging farmers in initial discussions was the development of an agricultural activity calendar that relates to the local soil types. The calendar details what and where crops are planted: typical dates of planting, weeding, and harvesting; farmer assessment of the fertility of each management unit; and typical fertility amendments carried out and why. With this information, the APSIM simulation tool (McCown et al., 1996, Keating et al., 2003) was explained to farmers and tested through a process of interactive discussions to ensure that the crop performance predictions were reasonable and, in a general sense, consistent with farmer experience for local conditions. This initial exercise helped develop confidence between the researchers and the farmers and also provided a common platform to build upon. A key step, when reporting crop performance data, is to agree with the participating farmers on common units for land area and crop yields; e.g., the number of 50-kg bags/acre rather than kilogram per hectare. Subsequent activities involved detailed interactions with individual farmers about their farming practice, household food security, and available resources.

A useful tool to use at this stage was the Resource Flow Map (RFM) (see Chapter 2 in this guide; Defoer and Budelman, 2000). Such maps/diagrams served to provide a clear picture of the individual farmer's resources and management practices but, more importantly, it was found to be an ideal generator of "what if" questions to be explored using the APSIM model. Some of the types of questions of interest to the farmers that emanated from the RFM sessions included:

1. Should I concentrate or spread the available manure/inorganic nitrogen (N) fertilizer?
2. Should I use N fertilizer in combination with manure or use it separately?
3. What will happen with maize yields if I use sc501, a medium-duration maize variety, instead of the commonly grown short-duration variety sc401?
4. What yield gain can I expect from fertilizer?
5. Should I spend my money on fertilizer or on weeding?

The results of the different scenarios were reported in two ways: (1) on the computer and (2) translated into simple pictures on flipcharts. Farmers enjoyed discussing the different scenarios in terms of extra grain and profit, particularly when an element of competition to guess the results was introduced. It was also encouraging that farmers' estimates of a known intervention generally coincided with model estimates.

First, the simulated variability of maize yields as a result of rainfall variability was discussed at each site using 10 years of weather data. For a sandy soil in Masvingo, it was concluded that three types of years could be distinguished between 1989 and 1998—one very bad year (1992), four bad years, and five normal years. Next, the question about concentrating fertilizer on a limited area or spreading it over the whole area was addressed. The choice was to apply two bags of ammonium nitrate (AN) fertilizer on one field of 2.5 acres or to spread it over two fields of 2.5 acres.

Table 1 summarizes the simulation results (expressed in bags of maize per field) for Zimuto Communal Area, Masvingo. All farmers agreed with the outcome of the APSIM model and said that they would normally spread the fertilizer over a larger area. Nevertheless, some stated that due to labor constraints they recently changed to concentrating their fertilizer on a limited area.

Second, the question about mixing or separating organic manure and fertilizer was addressed. It was decided to consider using manure from six cows and two bags of AN fertilizer on the same 2.5-acre field or to apply the manure on one field of 2.5 acres and the AN fertilizer on another of 2.5 acres. Simulation results are shown in Table 2 (expressed in 50 kg bags per field) for Zimuto. Although the model results suggested that it is better to separate fertilizer and manure application, the farmers who concentrate both on the same field do so because of labor limitations.

Table 1. APSIM Simulated Maize Yield in Number of 50-kg Bags on Two Fields of 2.5 Acres if Two Bags of AN Fertilizer are Applied on One Field Only (Concentrating) or Equally Over Both Fields (Spreading) Under Favorable and Unfavorable Weather Conditions—Zimuto Communal Area, Masvingo, Zimbabwe, Sandy Soil

	Concentrating			Spreading		
	Field 1	Field 2		Field 1	Field 2	
	2 Bags AN	No Inputs	Total	1 Bag AN	1 Bag AN	Total
Worst year	0	0	0	0	0	0
Bad year	18	7	25	18	18	36
Normal year	56	10	66	36	36	72

Table 2. APSIM Simulated Maize Yield in Number of 50-kg Bags on Two Fields of 2.5 Acres if Two Bags of AN Fertilizer and Animal Manure are Applied on One Field Only (Concentrating) or if the Two Bags of AN Fertilizer are Applied on One Field and Animal Manure on the Other (Spreading) Under Favorable and Unfavorable Weather Conditions—Zimuto Communal Area, Masvingo, Zimbabwe, Sandy Soil

	Concentrating			Spreading		
	Field 1	Field 2		Field 1	Field 2	
	2 Bags AN + Manure	No Inputs	Total	2 Bags AN	Manure	Total
Worst year	0	0	0	0	0	0
Bad year	18	7	25	17	10	27
Normal year	62	10	72	56	30	86

Third, the impact of changing maize variety from the short duration variety sc401 (110-120 days) commonly used in both areas to a medium duration variety such as sc501 (120-130 days) was investigated. Growing sc501 instead of sc401 had a detrimental effect on maize yields in most years (Figure 1), and farmers in Tsholotsho clearly appreciated this result.

The last two questions raised by farmers could not immediately be addressed in the field. However, APSIM can provide answers as shown below.

Figure 2 shows simulated maize yields for 48 years of climate records at Masvingo, Zimbabwe, for three N fertilizer treatments, assuming uniform management and low weed, pest, and disease incidence. Results with no fertilizer inputs show the low yields and relatively small year-to-year variation that smallholder farmers in the nearby communal land typically experience (Figure 2–

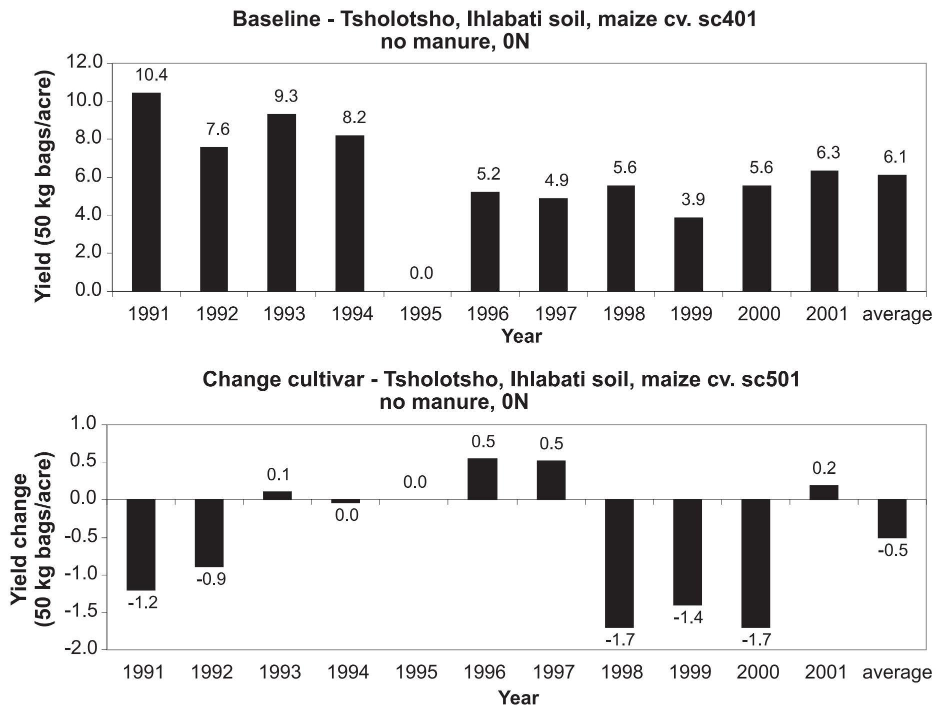

Figure 1. Simulated Maize Yields at Tsholotsho, Zimbabwe (Sandy Soil), for Short-Duration Cultivar sc401 and Simulated Maize Yield Change if Medium-Duration Cultivar sc501 is Grown

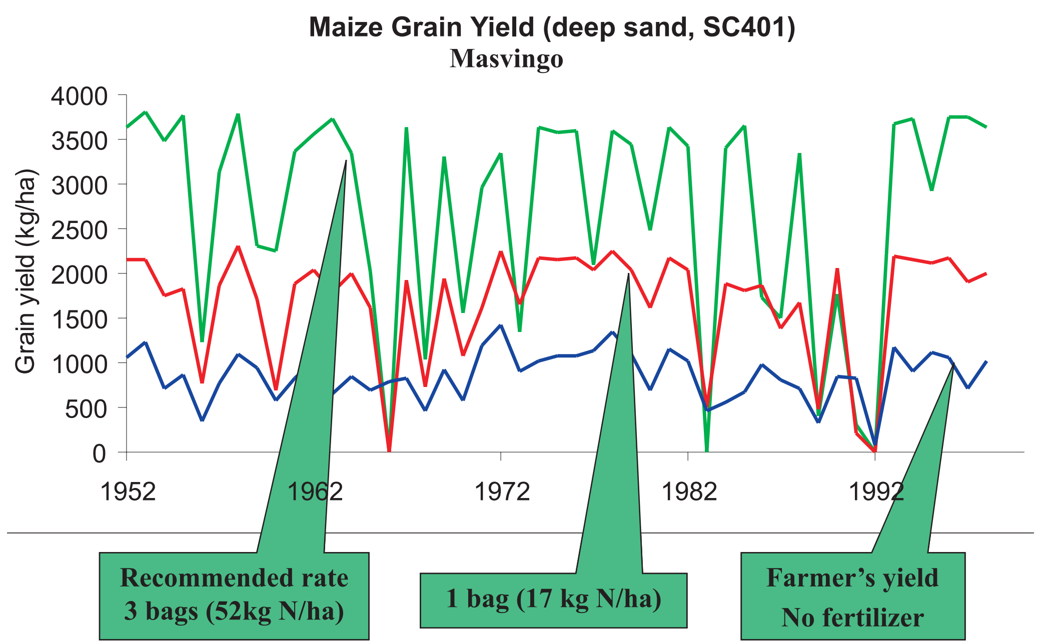

Figure 2. Simulated Maize Yields at Masvingo, Zimbabwe, for Three N Fertilizer Treatments—No Applied Fertilizer (Typical Farmer Yields), the Recommended Rate of Three Bags/ha (52 kg N/ha), and a Smaller Investment of One Bag/ha (17 kg N/ha)

Farmers' Yield). If the nitrogen (N) constraint is reduced with the application of fertilizer, simulated yields are highly variable and reflect the rainfall in this region. There are many years in which N fertilizer improves yield and, by implication, water use efficiency. There are also years when there is no yield increase and, hence, little or no return on the fertilizer investment.

The risk associated with the wide variations in yield with input of N fertilizer is one of the main reasons why farmers in dry regions do not use fertilizer (Figure 2) (Ahmed et al., 1997; Mapfumo and Giller, 2001; Scoones and Toulmin, 1999). However, contributing to this perception of high risk is a lack of appropriate information from extension services on what levels of fertilizer to apply (Figure 2—three bags of AN per ha). Currently, there are no research-based fertilizer recommendations for the drier regions of Zimbabwe (Mlambo and Tapfumaneyi, personal communication) or, for that matter, much of southern Africa; extension agents typically provide information to farmers by adjusting recommendations taken from the higher rainfall regions. Although these adjustments are typically downward to reflect the uncertain rainfall and economic situation of farmers in the drier regions, they are nonetheless high in relation to the farmers' risk perceptions and resource constraints (Ahmed et al., 1997). Considering the seasonal distribution of N responses, N fertilizer recommendations based on experimentation during the period 1993-98 would be expected to be very different in comparison with experimentation conducted during the period 1987-92 (Figure 2).

For the treatment options considered for simulated maize crops at Masvingo, Zimbabwe, the results indicate that the best return on investment is from 1 bag of AN/ha applied to a crop that is well weeded (Figure 3). The worst return, however, is from applying the same amount of fertilizer to an un-weeded crop. Investment in weeding rather than extra fertilizer (beyond 1 bag AN/ha) is clearly a viable option in this scenario. The tradeoffs

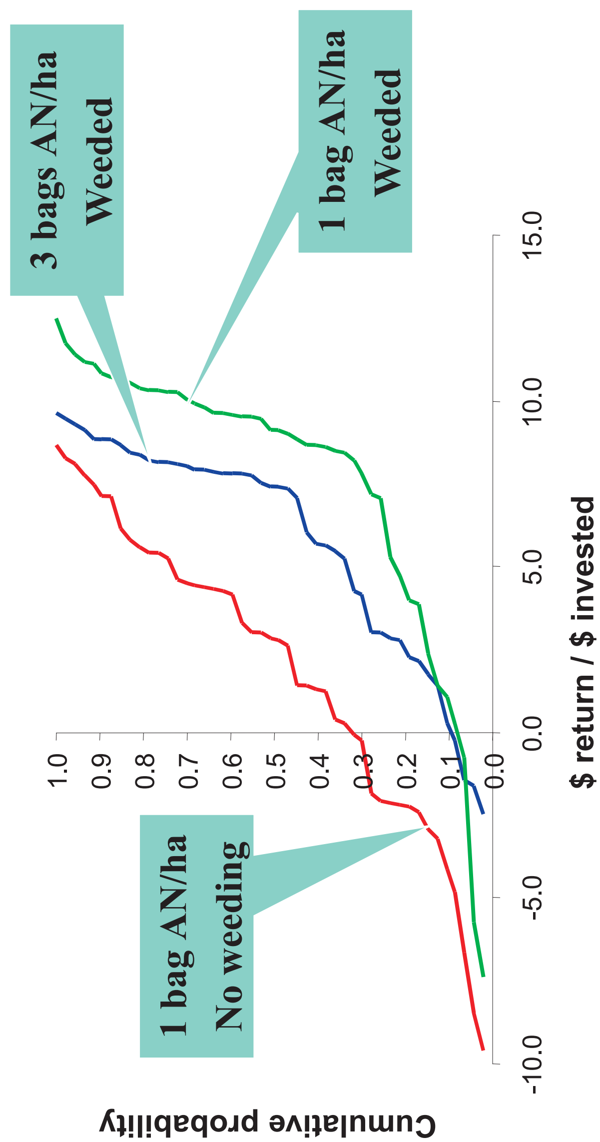

Figure 3. The Zimbabwe Dollar Return in Maize Grain Production per Zimbabwe Dollar Invested in N Fertilizer for Simulated Crops at Masvingo for the Two N Rates and the Effect of Weeding

of allocating limited capital resources between fertilizer purchases and hiring labor for extra weeding are generally not well known by researchers, extension agents, or farmers. An advantage of simulation in this case is that expected yield response and risk for lower rates of N fertilizer can be easily and efficiently quantified (Figures 2 and 3) and used to guide the design of on-farm verification trials. In conjunction with on-farm verification trials, the output can be formulated into more appropriate fertilizer recommendations for dry regions (Figures 2 and 3). This greatly improves current information being disseminated to farmers by extension officers.

When a new technology is developed in conjunction with smallholder farmers, neither researchers nor farmers have the experience to determine how it will perform outside the test period or under management conditions beyond that of the trial itself. Normally such knowledge takes years to accumulate. With a simulation tool that adequately describes the main effects of the technology on plant growth and soil processes (Carberry et al., 1999), an approximation of this knowledge is attainable in a more prompt manner. This can help guide future research on the technology or provide longer term data to conduct a more thorough economic analysis of the new technology, especially in relation to alternative investments.

Conclusions

Simulation can help farmers and researchers evaluate and interpret variable responses to on-farm experiments on soil fertility and, in conjunction with long-term climate data, provide an assessment of associated risk in production and profitability of a technology. It provides an effective and efficient framework for extrapolating research findings to other sites and promotes understanding of system processes, management conditions, and the long-term impacts. It can be used to explore tradeoffs between management options and the payoffs resulting from the allocation of scarce resources.

Clearly, such capability would enhance on-farm participatory research in smallholder farming systems. However, it should be recognized that to be broadly applied and effective, the modeling tool must be specified in terms of the cropping system, significant biophysical constraints, and management practices relevant to particular farming situations. This places a high demand on the capabilities and flexibility of the simulation tool in the first instance and the required soil, crop, and climate data in the next.

Despite these constraints, model-aided discussions with farmers about farm management practices are proving useful in developing research programs on soil fertility management by the farmers themselves. Our recent experiences with farmers, in using simulation models, provide further evidence of the role that risk, uncertainty, and learning play in the process of adopting new technologies. A primary advantage seen in linking FPR and simulation modeling is the co-learning that takes place between the researchers and the farmers about the impact of climatic risk. This clearly answers the skeptics who question the role of simulation in smallholder farming. In brief, computers and smallholder farmers do mix. ICRISAT has now begun farmer-led experimentation based on the scenarios developed as part of these interactions.

References

Ahmed, M. M., D. D. Rohrback, L. T. Gono, E. P. Mazhangara, L. Mugwira, D. D. Masendeke, and S. Alibaba. 1997. "Soil Fertility Management in Communal Areas of Zimbabwe: Current Practices, Constraints and Opportunities for Change." ICRISAT Southern and Eastern Africa Region Working Paper No. 6, Results of a diagnostic survey.

Ashby, J., and L. Sperling. 1994. "Institutionalizing Participatory, Client-Driven Research and Technology Development in Agriculture," Agricultural Administration (Research and Extension) Network Paper 49, ODI: London, UK, 21 p.

Braun, A. 2001. "Linking Logics II: Exploring Linkages Between Farmer Participatory Research and Computer Based Simulation Modelling." 15-20 October 2001. ICRISAT, Bulawayo, Zimbabwe, CD-ROM.

Carberry, P. S., Z. Hochman, R. L. McCown, N. P. Dalgliesh, M. A. Foale, P. L. Poulton, J.N.G. Hargreaves, D.M.G. Hargreaves, and M. J. Robertson. 2002. "The FARMSCAPE Approach to Decision Support: Farmers, Advisers, Researchers Monitoring, Simulation, Communication, and Performance Evaluation," *Agricultural Systems*, 74:141-177.

Carberry, P. S., M. E. Probert, J. P. Dimes, B. A. Keating, and R. L. McCown. 1999. "Role of Modeling in Improving Nutrient Efficiency in Cropping Systems," IN *Food Security in Nutrient-Stressed Environments: Exploiting Plants' Genetic Capabilities*," ICRISAT, Bulawayo, Zimbabwe, Sept. 1999.

Defoer, T., and A. Budelman. 2000. *Managing Soil Fertility in the Tropics. A Resource Guide for Participatory Learning and Action Research,* Royal Tropical Institute, Amsterdam, Netherlands.

Dimes, J. P. 2001. "Linking Logics: Farmer and Researcher Interactions on Farm Management and Simulation Modeling in Smallholder Farming Systems," IN *Proceedings of CIMMYT-ICRISAT Workshop on Linking Simulation Modeling and Farmer Participatory Research on Soil Fertility Management in Zimbabwe and Malawi, 24-29 Sept. 2000, Masvingo, Zimbabwe*, ICRISAT, Bulawayo, Zimbabwe and CIMMYT, Mt. Pleasant, Harare, Zimbabwe.

Dimes, J., L. Muza, G. Malunga, and S. Snapp. 2002. "Trade-Offs Between Investments in Nitrogen and Weeding: On-Farm

Experimentation and Simulation Analysis in Malawi and Zimbabwe," 7th Eastern and Southern Africa Regional Maize Conference and Symposium on Low-Nitrogen and Drought Tolerance in Maize, Nairobi, Kenya, February 11-15, 2002 (in press).

Engel, P.G.H., I. Visser, A. Guijt, and O. Melo. 2001. "Integrating 'Hard' and 'Soft' Systems Methods for Assessing Farmer Strategies in Ñube, Chile," IN *Deepening Rural Resource Management*, pp. 39-55.

Gowing, G.J.W., and M.D.B. Young. 1997. "Computer Simulation as a Tool for Technology Transfer: Interpreting and Extending Experimental Results on RWH for Maize Production," IN *Proc. 1st Int. Conf. Southern and Eastern Africa Society of Agricultural Engineers (SEASAE)*, Arusha, Oct. 1996.

Keating, B. A., P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth, J.N.G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J. P. Dimes, M. Silburn, E. Wang, S. Brown, K. L. Bristow, S. Asseng, S. Chapman, R. L. McCown, D. M. Freebairn, and C. J. Smith. 2003. "An Overview of APSIM, a Model Designed for Farming Systems Simulation," *European Journal of Agron*omy, 18:267-288.

Keating, B. A., D. C. Godwin, and J. M. Watiki. 1991. "Optimizing Nitrogen Inputs in Response to Climatic Risk," IN *Climatic Risk in Crop Production: Models and Management in the Semi-Arid Tropics and Subtropics,* pp. 329-358. R. C. Muchow and J. A. Bellamy (Eds.), CAB International, Wallingford.

Mapfumo, P., and K. E. Giller. 2001. "Soil Fertility and Management Strategies and Practices by Smallholder Farmers in Semi-Arid Areas of Zimbabwe," ICRISAT, Matopos Research Station, PO Box 776, Bulawayo, Zimbabwe and FAO, 66 p.

Marra, M., D. J. Pannell, and A. Abadi Ghadim. 2003. "The Economics of Risk, Uncertainty and Learning in the Adoption of New Agricultural Technologies," Where are We on the Learning Curve?" *Agricultural Systems*, 75:215-234.

McCown, R. L., G. L. Hammer, J.N.G. Hargreaves, D. P. Holzworth, and D. M. Freebairn. 1996. "APSIM: A Novel Software System for Model Development, Model Testing, and Simulation in Agricultural Research," *Agricultural Systems*, 50:255-271.

McCown, R. L., P. S. Carberry, M. A. Foale, Z. Hochman, J. A. Coutts, and N. P. Dalgliesh. 1998. "The FARMSCAPE Approach to Farming Systems Research," IN *Proceedings of the 9th Australian Agronomy Conference,* pp. 633-636, Wagga Wagga, NSW.

Robertson, M. J., P. S. Carberry, and M. Lucy. 2000. "Evaluation of a New Cropping Option Using a Participatory Approach With On-Farm Monitoring and Simulation: A Case Study of Spring-Sown Mungbeans," *Australian Journal of Agricultural Research,* 51:1-12.

Rose, C. W., and S. Adiku. 2001. "Conceptual Methodologies in Agro-Environmental Systems," *Soil and Tillage Research*, 58:141-149.

Ryan, J. G., and D. Spencer. 2001. "Future Challenges and Opportunities for Agricultrual R&D in the Semi-Arid Tropics," Patancheru 502 324, Andhra Pradesh, India, ICRISAT, 83 p.

Scoones, I., and C. Toulmin. 1999. "Policies for Soil Fertility Management in Africa: A Report Prepared for the Department of International Development. Institute for Development Studies, Brighton and International Institute for Environmental Development, London, 128 p.

Stewart, J. I. 1988. *Response Farming in Rainfed Agriculture,* Wharf Foundation Press, Davis, California.

Chapter 7

Using DSSAT to Derive Optimum Combinations of Cultivar and Sowing Date for Maize in Southern Togo

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More information on DSSAT can be found in Appendix 2

Introduction

Maize is the most important crop of Southern Togo with an average yield of about 1 t/ha in the main rainy season from April to June-July. Potential yields obtained at experimental stations under optimal growing conditions or through simulation modeling (Singh et al., 1999; IFDC, 2002) are much higher and can reach 6 t/ha. Farmers face a number of biophysical and socioeconomic constraints to bridge this important yield gap. Irregularity of rainfall is one constraint and constitutes an important risk factor. To reduce this risk, some farmers sow maize over a longer period. Farmers may also stagger sowing dates because of labor constraints or because they wish to harvest when prices are high (e.g., fresh maize early in the season).

The National Agricultural Research Institute in Togo (ITRA) is currently evaluating early- and very early-maturing maize cul-

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tivars. Such cultivars may be of particular importance for southern Togo, as it has a bi-modal rainfall pattern, with two growing seasons per year: the main rainy season from April to June-July and the second rainy season from September to November. Farmers may, therefore, gain from selecting the appropriate cultivar for a particular purpose and sowing date, through decreased risk and increased productivity; this renders fertilizer use more profitable.

Finding optimum sowing dates for maize in southern Togo through field experimentation would require repeated trials for a large number of years to capture rainfall variability. Moreover, findings for one area may not have much relevance for another because of differences in rainfall distribution and/or soil type. Decision support tools (DSTs), such as DSSAT, may be helpful here. DSSAT can provide probability distributions of maize yield for any combination of sowing date, varietal choice, soil type, and crop management, provided the model is validated for the growing conditions that are targeted and sufficient years of historical weather data are available.

The objective of the case study presented here was to use DSSAT:

- To identify optimum combinations of sowing date and cultivar choice for two agro-ecological regions in Southern Togo.
- To extrapolate these results for the whole of southern Togo using a Geographic Information System (GIS).

Approach

Field Experiments

The study was conducted in two villages in southern Togo, strongly differing in soil fertility and annual rainfall—Adjodogou (poor soils, low rainfall) and Sévé Kpota (relatively better soils and higher rainfall). A general description of these two villages is provided (Table 1).

Table 1. General Description of the Two Study Sites

Village	Adjodogou	Sévé Kpota
Geographic coordinates	6.33N, 1.57E	6.44N, 0.95E
Rainfall first season (mm, 20-year average; March 1-August 31)	629	654
Rainfall second season (mm, 20-year average; September 1-December 31)	186	323
Soil type	Rhodic Ferralsols	Plinthic Acrisols
Soil depth (m)	2.0	0.8
% clay	8	15
% organic matter	0.7	1.4
% total-N	0.045	0.112
Initial NO_3 (mg/kg)	8	13
Initial NH_4^+ (mg/kg)	13	26

In both villages, five farmers participated in a number of experiments conducted in 2001. Three maize cultivars (medium, early and very early duration) were grown (Table 2). Sowing dates ranged from April 19 to May 11 during the first rainy season and from September 10 to 20 during the second season. Each farmer represented one replication. A total of 150 kg NPK (15-15-15)/ha was applied at 15 days after sowing and 50 kg urea/ha at 45 days after sowing.

Table 2. Characteristics of the Three Maize Cultivars Used in the Field Experiments

Name	AB11	TZEComp4C2	TZESRWGua314
Duration (days)	90-95	84-89	79-83
Duration (class)	Medium	Early	Very early

Soil texture, organic matter, total nitrogen, and initial concentrations of NO_3 and NH_4 in the upper 20 cm of the soil were determined for each field at the onset of the first rainy season. Automatic weather stations were located at 200 m (Sévé Kpota) and 4 km (Adjodougou) from the experimental fields to monitor daily rainfall, maximum temperature, minimum temperature, and solar radiation. Detailed measurements such as the rate of leaf appearance and dates of silking and maturity were conducted throughout the growing seasons in both villages to estimate genetic coefficients for each of the varieties. At maturity, harvest index, grain yield, total above-ground biomass, stalk biomass, grain number per m^2, unit grain weight, and N-content of grain and stalk were determined from samples taken from two adjacent hills in all fields. At harvest, the number of cobs and yield per plot were determined. This information was used to calibrate and validate the model.

Model Calibration and Validation

The data from the experiments were used to develop parameter sets for the maize model of DSSAT (CERES-Maize, which stands for Crop Evaluation Through Resource and Environment Synthesis) for each cultivar (Jones et al., 1998). DSSAT was first run using default values of maize cultivars available in the model, but relatively large deviations were observed between simulated and observed crop phenology (date of silking and date of maturity) and simulated and observed maize yield. The poor performance of the model was at least partly due to the fact that genetic coefficients (related to time of silking, time of maturity, sensitivity to photoperiod, potential kernel number per ear, grain filling rate, and number of leaves per plant) were not available for the three cultivars used in the field experiments.

Genetic coefficients were calibrated until there was an agreement between measured and observed maize phenology data and maize yields for the first rainy season at Sévé Kpota, where growing conditions were more optimal when compared with the second season at Sévé Kpota and both seasons in Adjodogou (Figure 1).

Visual field observations indicated that response to drought was variable among the three tested cultivars. The very early-maturing cultivar (TZESRW x Gua314) was most sensitive, but no cultivar-specific parameter is incorporated in the model to reflect such a difference. Hence, effort was then placed on calibrating the soil root growth factor (SRGF), a soil parameter that expresses the extent to which root growth is distributed in the profile for water and nutrient absorption for each maize cultivar.

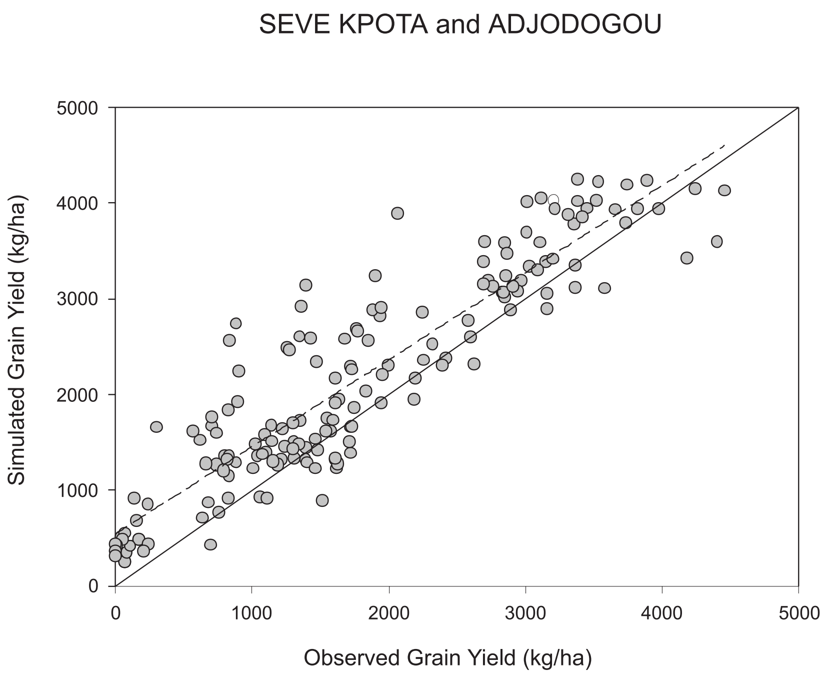

Figure 1. Comparison Between Observed and DSSAT Simulated Maize Yields (kg/ha) in Sévé Kpota and Adjodogou. (Data refer to yields obtained on five farmers' fields in each village for three sowing dates and three maize cultivars, both seasons. The solid line represents the 1:1 line; the dotted line represents the regression line [Y = 0.911X + 544, R^2 = 0.83]).

DSSAT was validated using the 2001 experimental data set from the second season at Sévé Kpota and both seasons at Adjodogou. This validation showed the importance of the availability of reliable soil data such as maximum rooting depth (restriction to root growth), bulk density, soil pH, soil moisture-holding capacity, and soil fertility status (total N, mineral N).

Model Application

DSSAT was subsequently applied to simulate the performance of different combinations of sowing date and maize cultivars over a number of years using historical rainfall covering 30 years for Sévé Kpota and 20 years for Adjodogou. The DSSAT built-in statistical weather generator (WGEN, Hansen et al., 1994) was used to estimate missing data on rainfall. Growth was assumed to be both nitrogen and water limited. The quantity and timing of nitrogen fertilization were kept unchanged as in the field trial—45.5 kg N/ha in 2 splits (22.5, 15 days after planting and 23, 45 days after planting).

For the first rainy season, simulations were conducted for both villages at 2-week intervals from April 12 to June 7. For the second rainy season, simulations were conducted at 10-day intervals from September 1 to October 11. Average simulated yields were plotted against the standard deviation of simulated yields. The standard deviation was used as a measure of variability of yield simulations and, therefore, can be seen as a proxy of risk related to sowing date (Figure 2).

Combining DSSAT and GIS

To extrapolate DSSAT results, obtained in the two villages, to other areas in Togo, an Information and Decision-Support System (IDSS) interfacing DSSAT crop models with GIS was developed. The IDSS is based on a prototype developed by IFDC for sorghum in the semi-arid tropics of India (Singh et al., 1993) and for wheat in Uruguay (Baethgen, 1998). The complexity of agro-

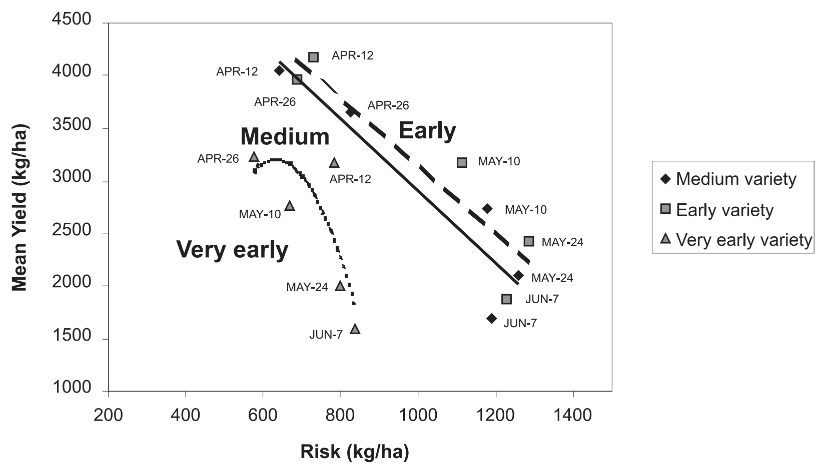

Figure 2. Average Yields (kg/ha) and Standard Deviations (kg/ha) (a proxy for risk) of Various Combinations of Varieties and Sowing Dates for the First Season, Using 30 Years of Historical Rainfall Data for Sévé Kpota. (Medium variety is AB11, early variety is TZEComp4C2, and very early variety is TZESRW x Gua314.)

ecosystems, the need for taking a long-term view of biophysical processes to assess sustainability, and the limited availability of research resources also support the utility of an IDSS.

The pedological map of Togo (Lamouroux, 1966) has been digitized; geo-referenced soil data on more than 500 representative soil profiles (ITRA, unpublished data) were subsequently entered in this map. To account for variability within a soil unit, data on soil profiles located within a soil unit were reviewed and organized in three categories: poor, medium, and good soil fertility, using C and K content as criteria.

There are only a few complete meteorological stations in Togo, but there are a large number of stations where rainfall is recorded. Each soil unit was assigned a set of meteorological data from a complete station and a rainfall station that were located inside or close to that particular soil unit. In case of large soil units with more rainfall stations, the soil unit was split into two sub-units with the same soil characteristics but different rainfall data.

DSSAT was run for each agro-ecological zone (i.e., specific combination of weather and soil type) and for different maize cultivars and sowing dates using actual weather data of 30 years.

Results and Discussion

DSSAT Calibration and Validation

After calibration of the model based on data of the first rainy season at Sévé Kpota, observed and simulated yields for both seasons and locations were compared. A close fit was noted between observed and simulated results ($r^2 = 0.83$), indicating that with correct inputs of soil and varietal characteristics, the DSSAT model captured maize yield response over different varieties, planting dates, locations, and seasons in a satisfactory way (Figure 1). The outliers in the simulated results are due to conditions that are not taken into account by DSSAT, such as weed infestation, bird damage, and shading from trees. This also shows the importance of understanding the limitations of the model being used and of eliminating or minimizing the effects of factors that are not simulated by the model; for example, by spraying herbicide or hand weeding.

Sowing Time and Varietal Choice

Results of simulations conducted for the main rainy season and staggered sowing dates from April 12 to June 7 are shown for Sévé Kpota (Figure 2). For an early sowing, a medium- or early-duration cultivar is preferred, compared with a very early variety because it gives higher yields and lower risk. Sowing after the end of April gives still slightly higher yields for the early variety as compared with the very early variety, but risks are also higher.

Results of the simulations conducted for the second rainy season and staggered sowing dates from September 1 to October 11 for Sévé Kpota are shown (Figure 3). Relatively low maize yields were simulated for all sowing dates, with a declining trend from about 2.0 t/ha for the September 1 sowing to about 0.75 t/ha for the October 11 sowing. Standard deviations declined, but at very low yield levels. These results illustrate the risk farmers take and justify their low expectations when growing a maize crop during the second rainy season.

The same trends were observed at Adjodogou, but yield levels were lower because of the less favorable growing conditions.

Simulations led to the following recommendations:

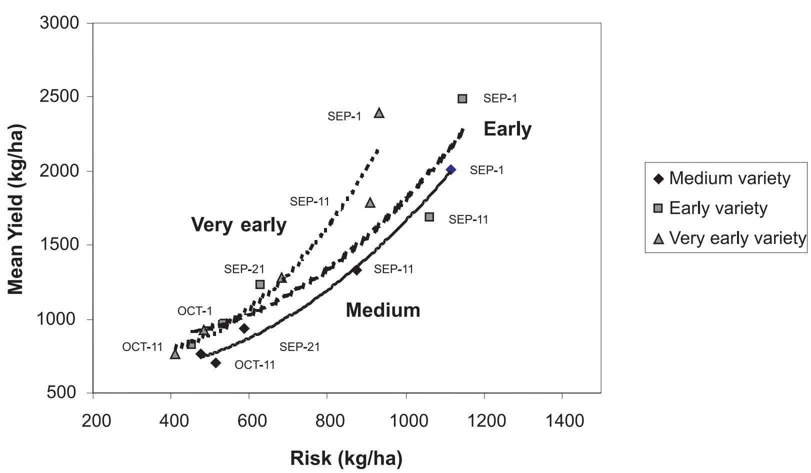

Figure 3. Average Yields (kg/ha) and Standard Deviations (kg/ha) (a proxy for risk) of Various Combinations of Varieties and Sowing Dates for the Second Season Using 30 Years of Historical Rainfall Data for Sévé Kpota (Medium variety is AB11, early variety is TZEComp4C2, and very early variety is TZESRW x Gua314)

Sévé Kpota

1. At the start of the first rainy season, the medium-duration variety will give the highest yield; from the end of April the early variety (TZEComp4C2) is preferred. Farmers did indeed prefer purchasing this variety when given the choice between the three maize cultivars tested in this study (Figure 4).
2. In the second (shorter) season, the very early-maturing cultivar proved to be the best compromise between a reasonable yield and a relatively low risk (Figure 3).

Adjodogou

1. The early variety appeared to be the best variety for the first rainy season. Many farmers, however, preferred the very early variety because it reduces the "hungry season" and because of its sweet taste, showing that factors other than yield and reduced risk play important roles.
2. The very early variety is the best if farmers have to sow late in the first season and for the whole of the second season.

Farmer Decision Support Tool

Based on these results, leaflets were made to help the farmers choose between varieties as a function of the preferred time of

Sowing Date	**Cultivar Name**			**Expected Yield (kg/ha)**
	AB 11	TZEComp4C2	TZESRW x Gua314	
12 April				4500 – 3400
26 April				4000 – 3000
10 May				3000 – 2400
24 May				2300 – 1800
7 June				1800 – 1200

Preference order: 1st 2nd 3rd

Figure 4. Leaflet Showing Preferred Maize Cultivar for Various Sowing Dates and Its Expected Yield for Sévé Kpota, Southern Togo

sowing. One of the leaflets shows various combinations of variety and sowing period and the expected range of yields of the preferred variety. The colors indicate, for each sowing period, the order in preference of the varieties though this does not consider other characteristics such as quality, resistance to birds, etc. The leaflet has been translated into the local language, Ewe, and has been distributed to farmers (Figure 4).

Combining GIS and DSSAT

Examples of results obtained from combining GIS and DSSAT are shown for Southern Togo (Figures 5 and 6). The results show average yields of a medium-duration maize variety (AB 11) for the various combinations of soil units and meteorological data over 30 years on good soils. The results pertain to early sowing and late sowing.

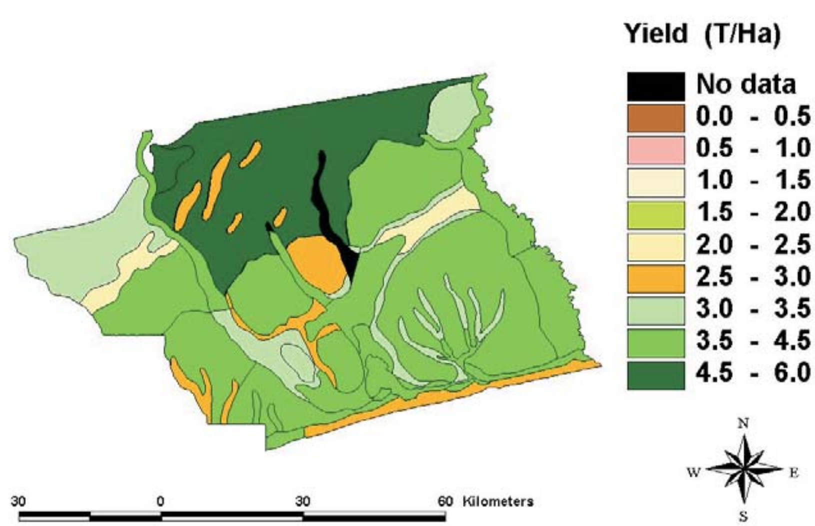

Figure 5. Average DSSAT-Simulated Maize Yields Over 30 Years of a Medium Duration Variety (AB11) if Sown Early (12 April)

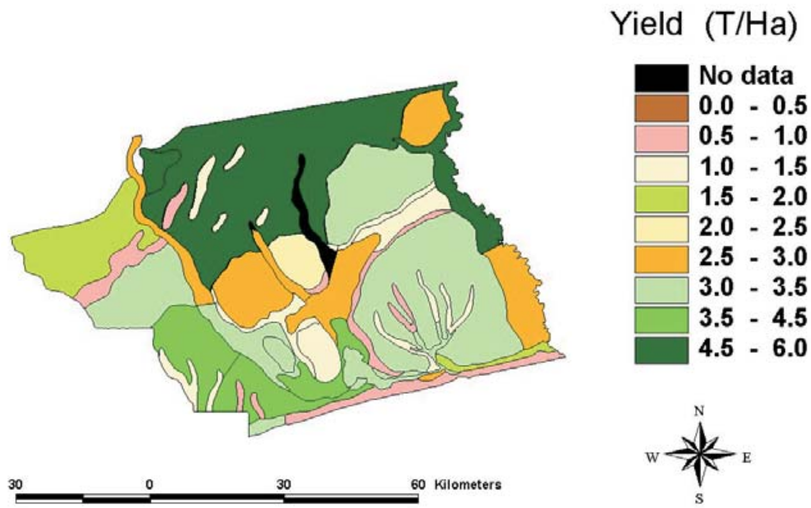

Figure 6. Average Maize Yields Over 30 Years of a Medium Duration Variety (AB11) if Sown Late (24 May)

Similar figures could be made for other combinations including soils of medium and poor fertility. The categorization into good, medium, and poor soils has been done based solely on analytical soil data; it should ideally be done in close collaboration with the farmers, possibly using local soil classification systems. In Southern Togo, for instance, farmers classify their soil according to color, e.g., black, red, and white soils. After identification of such categories, these should be characterized, resulting in a geo-referenced soil map in which each soil unit represents a number of soil categories. Because these categories may constitute an intricate pattern, it is useless to try to geo-reference them. Instead, it seems more efficient to use the descriptions of these categories as a basis for the simulations and to link the results of these simulations to the soil categories as identified by the local farmers and extension staff.

Conclusions

This case shows the potential of the use of DSSAT, especially in combination with a geo-referenced database; results obtained in one year and on a limited number of sites can be used to explore the possibilities for other areas and the associated risks. This constitutes a considerable improvement in the development of site-specific recommendations. At the same time, it offers the possibility of saving time and resources required for the development of these recommendations.

Although this seems very promising, it should be realized that availability and quality of data are essential prerequisites for the use of such tools. In this case, data used for the GIS database were from soil survey studies that were in some cases more than 30 years old. Obviously, soil fertility may have changed over time, but data interpretation may also be difficult. This holds true especially for the data on available P because different methods of analyses used make it difficult to compare different soils. This implies a need to continue to collect data and to improve the quality of the database. It should also be realized, that simulation models involve a limited number of factors. For instance, the effects of weeds, birds, pests and diseases, the presence of an intercrop, and P and K deficiencies are not or are poorly considered by the model. Results of such tools should therefore always be treated with caution, requiring further interpretation by researchers, extension staff, and farmers.

References

Baethgen, W. E. 1998. "Applying Scientific Results in the Agricultural Sector: Information and Decision Support Systems," IN *Proceedings of the Inter-American Institute for Global Change Research (IAI) Science Forum: Global Change in the Americas*, Arlington, Virginia, June 1998.

Hansen, J. W., N. B. Pickering, J. W. Jones, C. Wells, H. Chan, and D. C. Godwin. 1994. "Weatherman," IN G. Tsuji, G. Uehara, and S. Balas (Eds.), *DSSAT Version 3,* University of Hawaii, Honolulu, Hawaii, pp. 138-200.

IFDC—An International Center for Soil Fertility and Agricultural Development. 2002. *Collaborative Research Program for Soil Fertility Restoration and Management in Resource-Poor Areas of Sub-Saharan Africa*, Tech. Bull. 67, IFDC, Muscle Shoals, Alabama, U.S.A.

Jones, J. W., G. Y. Tsuji, G. Hoogenboom, L. A. Hunt, P. K. Thornton, P. W. Wilkens, D. T. Imamura, W. T. Bowen, and U. Singh. 1998. "Decision-Support System for Agrotechnology Transfer: DSSAT v3," IN: G. Y. Tsuji et al. (Eds.), *Understanding Options for Agricultural Production*, pp. 157-177. Kluwer Academic Publishers, Netherlands.

Lamouroux, R. 1966. "Carte Pédologique du Togo à l'Echelle de 1/1000000," Bureau for Overseas Scientific and Technical Research (ORSTOM), Lomé, Togo.

Singh, U., J. E. Brink, P. K. Thornton, and C. B. Christianson. 1993. "Linking Crop Models With a Geographic Information System to Assist Decisionmaking: A Prototype for the Semi-Arid Tropics," IFDC Paper Series P-19, IFDC, Muscle Shoals, Alabama, U.S.A.

Singh, U., H. van Reuler, V. Chude, K. Aihou, and P. Dejean. 1999. "Using Decision-Support Systems to Stimulate Resource-Conserving Practices," Paper presented at the MODSS'99 Conference, August 1-6, 1999, Brisbane, Australia.

Chapter 8

Decision Support Tools for Irrigated Rice-Based Systems in the Sahel

M.C.S. Wopereis,[1] S. M. Haefele,[2] M. Dingkuhn,[3] and A. Sow[2]

More information on RIDEV can be found in Appendix 10

Introduction

Rice (*Oryza sativa* L.) is becoming one of the primary staple food items of West Africa. Although irrigated lowlands only comprise approximately 10.5% of total regional rice area, these ecologies have the highest yield potential and contribute 26% to the regional rice supply (Maclean et al., 2002). Irrigated perimeters are found throughout West Africa from the desert margins in Mauritania and Niger to the humid forest zone of Sierra Leone and Nigeria.

The irrigated rice area in the Sahel and Sudan Savanna is about 0.35 Mha (Maclean et al., 2002). This extends from Senegal and Mauritania through Mali, Burkina Faso, Nigeria, and into Cameroon. In these areas, irrigation water is either pumped from tube wells and the main rivers or gravity fed from rivers and dams. Rice is direct, wet seeded, or transplanted and mainly grown in the wet season (July-November), with about 10%-20% of the

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farmers growing a second crop in the dry season (February-May) on the same field. Land preparation is usually tractor driven or by animal power. Average farmers' yields in irrigated systems in the Sahel are estimated at 4.5 t/ha (Wopereis et al., 1999).

Farmers who grow irrigated rice in the Sahel have to cope with significant temperature fluctuations during the year. Low temperatures at panicle initiation during the wet season and high temperatures around flowering during the dry season may cause spikelet sterility and, therefore, substantial yield loss. Timing of sowing and the type of cultivar to be used (short or medium duration) are critical, especially if two rice crops per year are grown on the same field. Moreover, timing of other crop management interventions, such as weeding, fertilizer applications, and harvesting, depend on the crop development stage, which is also influenced by temperature. Timing of such crop management interventions has an important impact on rice productivity (e.g., Wopereis et al., 1999; Haefele et al., 2002; Poussin et al., 2003). WARDA and partners have developed a set of decision support tools (DSTs) that can help farmers with management of the cropping calendar for irrigated rice in the Sahel. DSTs range from simple decision trees, tables, and cropping calendars to a more complex crop-growth simulation model. In this chapter, we illustrate the use of these tools through a number of case studies.

The Decision Support Tool RIDEV

The phenology model RIDEV, used in this study, was described by Dingkuhn (1995). It provides a time axis from development stage 0 (germination) to 2 (maturity). Progress along this axis from germination (0) to flowering (1) is driven by photo-period and temperature at the shoot apex. Since the shoot apex is submerged during most of the growth phases, floodwater temperature is simulated from air temperatures and leaf area index. Assuming that grain maturation is mainly driven by metabolic processes, progress from flowering (1) to maturity (2) is modulated by air temperature effects on daily maturation rate.

Chilling-induced spikelet sterility is simulated based on mean minimum air temperatures at booting to heading stage and plant-dependent critical lower temperatures. Heat-induced sterility is simulated based on high minimum and mean daily temperatures at the anthesis stage and plant-dependent critical upper temperatures. Model output does not account for baseline sterility of 5%-15%, which is not related to climate.

Model input data are sowing date, daily minimum and maximum temperatures, geographical latitude, photo-thermal characteristics of the rice cultivar, and planting method (transplanting or direct seeding). Photo-thermal characteristics of 49 cultivars were presented by Dingkuhn and Miézan (1995) and, today, characteristics of 95 cultivars are included in the model. Model outputs are the percentage of spikelet sterility, growth duration, and crop management recommendations based on crop phenology.

Characterization of Rice Environments

To get an overview of the extent of problems related to temperature stress in the Sahel, RIDEV simulations were conducted for three commonly grown rice cultivars using a weather database available at WARDA (Dingkuhn, 1995). The database contained 38 sites located in Senegal, Mauritania, Mali, Burkina Faso, Niger, and Tchad. For each of these sites, 10-33 years of historical weather data were available. RIDEV simulations showed that sowing between mid-September and mid-November was associated with near-total yield loss due to cold stress in all environments. Crop duration was longest when sown in November, increasing by 5 days per degree latitude in the continental Sahel. Greatest annual variation in duration was observed in the coastal west and extreme north of the Sahel. Different annual patterns of duration and yield loss were associated with climatic gradients along the courses of the Senegal and Niger Rivers. Based on the genotypes available to farmers, local rice-rice cropping calendars left little room for alternative calendars. Achieving a greater flexibility for cropping calendars would require the introduction of short-duration varieties.

RIDEV was used in this case to characterize rice-growing environments in terms of risk of yield loss due to temperature stress and variability in growth duration. Without the model this study would have been impossible to conduct. It would have required field experiments over 10-30 years at the 38 sites used in this study. Simulation modeling was able to capture the risk of temperature stress and the variability in growth duration as a function of sowing date and site and consider year-to-year variability.

Improving the Timing of Crop Management Interventions

Rice scientists from WARDA, Burkina Faso, Mali, and Senegal in collaboration with farmers' organizations and extension agencies have conducted combined agronomic and socioeconomic surveys in key irrigated rice systems in the Sahel to determine reasons behind farmers' decision making and their primary constraints and opportunities. Details are provided in Wopereis et al. (1999) and Haefele et al. (2001). Average farmers' yields in the surveys were between 3.8 and 7.2 t/ha, resulting in an overall average of 4.5 t/ha. Yields of individual farmers were highly variable, ranging from almost complete crop failure (0.3 t/ha) to very high yields (8.7 t/ha). High average yields and low yield variability were found in relatively old irrigation schemes, e.g., in the Niger office in Mali.

RIDEV was used to determine optimal timing of N fertilizer application (three splits coinciding with the start of tillering, panicle initiation, and heading), timing of drainage for harvesting (2 weeks after flowering), and timing of harvest (at physiological maturity) for every combination of sowing date and cultivar choice observed in the surveys.

The comparison of actual and optimal (according to RIDEV) timing of crop management interventions often revealed important discrepancies. An example for the Guédé irrigation scheme in Senegal (16°35'N, 15°02'W) is given in Figure 1. Lack of information on optimal timing and problems with access to inputs such as credit, seed, and fertilizer were among the main reasons that were cited by farmers (Haefele et al., 2002).

Poussin et al. (2003) used the RIDEV model to analyze growth cycles and yield loss due to temperature stress in surveys conducted in the Senegal River Valley. Model outcome showed that yield losses due to cold or heat stress conducted during flowering could be neglected and that harvest timing was close to physiological maturity. Analysis of soil samples revealed sufficient levels of soil P and K for rice growth and development. The authors concluded that yield variability was, therefore, mostly due to differences in crop management (other than choice of sowing and harvest date) at the farmer level. RIDEV simulations allowed the separation of farmer fields in well-managed plots and poorly managed plots as far as N fertilizer application was concerned. Subsequent principal component analyses identified sub-optimal weed and N fertilizer management as the main factors driving yield variability in farmers' fields. Haefele et al. (2000) confirmed this finding by evaluating improved soil fertility and weed management practices with farmers in Mauritania and Senegal. Improved fertilizer management increased grain yield by 0.9 t/ha; whereas the recommended weed management resulted in a yield increase of 1.0 t/ha. The effect of recommended management practices was additive and gave a mean yield increase of 1.8 t/ha compared with farmers' practices. The value/cost ratios were between 2.1 and 4.6 for the improved treatments, and improved soil fertility and weed management resulted in an increase in net revenues of 40%-85% compared with farmers' practice.

Cropping Calendar Tables—WARDA staff summarized RIDEV output in tables for use by village communities and extension agents in the field. An example is given in Table 1 for the irrigation schemes around Podor (16°35'N, 15°20'W) in the

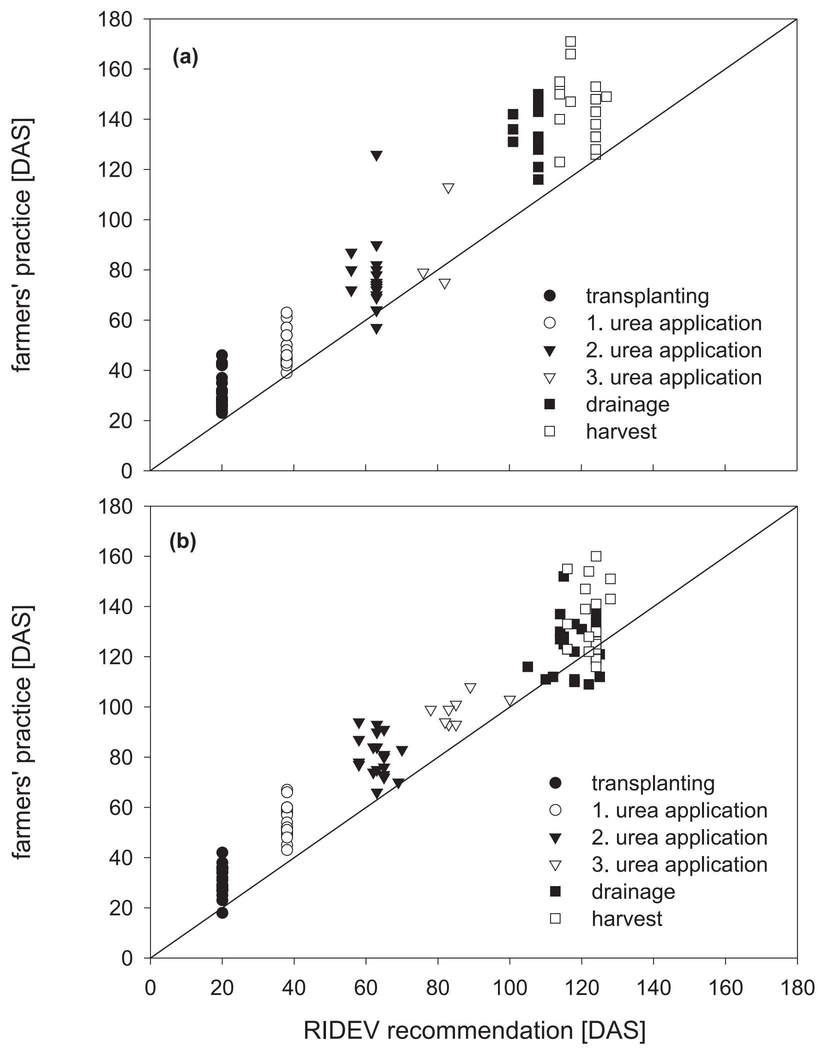

Figure 1. Actual Timing of Farmers' Practice in Comparison With Optimal Timing of Crop Management Interventions in Guédé, Senegal During the 1996 Wet Season (a) and the 1997 Wet Season (b) in Days After Sowing (DAS). Optimal Timing Was Derived Using the RIDEV Simulation Model.

Table 1. RIDEV Estimated Cropping Calendars Using 7-Day Intervals for Transplanted Rice, Cultivar Jaya, During the Wet Season in Podor, Senegal (Based onSimulations Using 30 Years of Historical Weather Data)

Sowing Date	Trans-planting Date	First Urea Split	Second Urea Split	Third Urea Split	Date of Flowering	Date of Last Drainage	Harvest Date	Mean % Sterility	Years >30% Sterility	Cropping Cycle (days)
June 23	July 13	July 31	Aug 27	Sept 16	Sept 26	Oct 11	Oct 25	1	1	125
June 30	July 20	Aug 7	Sept 2	Sept 22	Oct 2	Oct 17	Oct 31	3	2	124
July 7	July 27	Aug 14	Sept 8	Sept 29	Oct 9	Oct 23	Nov 6	4	1	125
July 14	Aug 3	Aug 21	Sept 14	Oct 5	Oct 15	Oct 29	Nov 12	1	1	125
July 21	Aug 10	Aug 28	Sept 21	Oct 11	Oct 21	Nov 5	Nov 19	0	0	125
July 28	Aug 17	Sept 4	Sept 28	Oct 18	Oct 28	Nov 12	Nov 26	0	0	126
Aug 4	Aug 24	Sept 11	Oct 5	Oct 26	Nov 5	Nov 19	Dec 3	0	0	128
Aug 11	Aug 31	Sept 18	Oct 13	Nov 3	Nov 13	Nov 27	Dec 11	1	1	131
Aug 18	Sept 7	Sept 25	Oct 23	Nov 12	Nov 22	Dec 7	Dec 21	9	4	135
Aug 25	Sept 14	Oct 2	Nov 2	Nov 22	Dec 2	Dec 17	Dec 31	20	14	140
Sept 1	Sept 21	Oct 9	Nov 14	Dec 5	Dec 15	Dec 29	Jan 12	54	23	147
Sept 8	Sept 28	Oct 16	Nov 28	Dec 19	Dec 29	Jan 12	Jan 26	71	30	154

Senegal River Valley. Values are averages for simulations conducted at 7-day intervals over a period of 33 years of historical weather data. The table shows the best timing of crop management interventions as a function of the sowing date and cultivar used and also shows the risk of yield loss due to temperature stress. Using RIDEV, similar tables can be made for any site x sowing date x cultivar choice x crop establishment method combination in the Sahel, provided weather data are available. The simulations also pinpoint the risk related to a certain sowing date. Although the mean sterility percentage is only 9% if rice is sown on August 18 (which would hardly influence grain yields), sterility was clearly above 30% in 4 years (Table 1). Therefore, considerable yield and investment losses can be expected in 4 out of 30 years for that sowing date.

Cropping Calendar Posters—Although the cropping calendar tables provide a quick and easy reference, they are not particularly suitable as discussion and learning tools. RIDEV outcome was, therefore, captured on posters depicting the optimal cropping calendar for a given site, using the most common crop establishment method, sowing date, and cultivar grown. An example is given in Figure 2. Such cropping calendar posters proved extremely useful during field visits and discussions with farmers. They allow building a discussion around all management interventions that are needed during the growth cycle of rice. Field water management is also depicted in the poster. Drainage of the field before herbicide and fertilizer applications and final drainage 15 days before harvest are required. These posters are specific to location, crop establishment technique, sowing date, and cultivar choice and can be adapted easily using RIDEV.

Getting It All Together—Development of Integrated Crop Management (ICM) Options

Based on crop simulation modeling, field surveys, and field experiments conducted on- and off-station, WARDA and its partners developed improved integrated crop management (ICM)

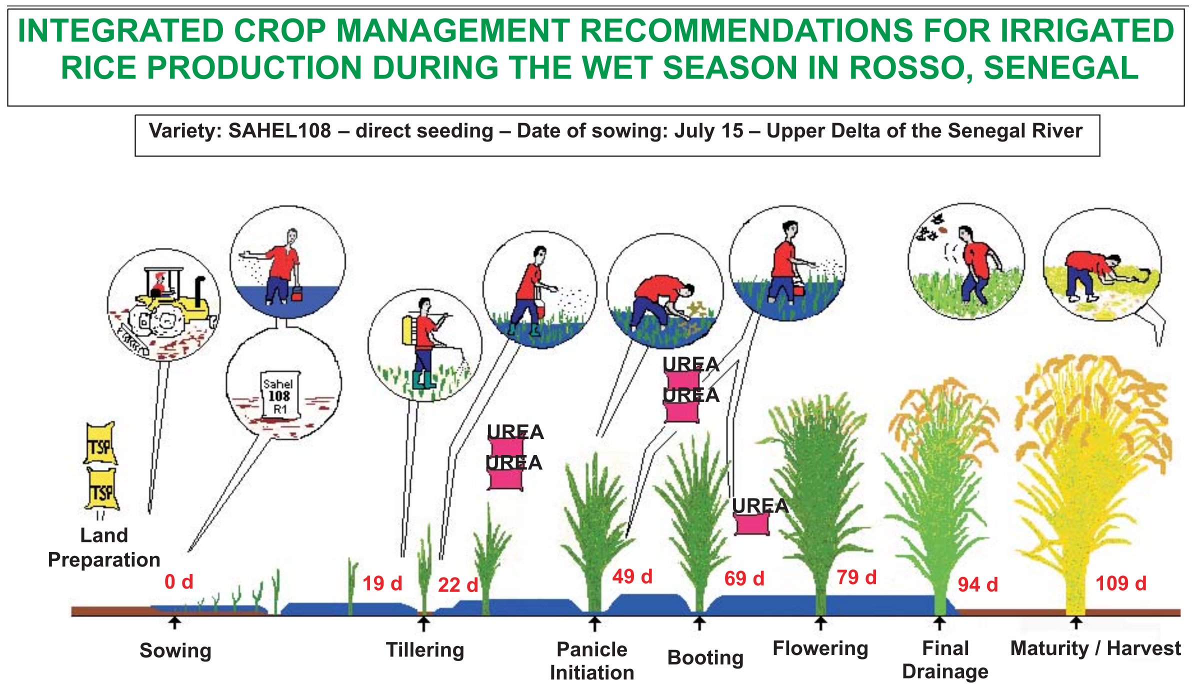

Figure 2. ICM Poster for Direct-Seeded Rice, Cultivar: Sahel 108, Site: Rosso, Senegal, Sowing Date: July 15, Wet Season. The Poster Can Be Adapted Easily for Any (Site x Cultivar x Sowing Date x Crop Establishment Technique) Combination of Irrigated Rice Grown in the Sahel.

options for irrigated rice cropping in the Sahel, which are within farmers' means. For the Senegal River Valley, these options have been summarized in a manual (WARDA and SAED, 2000) and two-page leaflets. The manuals and leaflets give a farming calendar for best-bet management, but relevant information is given to enable farmers to adapt them according to their means. ICM options for the Senegal River Valley include the following:

- Land Preparation—Cultivate on soil suitable for irrigated rice (i.e., heavy clay soils, local soil series terminology – Hollaldé and Faux-Hollaldé soils) and make sure the field is properly tilled and leveled.
- Varietal Choice—Use pre-germinated certified (or high quality) seeds; for the dry season (DS) – Sahel 108 (good grain quality but salinity sensitive) or I Kong Pao (low grain quality, salinity tolerant); and for the wet season (WS) – Sahel 108, Jaya, Sahel 201, Sahel 202.
- Sowing Date—Guided by RIDEV to avoid yield loss due to cold or heat.
- Seeding Rates—Use certified (or high quality) seed and 100 and 40 kg/ha, respectively, for direct seeding and transplanting.
- Maximum Recommended Fertilizer Rates—100 kg/ha triple superphosphate (TSP, 20% P) or diammonium phosphate (DAP, 20% P, 18% N) and 250 to 300 kg/ha urea (46% N), depending on location along the Senegal River. TSP is applied as a base fertilizer and urea is applied in three splits. The first dose of 40% is applied at the start of tillering and another dose of 40% at panicle initiation. A final dose of 20% is applied at the booting stage of the crop. Timing is guided by RIDEV.
- Weed Management—A mixture of 8 L/ha of Propanil and 1 L/ha of 2,4D applied a few days before first urea application (at 2-3 leaf stage of the weeds) in conjunction with one manual weeding before the second urea application.
- Water Management—Directed at maximizing the efficiency of fertilizers and herbicides, consists of applying herbicides in completely drained fields and reducing water levels in the field to a minimum for about 4-5 days at each fertilizer application.

The rice field is completely drained 15 days after flowering to promote uniform ripening of the grains but primarily to allow for a timely harvest.

- Harvest and Post-Harvest—Harvesting at maturity, i.e., if about 80% of the panicles are yellow. Threshing should be within 7 days after timely harvest.

These improved ICM practices were evaluated with over 300 farmers in the Senegal River Valley in both Senegal and Mauritania. Significant gains in yield (average—close to 2 t/ha) and net returns per hectare were obtained from ICM although input use levels and total production costs per hectare were similar to current farmer practices. Profitability and productivity gaps between ICM and farmers' practices could be largely explained by differences in the management of available resources and not input use levels. More detailed studies in 2001 and 2002 (Kebbeh and Miézan, 2003) in Senegal and Mauritania indicated that productivity gains are directly related to the number of ICM options that farmers are able to implement. Through ICM, farmers were able to increase rice productivity and at the same time maintain or even increase the quality of the natural resource base. Increased fertilizer and herbicide use efficiencies will reduce losses of N and herbicides to the environment. The DSTs developed by WARDA were instrumental in deriving these ICM options for a range of environmental conditions relevant to farmers (i.e., sowing date x site x cultivar choice x crop establishment method combinations) and in estimating risk. This would have been impossible to achieve through field experimentation only.

Conclusions

RIDEV was used for a variety of purposes—characterization of rice-growing environments at a regional scale, analysis of farmer management practices, and the development of ICM options. RIDEV was also used to estimate risk of yield loss due to temperature stress associated with a certain sowing date x site x cultivar combination. This type of knowledge is of great importance to farmers and cannot be achieved with field experimentation. Model outcome was translated into DSTs that can be more readily used by farmers. The cropping calendar DST (Figure 2) proved to be extremely useful in farmer discussions and as a learning tool in general.

WARDA, National Agricultural Research and Extension Systems (NARES), and NGOs from Mauritania and Senegal are now exploring ways to scale up results from these studies to a much larger number of farmers. Our experience has shown that what farmers need is not rigid recommendations detailing a precise package that must be adopted, but rather options—choices from which they can select those components that would be most beneficial to them. Best results are obtained if these options are developed through partnerships, involving farmers and other rice development stakeholders, specific to the technology involved. This ensures that technologies are suitable for their target environment and that training materials are appropriate for potential users. DSTs can play a key role in speeding up research and in the development of improved crop management options with farmers.

References

Dingkuhn, M., and K. M. Miézan. 1995. "Climatic Determinants of Irrigated Rice Performance in the Sahel. II. Validation of Photothermal Constants and Characterization of Genotypes," *Agricultural Systems*, 48:411-434.

Dingkukn, M. 1995. "Climatic Determinants of Irrigated Rice Performance in the Sahel. III. Characterizing Environments by Simulating the Crop's Photothermal Responses," *Agricultural Systems*, 48:435-456.

Haefele, S. M., M.C.S. Wopereis, and C. Donovan. 2002. "Farmers' Perceptions, Practices, and Performance in a Sahelian Irrigated Rice Scheme," *Experimental Agriculture*, 38(02):197-210.

Haefele, S. M., M.C.S. Wopereis, C. Donovan, and J. Maubuisson. 2001. "Improving Productivity and Profitability of Irrigated Rice Production in Mauritania," *European Journal of Agronomy*, 14(3):181-196.

Haefele, S., D. E. Johnson, S. Diallo, M.C.S. Wopereis, and I. Janin. 2000. "Improved Soil Fertility and Weed Management is Profitable for Irrigated Rice Farmers in Sahelian Africa," *Field Crops Research*, 66:101-113.

Kebbeh, M., and K. M. Miézan. 2003. "Ex-Ante Evaluation of Integrated Crop Management Options for Irrigated Rice Production in the Senegal River Valley," *Field Crops Research*, 81:87-94.

Maclean, J. L., D. C. Dawe, B. Hardy, and G. P. Hettel, (Eds.). 2002. *Rice Almanac*. Los Baños (Philippines): International Rice Research Institute, Bouaké (Côte d'Ivoire): WARDA, Cali (Colombia): International Center for Tropical Agriculture, Rome (Italy): Food and Agriculture Organization, 253 p.

Poussin, J. C., M.C.S. Wopereis, D. Debouzie, and J. L. Maeght. 2003. "Determinants of Irrigated Rice Yield in the Senegal River Valley," *European Journal of Agronomy* (in press).

WARDA and SAED. 2000. Manuel Pratique Pour la Riziculture Irriguée dans la Vallée du Fleuve Sénégal. West African Rice Development Association, BP 96, St. Louis, Senegal / Senegalese Irrigation and Extension Authority, 100 p. + Annexes.

Wopereis, M.C.S., C. Donovan, B. Nebié, D. Guindo, and M. K. N'Diaye. 1999. "Soil Fertility Management in Irrigated Rice Systems in the Sahel and Savanna Regions of West Africa. Part I. Agronomic Analysis," *Field Crops Research*, 61:125-145.

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More information on SARRA-H can be found in Appendix 16

Water determines the length of the growing season and the potential yield of dryland crops in the West African Sahel and Sudan savannahs. Thereby, it also determines the capacity of these crops to use nutrients. The predominant crops in this environment are C4-type cereals, millet, and sorghum, which are commonly sown on variable dates, depending on the perceived onset date of the rainy season (Vaksmann et al., 1996; Sivakumar, 1988). Depending on whether the crop is traditional (photo-period sensitive) or improved (insensitive), it will reach maturity either at a relatively stable calendar date or after genotype specific growth duration (Bacci and Reyniers, 1998). During that period, the crop will undergo variable degrees of drought, with variable effects on yield, because the phenological phases of the crop differ in stress sensitivity.

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The processes governing these relationships are well known. The problem, however, is how to translate this scientific knowledge into information on the risk of crop failure, thus permitting the extension worker to give better informed advice or the politician to initiate timely relief operations. Since the devastating droughts of the 1970s, this challenge has been addressed with new regional mechanisms for climatic data acquisition and pooling (AGRHYMET, for the nine member countries of Permanent Interstate Committee for Drought Control in the Sahel [CILSS]), continuous crop yield monitoring (Maraux et al., 1994), and seasonal yield forecasting (the Crop Water Diagnosis [DHC] system of AGRHYMET). Such activities require simple and robust tools relating climate variability to agronomic impact. Two such generic tools are widely used in the tropics; namely, the Cropwat model of the Food and Agriculture Organization of the United Nations (FAO) (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979) and the System for Regional Analysis of Agro-Climatic Risks (SARRA) (Baron et al., 1999) developed by CIRAD and its partners in West Africa. SARRA, in a variety of versions carrying different names, has become the "industry standard" in the CILSS countries and will be presented here.

SARRA is a simple model simulating the water balance of an annual crop at the plot scale and at the regional scale by extrapolation. Versions exist for the analysis of weather data files (SARRA-MET), the crop/water balance-based evaluation of climatic patterns and situations (SARRA-BIL), and the establishment of geo-referenced crop/water balance files that permit agro-climatic zoning (SARRA-ZON). A specialized version of the model, called DHC (Samba, 1998), is used by national agrometeorological services and AGRHYMET for seasonal yield forecasting at the regional scale. Last, a full crop model has recently been built around SARRA, called SARRA-H (H for "habillé" or "dressed") (Samba et al., 2001).

Data Requirements and Parameters

SARRA operates at a daily time step with rains replenishing a topsoil compartment of variable depth and evapotranspiration (ET) depleting it. The model therefore uses two climatic variables—rainfall and atmospheric demand (potential evapotranspiration [ETP]; Doorenbos and Pruitt, 1977)—a small number of parameters describing volumetric soil water-holding capacity (RU = potential water storage above the wilting point), and the duration (in days) of various growth phases. These, in turn, are characterized by forced dynamics of a crop coefficient (Kc—unitless) and a progress rate of the root front (distance.d^{-1}). Furthermore, a number of empirical constants set the rainfall criteria that would initiate sowing, the modalities for an automatic test during seedling stage for stress-induced crop failure, and the option for automatic replanting in the case of failure. Last, empirical constants are used in a simple rule to estimate runoff, which is thought to be a fixed fraction of daily precipitation exceeding a critical value.

Water Balance

The SARRA water balance is summarized in Figure 1. An important feature, particularly developed for very seasonal rainfall patterns that have a pronounced dry period, is the simulation of a wetting front. The wetting front descends in the course of the rainy season, mainly fed by larger rain events (runoff subtracted) that over-saturate the already wet soil layers. The root front is limited by the wetting front and, therefore, follows the wetting front with a variable delay, depending on the rate of root front progression. This modeling concept evidently requires simulations to start well before sowing, ideally at the onset of the rainy season when the soil profile is dry.

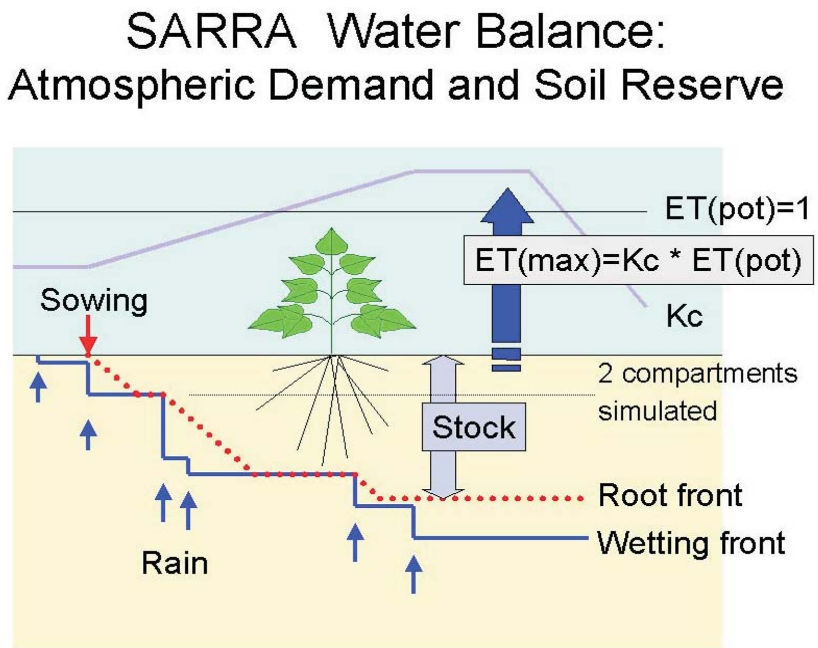

Figure 1. Main Components of the SARRA Water Balance

The topsoil is divided into a surface layer of fixed thickness (20 cm for free-draining soils in the Sahel) that serves to calculate surface humidity in the absence of a crop and a soil compartment of variable thickness. The latter increases in depth as the root front progresses, thereby increasing the soil/water compartment available for extraction. A single variable describes soil/water status for this layer called relative soil humidity (RSH), which has the same meaning as the Fraction of Transpirable Soil Water (FTSW). It describes the fraction of RU available to the plant (above the wilting point) in the root zone.

Water extraction from the soil is a function of the atmospheric demand ETP, transformed in two stages to express crop demand. The first transformation is the multiplication Kc (based on forced dynamics according to the developmental stage), resulting in maximal evapotranspiration (ETM) under stress-free conditions:

$$ETM = Kc * ETP \qquad (0 < Kc < ca.\ 1.5)$$

The second transformation corresponds to the effect of drought, using the Eagleman equation (Eagleman, 1971). This equation, which has a similar effect as the P-factor of FAO (Doorenbos and Kassam, 1979), translates FTSW into a relative reduction of evapotranspiration, resulting in ETR (R for “real” or actual):

$$ETR = ETM * fn(FTSW, ETP)$$

The Eagleman equation, which is entirely empirical, describes a non-linear decrease in the ratio ETR/ETM as FTSW declines, with ETP enhancing this response. Consequently, ETR is more sensitive to soil/water deficit when atmospheric demand is high. ETR(i) describes the amount of water evapotranspired on day (i), and thus affects soil/water status on the subsequent day.

Drought Index and Yield Estimation

SARRA or SARRA-derived yield estimations are entirely water balance driven without directly considering the assimilation of carbon. The term ETR/ETM (0…1) figures as a daily **index of water status**, 1 being non-stressed and 0 being stressed to the wilting point. This index can be used in many ways; for example, as a diagnostic tool to be applied in real time at the plot or regional level and integrating the recent hydrological past to estimate a current status. If ETR is actual water use of the crop and ETM is potential water use, a number of useful, secondary indexes can be derived:

ETR/ETM(i)
= physiological drought level on day (i)

$\Sigma ETR_{\text{(growth cycle)}}$

= rough indicator for **total biomass produced**, assuming that water use efficiency is constant and transpiration >> evaporation. (If a closed crop canopy is established late, it may be useful to consider only the post-establishment period.)

$\Sigma ETR_{(growth\ cycle)} / \Sigma ETM_{(growth\ cycle)}$

= similar to ΣETR, but expressed as a fraction of the potential

$\Sigma ETR_{(critical\ phase)} / \Sigma ETM_{(critical\ phase)}$

= Stress level during a physiologically critical phase, such as flowering, which is frequently indicative of **harvest index** (HI)

$\Sigma ETR_{(growth\ cycle)} / \Sigma ETM_{(growth\ cycle)} * \Sigma ETR_{(critical\ phase)} / \Sigma ETM_{(critical\ phase)}$

= indicator of **water limited yield**, conceptually seen as **biomass * HI**, and called **IRESP**

In fact, IRESP was found to be strongly correlated with on-farm millet yields surveyed and aggregated at the village level in Senegal, Mali, Burkina Faso, and Niger in 1988-90 (Maraux et al., 1994), resulting in the following correlation:

$$\text{Grain yield (kg/ha)} = 11.3\ \text{IRESP} - 128$$
$$N = 90,\ R^2 = 0.66$$

Specialized Versions of SARRA

Three fully documented versions of SARRA are available and have been translated from French into Portuguese, Spanish, Indonesian, and English (but no English version of the manuals is available) (Baron et al., 1996). Their format—Pascal programming under DOS, classical multiple-choice menus—may be outdated, but SARRA remains a widely used tool in applied agricultural research and development; for example, in West Africa and Brazil. The software, distributed by CIRAD, is freely available for non-commercial users, subject to a license agreement.

Three specialized versions of SARRA exist:

- SARRA-MET: This version allows pluri- and intra-annual analyses of station weather data, including frequency distributions, some other statistical analyses, and graphic outputs. Output files are in ASCII format and thus, accessible to common spreadsheets.
- SARRA-BIL: This version translates series of weather data into plot-level water balances and permits their intra- and inter-annual statistical analysis similar to that of SARRA-MET.
- SARRA-ZON: Performs water balance calculations on a large number of geo-referenced weather data and prepares them for zoning studies (which, however, require complementary software such as Surfer or GIS tools).

Examples of applications of SARRA for millet in West Africa and for maize in Brazil are given in Affholder (1997) and Affholder et al. (1997).

DHC—A Yield Forecasting System for the CILSS Countries Based on SARRA

In 1991, Diagnostic Hydrique des Cultures (DHC) was adopted by AGRHYMET as a means to predict grain yields in the course of the cropping season for the nine CILSS countries, namely Burkina Faso, Cape Verde, Guinea-Bissau, Mali, Mauritania, Niger Republic, Senegal, Tchad, and Gambia (Girard et al., 1991). This modeling system uses, through the AGRHYMET network, near-real time, daily rainfall records from approximately 180 locations to simulate the hydric evolution of the current season's millet crop, and extrapolates the analysis into the future part of the cropping season by consulting historical records. Similarly, because ETP data are frequently unavailable and would have to rely on a much sparser network of stations, historical and decadal means of ETP, kriged for the region (using geospatial analysis), are used for the entire crop cycle. Sowing dates are generally simulated using farmers' rainfall-based criteria. Yield predictions are surprisingly good (Example: end-of-season simulations for 10 administrative regions in Senegal, Figure 2), and are released to the public as maps in the course of the summer season by AGRHYMET (www.agrhymet.ne) and FAO.

A modified system called DHC-CP (Crop Water Diagnosis and Rainfall Patterns) uses Meteosat images for rainfall estimations and a probabilistic rainfall generator (Goze, 1990) to adapt them to plot-level frequency distributions on geo-referenced grid cells. This system, although operational, is currently not being used.

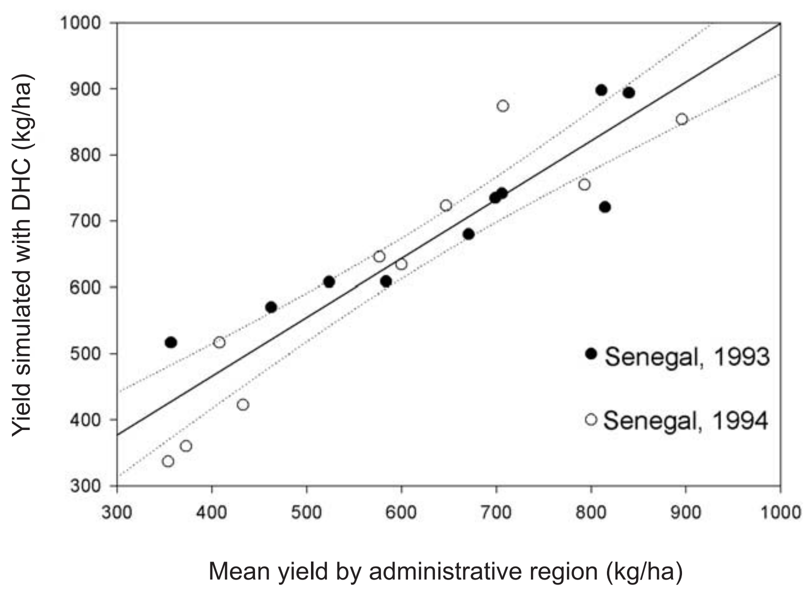

Figure 2. Relationship Between Simulated and Observed Millet Grain Yields in 10 Administrative Regions in Senegal Using SARRA/DHC

SARRA-H—A Full Crop Model

In 2000, a collaborative effort was initiated between CIRAD, AGRHYMET, and several European partners within the Predictability and Variability of Monsoons and the Agricultural and Hydrological Impacts of Climate Change (PROMISE) project (http://ugamp.nerc.ac.uk/promise) to develop new tools to measure the impact on agriculture of seasonal and long-term climate predictions. Specifically for West Africa, SARRA was expanded to become a complete crop model called SARRA-H, that simulates water and radiation limited biomass production and partitioning, and is sensitive to sowing density and photo-period. The model simulates attainable yield in that it considers environmental factors that are beyond the farmer's control (water, soil texture, meteorology) but not resources that can be managed (nutrients). The software, written in DELPHI language, operates under MS-Windows, combines models and database management, and offers an extensive graphic interface. As in the original version of SARRA, sowing dates can be forced or simulated.

For millet, SARRA-H has been calibrated in Senegal on research station experiments and validated on independent station experiments and extensive on-farm yield surveys, covering an N-S climatic gradient within the country and using yield data aggregated at the level of administrative regions. The model explained 78% of on-farm yield variability, despite a huge, unexplained gap between attainable and actual yields (roughly, factor 3; Baron et al., 2003).

Figure 3 shows a partial result of a model application aiming at identifying appropriate decision criteria for sowing dates of millet in the Sahel, in this particular case for Niamey (Sultan, 2002). The farmers' local decision rule (sowing after the first rain ≥ 20 mm, resowing after 20 days if crop establishment fails due to drought) was compared with sowing on the "true," regional onset date of monsoons, determined with meteorological models. These dates were then evaluated against the retrospec-

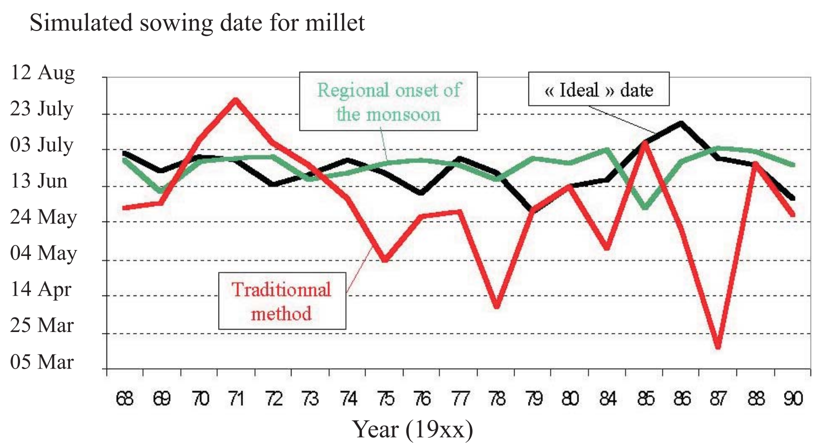

Figure 3. Simulated Sowing Dates for Millet at Niamey From 1968 to 1990 Using Three Criteria. Red: Farmers' Rule Based on Local Rain Events. Green: Regional Meteorological Rule Based on Onset of Monsoon. Black: Retrospectively "Ideal" Dates Giving the Highest Simulated Yields (Sultan, 2002).

tively "ideal" sowing date using crop simulation. This exclusively climate and hydrology driven analysis suggests that over a 32-year period, the farmers' local criterion gives much more variable sowing dates than the regional criterion, and the regional criterion gives sowing dates that are very close to the simulated optimum. This translates into 75% ± 26% SD of maximal yield (optimal date) using the regional criterion, as opposed to 56% ± 36% SD for the farmers' rule. However, the result must be interpreted with caution because it does not consider the higher soil N availability and lower weed pressure associated with earlier (farmers') sowing dates.

The currently available version of SARRA-H is for rainfed cereals, but prototype versions already exist for groundnut and oil palm, and a broader range of crops is ultimately envisaged, including cotton and aquatic rice. These models can be used regionally to evaluate the impact of climatic variations at various temporal and physical scales but also at the plot scale to measure yield gaps (on-farm versus attainable, attainable versus potential yield), to test decision rules for sowing dates and the choice of varietal types (e.g., degree of photo-period sensitivity). SARRA-H is available on a collaborative basis subject to license agreement, and training courses are conducted annually at CIRAD. The model is so far only available in French (documentation on CD-ROM). For more information contact vincent.bonnal@cirad.fr.

A presentation of simple models that relate climate to field-level water balance, and water balance to crop performance has been given here. Although conceived and routinely applied at the regional scale for yield forecasting, early drought alert, and prediction of climatic impacts on crops, these tools can also be used at the plot scale for diagnostic purposes.

Affholder, F. 1997. "Empirically Modeling the Interaction Between Intensification and Climatic Risk in Semi-Arid Regions," *Field Crops Research*, 52:79-93.

Affholder, F., G. C. Rodrigues, and E. D. Assad. 1997. "Modelo Agroclimatico para Avaliacao do Comportamento do Milho na Regiao dos Cerrados (Agroclimatic Model for Evaluation of Maize Behavior in the Cerrado Region)," *Pesquisa Agropecuaria Brasileira,* 32:993-1002.

Bacci, L., and F. N. Reyniers (Eds.). 1998. "Le Futur des Céréales Photopériodiques pour une Production Durable en Afrique Tropicale Semi-Aride," Actes du Séminaire International. 27-30 Avril 1998, Florence, Italie. Ed. CeSIA, Florence, Italie, CIRAD, Montpellier, France, 270 p.

Baron, C., F. N. Reyniers, A. Clopes, and F. Forest. 1999. "Applications du Logiciel SARRA à l'Etude de Risques Climatiques," *Agriculture et Développement,* 24:89-97.

Baron, C., A. Clopes, P. Perez, B. Muller, and F. Maraux. 1996. "Manuels d'Utilisation de SARRAMET," 45 p., SARRABIL 35 p., et SARRAZON, 29 p., CIRAD, Montpellier, France.

Baron, C., B. Sarr, V. Bonnal, O. Diouf, and M. Dingkuhn. 2003. "SARRAH, A Crop Model for PROMISE," Oral Presentation on the Conference "Monsoon Environments: Agricultural and Hydrological Impacts of Seasonal Variability and Climate Change," ICTP, Trieste, Italy, March 24-28, 2003.

Doorenbos, J., and A. H. Kassam. 1979. "Yield Response to Water," FAO Irrigation and Drainage Paper No. 33. FAO, Rome, Italy, 193 p.

Doorenbos, J., and W. O. Pruitt. 1977. "Guidelines to Predicting Water Requirements," FAO Irrigation and Drainage Paper No. 24. FAO, Rome, Italy, 179 p.

Eagleman, J. 1971. "An Experimental Derived Model for Actual Evapotranspiration," *Agricultural Meteorology,* 8:385-394.

Girard, X., B. Baron, and B. Cortier. 1991. "DHC Version 4. Logiciel de Diagnostic Hydrique des Cultures," Manuel d'Utilisation. AGRHYMET, Niamey, Niger Republic.

Goze, E. 1990. "Modèle Stochastique de la Pluviométrie au Sahel. Application à l'Agronomie. Générateur des Pluies," Thèse de Doctorat, Université de Montpellier II, France, 1990.

Maraux, F., C. Baron, F. Forest, J. Imbernon, and H. Ouaidrari. 1994. "Prévisions de Rendement du Mil en Afrique Sahélienne; l'Expérience du CIRAD." FAO, Colloque Villefranche sur Mer, 24-27 Octobre 1994.

Samba, A. 1998. "Les Logiciels Dhc de Diagnostic Hydrique des Cultures. Prévision des Rendements du Mil en Zones Soudano-

Sahéliennes de l'Afrique de l'Ouest," *Sécheresse,* 9(4):281-288.

Samba, A., B. Sarr, C. Baron, E. Gozé, F. Maraux, B. Clerget, and M. Dingkuhn. 2001. "La Prévision Agricole à l'Echelle du Sahel," IN E. Malézieux, G. Trébuil, and M. Jaeger (Eds.) *Modélisation des Agro-Ecosystèmes et Aide à la Décision*. CIRAD and INRA, Montpellier, France, pp. 243-262.

Sultan, B. 2002. "Etude de la Mise en Place de la Mousson en Afrique de l'Ouest et de la Variabilité Intra-Saisonnière de la Convection. Applications à la Sensibilité des Rendements Agricoles," Ph.D. Thesis, University Paris, 7 Decembre 2002. 283 p.

Sivakumar, M.V.K. 1988. "Predicting Rainy Season Potential From the Onset of Rains in Southern Sahelian and Soudanian Climatic Zones of West Africa," *Agricultural Meteorology,* 42:295-305.

Vaksmann, M., S. B. Traore, and O. Niangado. 1996. "Le Photopériodisme des Sorghos Africains," *Agriculture et Développement*, 9:13-18.

Chapter 10

Evaluating Options for Soil Organic Carbon Maintenance Under Intensive Cropping in the West African Savanna Using the Rothamsted Carbon (RothC) Model(*)

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More information on the Rothamsted Carbon model can be found in Appendix 4

Introduction

Organic matter plays an important role in the soil as it influences, e.g., nutrient supply, structure, water-holding capacity, and soil life. In sub-Saharan Africa, declining levels of soil organic matter constitute a threat to the sustainability of many agricul-

*This case is a revised version of a case study made by J. Diels, K. Aihou, E.N.O. Iwuafor, R. Merckx, O. Lyasse, N. Sanginga, B. Vanlauwe, and J. Deckers. 2002. "Options for Soil Organic Carbon Maintenance Under Intensive Cropping in the West African Savanna," IN B. Vanlauwe, J. Diels, N. Sanginga, and R. Merckx, (Eds.), *Integrated Plant Nutrient Management in Sub-Saharan Africa: From Concept to Practice*, pp. 299-312, Commonwealth Agricultural Bureau (CAB) International, Wallingford, Oxon, United Kingdom.

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tural systems in this continent. This situation is, on the one hand, caused by the high decomposition rates of soil organic matter (SOM) due to the year-round high temperatures and, on the other hand, by poor organic matter management. Substantial nutrient losses occur due to the burning of crop residues and to improper animal manure collection and storage in areas with crop-livestock integration. Techniques that promote soil organic carbon (SOC) such as agro-forestry, the cultivation of green manures, optimal use of animal manure, and mulching are widely advocated. However, success has been limited.

Obtaining empirical knowledge about SOM development is difficult because changes in the organic matter status of the soil happen slowly over many years. Fortunately there are a number of long-term trials that have allowed scientists to gain insight into SOM dynamics. One set of such experiments, the Rothamsted long-term field experiments, was used to develop and test the Rothamsted Carbon model (RothC) (Jenkinson et al., 1987; Jenkinson, 1990; and Jenkinson et al., 1991). Other long-term experiments throughout the world are described in the SOMNET database (Smith et al., 1996); unfortunately the database does not contain many experiments from tropical Africa where conditions are very different. Nevertheless, a number of long-term experiments do exist in sub-Saharan Africa.

The objective of the study presented was to use data from long-term trials and knowledge of SOM dynamics, captured in RothC to conduct a number of ex-ante evaluations of land use change options that are intended to improve the SOM status of the soil. Such evaluations may be used to select one or more of the most promising options under a variety of conditions, thus saving precious resources. RothC was first tested using data from a number of long-term experiments conducted in West Africa and subsequently used to evaluate the effects of a number of alternative cropping systems on the level of SOM in southern Benin.

Testing the RothC Model

The RothC-26.3 model (Coleman and Jenkinson, 1995) translates information on quality and quantity of plant litter, entering the soil, into changes of SOC contents (expressed in Mg C/ha), thereby accounting for the effects of temperature, soil moisture, clay content (or CEC), and litter quality on the rate of decomposition.

The RothC model was first tested using data from a number of long-term field experiments in Samaru and Ibadan (Nigeria) and Kumasi (Ghana) (Table 1).

Table 1. Location, Geographic Coordinates, Type, and Application Rate of Organic Amendments, Trial Duration and Literature Reference of the Data Shown in Figure 1

Location[a]	Type of Organic Amendment	Application Rate (Mg DM/ha/yr)	Duration of Trial (yr)	Reference
1. Samaru	Manure	9.4	20	(Jones, 1971)
2. Samaru	Manure	3.8	18	(Jones, 1971)
3. Samaru	Groundnut shells	5.0	9	(Jones, 1971)
4. Ibadan	Maize stover	12.0	5	(Juo et al., 1995)
5. Ibadan	Maize stover	5.5	10	(Kang, 1993)
6. Ibadan	*Leucaena*[b]	7.1	12	(Diels et al., unpubl.)
7. Ibadan	*Senna*[(2)]	5.5	12	(Diels et al., unpubl.)
8. Kumasi	Grass mulch	5.0	19	(Ofori, 1973)

a. Geographic coordinates are 11.2°N, 7.6°E for Samaru; 7.5°N, 3.9°E for Ibadan; and 6.7°N, 2.4°W for Kumasi.

b. Prunings from alley cropping systems with *Leucaena leucocephala* Lam. (de Witt), and *Senna siamea* (Lam.) H. Irwin & Barneby hedgerow trees, respectively.

Datasets were selected from replicated experiments that had a paired set of treatments: one treatment that received high annual application rates of plant residues or manure and one that was managed in the same way, except that it did not receive organic amendments. The difference between the reported SOC levels in the top 15 cm of the soil at the end of the trial was an indication of the SOC buildup resulting from the organic resources applied annually.

Comparing the simulated results by the RothC model with the measured results, the observed normalized SOC buildup was calculated as (SOC_{OM}–$SOC_{control}$)/(annual OM application rate in Mg C/ha), where SOC_{OM} is the SOC content (Mg C/ha) in the treatment that received annual applications of organic amendments, and $SOC_{control}$ is the SOC content in the control treatment that did not receive organic amendments. The numbers in Figure 1 refer to the locations in Table 1.

The RothC model gave a good prediction of the SOC buildup in six out of eight datasets; only two of the eight data points significantly deviate from the 1:1 line (Figure 1). For data point No. 5, the wide confidence interval indicated that the deviation could be due to field variation as well. Data point 6 came from the same alley-cropping experiment as point 7 (Table 1). The total biomass production in the *Leucaena leucocephala* and the *Senna siamea* agro-forestry systems was about equal, and the model translated this into an equal buildup of SOC. The fact that the observed SOC buildup in the *Leucaena* system (No. 6) was much lower than in the *Senna* system (No. 7) could be due to the higher litter quality of *Leucaena*. The data in Figure 1 did not allow testing the capability of the model to properly account for litter quality. This is due to the confounding of litter quality and length of growing period (optimal moisture conditions for decomposition) in the available data; only data for more resistant organic inputs (manure and groundnut shells) were available for the drier

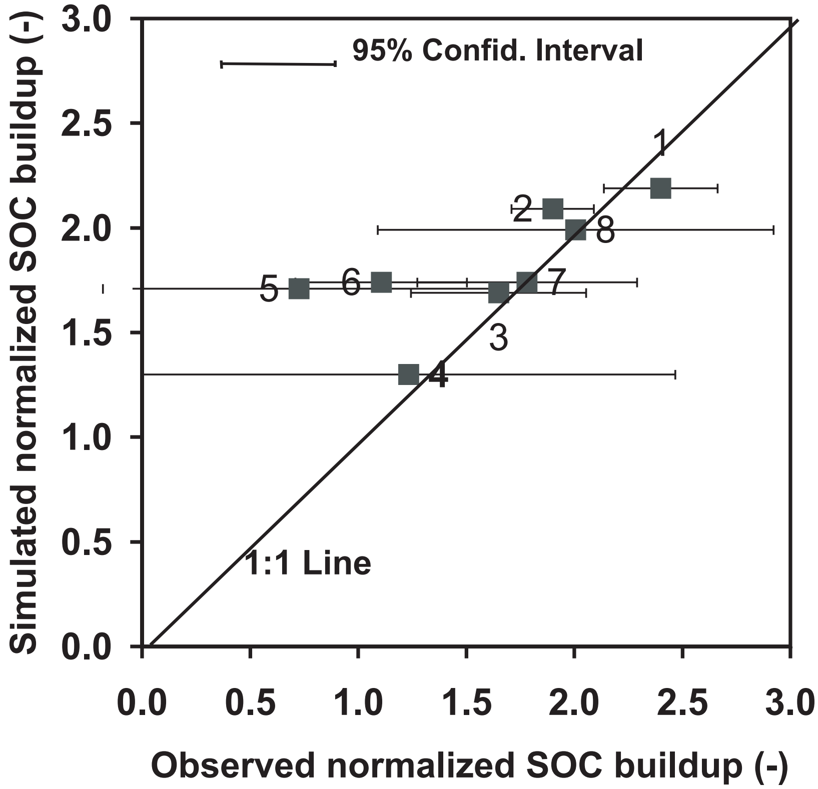

Figure 1. Simulated Against Measured Normalized SOC Buildup From Long-Term Experiments in West Africa

region (Samaru), while these materials were absent in the wetter sites.

The effect of litter quality is taken into account in the model by assigning ratios of the fractions of decomposable plant material (DPM) and resistant plant material (RPM) to the incoming organic materials. This ratio controls the short-term decomposition rate. The authors of the model provide some indications regarding the DPM/RPM ratios for a number of categories of incoming plant material; e.g., the DPM/RPM ratios for agricultural crops and improved grassland is 1.44. There may be differences between crops, however, and it would be useful to be able to further distinguish between crops that have different decomposition rates. Here another decision-support system such as ORD may be useful (Palm et al., 2001, see Appendix 12). The data on plant quality, characteristics, and decomposition behavior in this database could guide the choice of the appropriate DPM/RPM ratio.

RothC Application

Two common rotations in southern Benin are the continuous maize/cowpea and the maize/cotton relay cropping systems (Table 2). Various organizations have developed cropping sys-

Table 2. Quantity of Crop and Weed Residues Returned to the 15 cm Topsoil (in Mg dry matter/ha/y)

System[a]	Maize Stover and Roots	Cotton, *Mucuna,* or Cowpea Haulms + Roots	Prunings (*Cajanus* or *Senna*)	Weeds	Total
Maize/cotton relay cropping (conventional)	2.4	0.2[b]	0.0	5.4	8.0
Maize/cowpea rotation	0.2[c]	2.1	0.0	4.3	6.6
Maize/*Cajanus cajan* relay crop	2.4	0.0	5.5	4.1	12.0
Maize/*Mucuna pruriens* relay cropping	2.4	7.3	0.0	2.8	12.5
Maize/cotton relay with *Senna siamea* mulch[d]	2.4	0.2[b]	3.8	5.4	11.8

a. Two crops are grown in a year, either in rotation or as a relay system; the same two crops are continuously grown every year.
b. Farmers burn remaining weeds and cotton residues before planting maize.
c. Farmers burn maize and weed residues before planting the second-season cowpea crop. Burning is not practiced in the relay cropping systems.
d. *Senna siamea* trees planted as 1,600 m hedgerows per ha and pruned twice a year.

tems that return more organic matter to the soil: a maize/mucuna relay cropping system and a maize/cotton relay with *Senna siamea* mulch relay system. The question now is to what extent alternative cropping systems contribute to the SOC buildup.

An ex-ante evaluation was therefore carried out using the RothC model to investigate the effect of the two conventional production systems (maize/cowpea and maize/cotton relay systems) and three alternative production systems (maize/cajanus relay cropping system, maize/mucuna relay cropping system and a maize/cotton relay with *Senna siamea* mulch relay system) on SOC buildup.

It is assumed that maize receives mineral fertilizer at 90 kg N, 30 kg P, and 30 kg K per ha and that cotton receives the recommended rate of compound fertilizer. In the conventional system, crop and weed residues that return to the soil, amount to 8.0 Mg DM/ha/y [4 Mg C/ha/y] The alternative systems are supposed to return 12.0 Mg DM/ha/y [6 Mg C/ha/y] to the soil (Table 2).

The alternative systems increase the SOM levels in the soil; after 20 years, the increase in SOC level realized with these "high biomass production" systems is in the order of 7 Mg C/ha or an increase of only 0.33% C in the top 15 cm of the soil (Figure 2). Achievable biomass production figures are likely to be higher in the humid forest zone (longer growing season), but definitely lower in dryer regions. The simulations also show that the increase in SOM will be slow. The increase in CEC and available water, known to increase roughly proportional to SOC content, will, therefore, be small during the first 5 years.

This case study shows how the RothC model can be used in estimating the effects of the application of organic amendments on SOM levels. Although it is only a model, it cautions against over-optimistic expectations of the effects of alternative cropping systems that produce high quantities of biomass on SOM

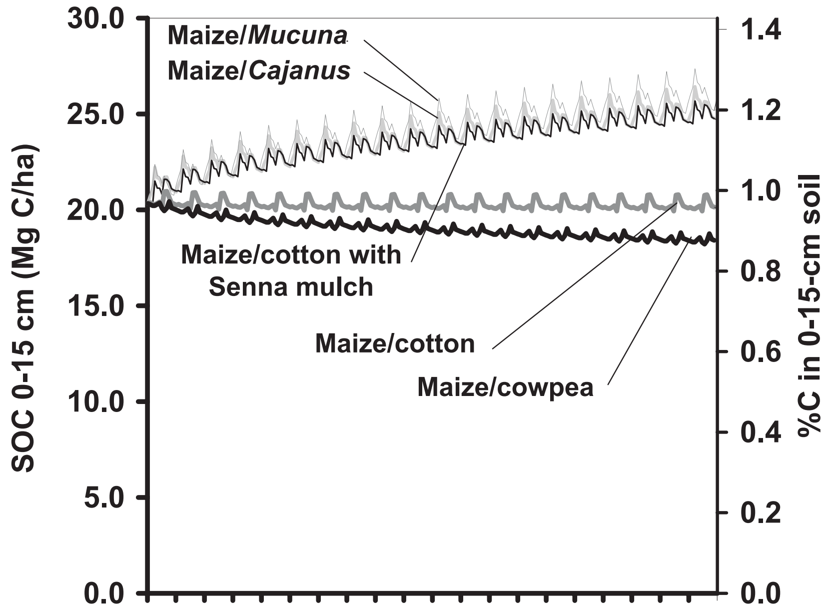

Figure 2. SOC Buildup Calculated With the RothC Model for Different Cropping Systems in the Coastal Savanna of Benin.

levels: Improvement of soil properties that vary in proportion to the SOC content (CEC, pH buffer capacity, water-holding capacity) will thus be slow. It will take a significant time period for the farmer to bring about a small increase in SOM, and the question is whether it is sufficiently attractive for the farmer to change his/her cropping system. This slow result might be one of the reasons why the acceptance of such cropping systems has been slow in West Africa.

On the other hand, it should be realized that application of organic resources may also have other beneficial effects on the soil and hence on productivity; benefits that are not related to the increase of the SOC content as such. One example is its mulching effect—providing a newly sown crop with a good start due to favorable soil moisture conditions as is sometimes witnessed under Mucuna residues. Recycling crop residues obviously also saves the nutrients that would otherwise be lost. Moreover, several studies indicated that a combined application of organic matter and N fertilizer can lead to positive interactions between the two sources of nitrogen during the first season after the application (Vanlauwe et al., 2001; Iwuafor et al., 2002). Although such interactions are still poorly understood (Vanlauwe et al., 2002) they are unlikely to be related to the buildup of SOC. The RothC model does not provide direct information about these aspects not related to SOC contents.

References

Coleman, K., and D. S. Jenkinson. 1995. RothC-26 3. *A Model for the Turnover of Carbon in Soil: Model Description and Users Guide,* Institute of Arable Crops Research (IACR), Rothamsted, Herts, United Kingdom, 30 p.

Iwuafor, E.N.O., K. Aihou, J. S. Jaryum, B. Vanlauwe, J. Diels, N. Sanginga, O. Lyasse, J. Deckers, and R. Merckx. 2002. "On-Farm Evaluation of the Contribution of Sole and Mixed Applications of Organic Matter and Urea to Maize Grain Production in the Savanna," IN B. Vanlauwe, J. Diels, N. Sanginga, and R. Merckx (Eds.), *Integrated Plant Nutrient Management in Sub-Saharan Africa: From Concept to Practice*, pp. 185-197, CAB International, Wallingford, Oxon, United Kingdom.

Jenkinson, D. S. 1990. "The Turnover of Organic Carbon and Nitrogen in Soil," *Philosophical Transactions of the Royal Society*, B. 329:361-368.

Jenkinson, D. S., D. E. Adams, and A. Wild. 1991. "Model Estimates of CO_2 Emissions From Soil in Response to Global Warming," *Nature*, 351(6322):304-306.

Jenkinson, D. S., P.B.S. Hart, J. H. Rayner, and L. C. Parry. 1987. "Modeling the Turnover of Organic Matter in Long-Term Experiments at Rothamsted," *INTECOL Bulletin* 15:1-8.

Jones, M. J. 1971. "The Maintenance of Soil Organic Matter Under Continuous Cultivation at Samaru, Nigeria," *Journal of Agricultural Sciences, Cambridge,* 77:473-482.

Juo, A.S.R., K. Franzluebbers, A. Dabiri, and B. Ikhile. 1995. "Changes in Soil Properties During Long-Term Fallow and Continuous Cultivation After Forest Clearing in Nigeria," *Agriculture, Ecosystems and Environment,* 56:9-18.

Kang, B. T. 1993. "Changes in Soil Chemical Properties and Crop Performance With Continuous Cropping on an Entisol in the Humid Tropics," IN K. Mulongoy and R. Merckx (Eds.), *Soil Organic Matter Dynamics and the Sustainability of Tropical Agriculture*, pp. 297-305, John Wiley & Sons Ltd., Chichester, United Kingdom.

Ofori, C. S. 1973. "Decline in Fertility Status of a Tropical Forest Ochrosol Under Continuous Cropping," *Experimental Agriculture,* 9:15-22.

Palm, C. A., C. N. Gachengo, R. J. Delve, G. Cadisch and K. E. Giller. 2001. "Organic Inputs for Soil Fertility Management in Tropical Agroecosystems: Application of an Organic Resource Database," *Agriculture, Ecosystems and Environment,* 83:27–42.

Smith, P., J. U. Smith, and D. S. Powlson. 1996. "Soil Organic Matter Network (SOMNET): 1996," *Model and Experimental Metadata,* GCTE Report 7, GCTE Focus 3, Wallingford, Oxon, 259 p.

Vanlauwe, B., J. Wendt, and J. Diels. 2001. "Combined Application of Organic Matter and Fertilizer," IN G. Tian, F. Ishida, and J.D.H. Keatinge (Eds.), *Sustaining Soil Fertility in West Africa*, pp. 247-279, SSSA Spec. Publ. No. 58, SSSA, Madison, Wisconsin, U.S.A.

Vanlauwe, B., C. A. Palm, H. K. Murwira, and R. Merckx. 2002. "Organic Resource Management in Sub-Saharan Africa: Validation of a Residue Quality-Driven Decision Support System," *Agronomie,* 22:839-846.

Chapter 11

Perspectives for the Use of Decision Support Tools in Agricultural Research and Development in Sub-Saharan Africa

T.E. Struif Bontkes[1] and M.C.S. Wopereis[1]

An integrated approach is needed for agricultural research and development to provide answers to problems related to food security and sustainable resource management in sub-Saharan Africa. Izac and Sanchez (2001) described the paradigm shift that is currently taking place in international research from a focus on germ plasm and technology development for raising productivity to an integrated natural resource management (INRM) approach. INRM is generally understood as "the responsible and broad-based management of the land, water, forest, and biological resource base (including genes) needed to sustain agricultural productivity and avert degradation of potential productivity" (Hagmann et al., 2002).

An essential entry point to INRM is integrated soil fertility management (ISFM) because soil fertility is often key to farmer families' livelihood in sub-Saharan Africa. ISFM is an approach that tries to make the best use of inherent soil nutrient pools, locally available amendments, and mineral fertilizers to increase land productivity while maintaining or enhancing soil fertility in the broadest sense; i.e., nutritional, biological, and physical soil properties.

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Besides a more integrated approach to agricultural research and development, it is also increasingly being realized (e.g., Douthwaite et al., 2002) that for agricultural research to be effective in diverse and relatively unfavorable production environments, it has to deviate from the traditional "transfer of technology track," where research develops a technology, which is handed over to the extension agency that then takes care of transfer to the farmer. This "conveyor-belt" approach may work in favorable production environments that are relatively uniform and for comparatively simple technologies, such as crop cultivars. However, the reality of smallholder agriculture in sub-Saharan Africa is far too dynamic and diverse for such an approach to work. This requires participatory learning and action research (PLAR) approaches in which farmers and other agricultural development stakeholders learn through their joint experiences and modify their actions accordingly.

ISFM and INRM require cycles of diagnosis and reflection—action planning—joint experimentation and evaluation that need to be implemented jointly by all stakeholders and that touch upon socio-economic and biophysical issues that intervene at different temporal and spatial scales. As shown in this guide, decision support tools (DSTs) can play a role in combining a more integrated approach in agricultural research and development with PLAR approaches.

A large number of DSTs have been developed during the past two decades and much work is being done to improve them; new ones are also being developed. This is a sign that scientists are eager to apply their knowledge and to receive feedback to improve their DSTs. The bottleneck is not the supply side of DSTs but rather the demand side. It is therefore important to pay more attention to factors that determine the demand for such tools. This may also help developers in designing new DSTs or in improving existing ones. This guide has attempted to contribute to that process by the presentation of a number of DSTs and their use through case studies. It must be stressed, however, that the DSTs presented here are by no means exhaustive.

The focus in this guide is on DSTs for improved ISFM, although some cases, such as the DSSAT case (Chapter 7) and the RIDEV case (Chapter 8) lie somewhere on the continuum between ISFM and INRM, and Chapter 9 (SARRA) focuses on management issues related to water supply. The appendixes provide an overview of the main characteristics of the tools.

This guide has shown that DSTs differ greatly in complexity, ranging from relatively complex crop growth models to simpler DSTs, such as tables, decision trees, and figures, which can be used directly by extension staff in their discussions with farmers. One example is the use of decision trees that help select appropriate legumes (Appendix 15) or estimate the effect of organic resources on soil fertility build-up (ORD, Appendix 12).

Simple DSTs are often translations of the results of the more complex tools such as APSIM, DSSAT, and RIDEV. Such tools and relatively simple tools such as resource flow maps (RFMs) are suitable to be used in combination with PLAR approaches. Examples can be found in the DSSAT and QUEFTS cases in Southern Togo (Chapters 7 and 5), in the RIDEV case (Chapter 8), and in the chapters where use was made of RFMs (NUTMON in Chapters 2, 3, and 6). Although participatory modeling is especially crucial for social processes, it is still rarely applied.

In the RFM cases, emphasis is placed on the qualitative aspects. They are more flexible and permit a direct involvement of the farmers in the application of the tool. Drawing qualitative RFMs may already provide very useful insights. For quantification of these maps, data are still required about yields, application of fertilizer, animal manure, etc. Estimates of nutrient contents of the various materials may be provided by the tool; e.g., NUTMON. Another tool that helps to make a qualitative analysis is NuMaSS (Chapter 4); it permits diagnosing problems using field observations such as indicator plants and deficiency symptoms of crops.

From a more technical viewpoint, DSTs are often essential to understand systems performance because of the sheer complexity of interacting processes that occur over different timeframes. Some processes can be studied during one growing season, others require decades of study, and in practice such studies are only possible through simulation, as illustrated in Chapter 10 with the RothC model. Process-based models can "mimic" a virtual crop or cropping system over many years in a very short time span as was illustrated in Chapters 6-9 and are, therefore, fast and relatively inexpensive. If confidence is obtained in a technology or approach, DSTs may be helpful in identification of its extrapolation domains, especially if combined with GIS, as was highlighted in Chapters 7 (DSSAT), 8 (RIDEV), and 9 (SARRA).

All tools address only a limited number of aspects; there are no comprehensive tools to address ISFM let alone INRM, and it is doubtful whether such models will ever exist. The quest for comprehensive models is thwarted by complexity and heavy data requisites, often requiring a long time to develop, test, and validate. It is interesting to cite here Sayer and Campbell (2001) who advocate the concept of "throw-away" models; i.e., computer-implemented models that are built in a few days to solve a particular problem and then discarded. Participants in the closing workshop of the Client-Oriented Systems Toolbox for Technology Transfer Related to Soil Fertility Improvement and Sustainable Agriculture (COSTBOX) project, which was the basis of this guide, expressed impatience with model developers that continue to fine-tune their tools without moving to the application phase in the real world (IFDC, 2003).

It is therefore important to select the appropriate tool (or combination of tools) to solve a particular problem. Tools that use meteorological data such as DSSAT, APSIM, RIDEV, or SARRA are useful to estimate risks, which is often a very important consideration for the farmer. These models are less useful in estimating fertilizer requirements because they usually include only nitrogen (N). To answer such questions, tools such as QUEFTS (N, P, and K) or NuMaSS (N, P, and soil acidity) are more appropriate, whereas tools that calculate nutrient balances may also be helpful (NUTMON, ResourceKIT). For problems of a more long-term nature, APSIM or the newest version of DSSAT (Gijsman et al., 2002) may be used but also the RothC model would be helpful. The latter permits estimating the effects of organic amendments over longer time frames. Tools exist that may help estimating data that are rarely measured using more generally available data. For example, SOILPAR can be used to estimate hydraulic conductivity curves from soil texture data.

In case the problem to be solved goes beyond the scope of a particular tool, the use of combinations of tools should also be considered; e.g., Haefele et al. (2003) combined QUEFTS, RIDEV, and a crop growth model to derive recommendations for soil fertility management in irrigated rice systems in the Sahel. When selecting a DST, one should be aware of its data requirements, which may sometimes be prohibitive for the objective pursued.

Despite the availability of a broad range of tools and the implementation of various projects to promote them, DSTs are still rarely used in agricultural research and development in sub-Saharan Africa. The development of a toolbox of DSTs, from which the most appropriate ones can be used to solve a particular problem, seems to be a promising approach. Nevertheless, availability of reliable data remains a primary constraint in the use of quantitative DSTs. Collection of data is often a very time-consuming and resource-consuming activity. Including standard datasets in the tools can reduce data collection, but they are often not sufficiently site-specific. Moreover, providing default values may lead to "laziness" instead of looking for the real values; one may simply go for the default value, which may lead to unrealistic results. It is therefore important to always critically evaluate the outcome of the DSTs.

Kropff et al. (2001) argue for the establishment of regional databases, using existing data of the international and national research institutes that are freely available. The COSTBOX project developed a geo-referenced database for soil and climate for Togo and Benin based on existing data, which was used in the DSSAT case reported in Chapter 7. However, part of the data was more than 20 years old, some of a doubtful quality, and others did not fit the data requirements of the tool. For example, data on available P in existing databases were based on analytical methods that are no longer used. The extent to which data should be freely accessible also remains a subject of debate because most of the institutes consider the sale of data a highly necessary source of income.

To ensure data quality, national analytical laboratories need to be properly equipped with trained staff and adequate instruments. To maintain the standard of such laboratories, they should ideally become members of one of the international networks on quality control; e.g., Wageningen Evaluation Programs for Analytical Laboratories (WEPAL—www.wepal.nl) or Soil and Plant Analytical Laboratories Network of Africa (SPALNA—spalna@cgiar.org). As an alternative to the often expensive and time-consuming laboratory analyses, soil test kits could be used. If doubts exist about the quality of the soil analyses or the appropriateness of regression equations linking relatively easy-to-measure soil parameters to indigenous soil nutrient supply, nutrient-omission trials can be carried out at the farm level. In such trials, the crop receives adequate levels of fertilizer nutrients except for one nutrient. Grain yield or nutrient uptake can be used as a proxy for the soil-supplying capacity of the missing nutrient. This approach has been especially advocated for flooded rice in Asia (Fairhurst and Witt, 2002) and West Africa (Wopereis et al., 1999) but may also show promise for other production systems.

African scientists show a great interest in these tools, and the cases illustrate that there is certainly a scope for the use of DSTs in sub-Saharan Africa. This requires, however, an approach that goes beyond short duration projects that often promote a single tool. National research institutes should establish core groups that encourage the use of DSTs by colleagues and assist them in the application of these tools (Matthews and Stephens, 2002). Members of these groups need to be well-trained and receive initial on-the-job training. They should be able to work full-time on this assignment. Scientists who are members of the core groups need to be supported and coordinated by an African center that specializes in the development and application of DSTs. Such a center should preferably be established at a university to ensure that students become acquainted with the use of such tools and with systems analysis and modeling that constitute the basis of many of these tools. One of the tasks of such a center is to test and adjust the tools to broad agro-ecological regions, preferably in collaboration with the developers of the various DSTs.

The next step is to make this information available to the end users—extension staff and farmers. This requires close interaction between research and extension institutions and should be assigned to a department within the research institute that has close links with the extension department. Information generated needs to be transformed in such a way that it is easy to use and relevant for the end users. To be relevant, it should address the peculiarities of the problem and provide the farmer with alternative options to solve his/her problem. For example, the information may include fertilizer recommendations adapted to the soil, crop, and the amount of money the farmer is willing to invest in fertilizer, or advice on the best combination of sowing date and variety, as shown in the QUEFTS and DSSAT cases in Southern Togo (Chapters 5 and 7). The establishment of research and extension structures that are closely linked and respond to acute problems and opportunities in the field, using PLAR approaches and DSTs wherever feasible, would definitely be a much-needed step forward toward the improved well-being of rural and urban poor in sub-Saharan Africa.

References

Douthwaite, B., J.D.H. Keatinge, and J. R. Park. 2002. "Learning Selection: An Evolutionary Model for Understanding, Implementing and Evaluating Participatory Technology Development," *Agricultural Systems,* 72:109-131.

Fairhurst, T., and C. Witt (Eds.). 2002. *Rice. A Practical Guide to Nutrient Management,* Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC) and International Rice Research Institute (IRRI), 89 p. + Appendixes.

Gijsman, A. J., G. Hoogenboom, W. J. Parton, and P. C. Kerridge. 2002. "Modifying DSSAT Crop Models for Low-Input Agricultural Systems Using a Soil Organic Matter-Residue Module From Century," *Agronomy Journal,* 94:462-474.

Haefele, S. M., M.C.S. Wopereis, M. K. Ndiaye, and M. J. Kropff. 2003. "A Framework to Improve Fertilizer Recommendations for Irrigated Rice in West Africa," *Agricultural Systems,* 76(1):313-335.

Hagmann, J., E. Chuma, K. Murwira, M. Connolly, and P. Ficarelli. 2002. "Success Factors in Integrated Natural Resource Management R&D: Lessons From Practice," *Conservation Ecology,* 5(2):29. [online] URL: http://www.consecol.org/vol5/iss2/art29.

IFDC. 2003. *Atelier sur l'Utilisation des Modèles et des SIG dans l'Agriculture*. Décembre 13, 2002, Lomé, Togo.

Izac, A.M.N., and P. A. Sanchez. 2001. "Towards a Natural Resource Management Paradigm for International Agriculture: The Example of Agroforestry Research," *Agricultural Systems,* 69:5-25.

Kropff, M. J., J. Bouma, and J. W. Jones. 2001. "Systems Approaches for the Design of Sustainable Agro-Ecosystems," *Agricultural Systems,* 70:369-393.

Matthews, R. B., and W. Stephens (Eds.). 2002: *Crop-Soil Simulation Models: Applications in Developing Countries*, Cranfield University, United Kingdom, 304 p.

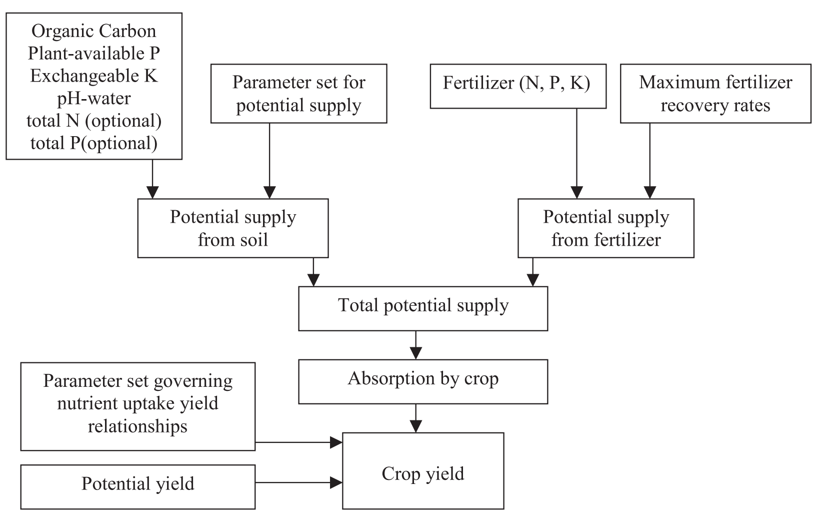
Sayer, J. A., and B. Campbell. 2001. "Research to Integrate Productivity Enhancement, Environmental Protection, and Human Development," *Conservation Ecology,* 5(2):32. [online] URL: http://www.consecol.org/vol5/iss2/art32.

Wopereis, M.C.S., C. Donovan, B. Nebié, D. Guindo, and M. K. N'Diaye. 1999. "Soil Fertility Management in Irrigated Rice Systems in the Sahel and Savanna Regions of West Africa. Part I. Agronomic Analysis," *Field Crops Research,* 61:125-145.

Appendix 1. QUEFTS

Name: QUEFTS: Quantitative Evaluation of the Fertility of Tropical Soils
Authors: B. H. Janssen, F.C.T. Guiking, D. Van der Eijk, E.M.A. Smaling, J. Wolf, and H. Van Reuler
Address: Wageningen University and Research Center, P.O. Box 8005, 6700 EC, Wageningen, Netherlands
E-Mail: Bert.Janssen@wur.nl
Availability: The software can be obtained at a nominal price from the above-mentioned e-mail address.

QUEFTS was developed at the Wageningen University. It is a simple static model that runs under MS-DOS. It allows estimation of crop yield based on a number of parameters (see figure and data requirements) that are generally available. The model was tested for maize in Surinam and in two agro-ecological regions in Kenya. However, it is possible to use it also for other crops and other agro-ecological regions by adapting the parameters.



In addition the tool allows onducting a simple economic analysis about the profitability of the use of fertilizer. An interesting feature of the model is the determination of the optimal ratio between N, P, and K fertilizer.

Data Requirements:

Organic carbon
Plant-available P
Exchangeable K
Total N (optional)
Total P (optional)
pH-water
Maximum recovery rates of fertilizers
Potential yield of the crop

Further Reading

Haefele, S. M., M.C.S. Wopereis, M. K. Ndiaye, and M. J. Kropff. 2003. "A Framework to Improve Fertilizer Recommendations for Irrigated Rice in West Africa," *Agricultural Systems,* 76(1):313-335.

Haefele, S. M., M.C.S. Wopereis, M. K. Ndiaye, S. E. Barro, and M. Ould Isselmou. 2003. "Internal Nutrient Efficiencies, Fertilizer Recovery Rates and Indigenous Soil Nutrient Supply of Irrigated Lowland Rice in the Sahel and the Sudan Savanna," *Field Crops Research,* 80(1):19-32.

Janssen, B. H., F.C.T. Guiking, D. Van der Eijk, E.M.A. Smaling, J. Wolf, and H. Van Reuler. 1990. "A System for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS)," *Geoderma,* 46:299-318.

Janssen, B. H. 1998. "Efficiency Use of Nutrients: An Art of Balancing," *Field Crops Research,* 56:197-201.

Smaling, E.M.A., and B. H. Janssen. 1993. "Calibration of QUEFTS, A Model Predicting Nutrient Uptake and Yields From Chemical Soil Fertility Indexes," *Geoderma,* 59:21-44.

Appendix 2. DSSAT

Name:	Decision-Support System for Agrotechnology Transfer
Authors:	The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT)
E-Mail:	icasa@icasa.net
Website:	http://www.icasa.net/dssat/index.html
Availability:	The DSSAT 3.5 package can be ordered through the above mentioned website of the International Consortium for Systems Applications in Agriculture (ICASA). The costs are US $495 + shipping costs.

DSSAT 3.5 is a MS-DOS-based software package integrating the effects of soil, crop phenotype, weather, and management options. By simulating probable outcomes of crop management strategies, DSSAT offers user information with which to rapidly appraise new crops, products, and practices for adoption.

DSSAT also allows users to compare simulated outcomes with observed results.

The DSSAT software allows linking the crop models with Geographic Information Systems (GIS).

The following crops are included:

Wheat	Sorghum	Peanut	Millet	Tomato
Maize	Dry Bean	Cassava	Soybean	Sunflower
Barley	Chick Pea	Potato	Sugarcane	Pasture
Rice				

The DSSAT shell also allows other crop models to be run, if those follow the ICASA standards.

DSSAT is being used as a:

- Teaching and training tool by providing interactive responses to "what if" questions related to improved understanding of the influence of season (weather), location (site and soil), and management on growth processes of plants.
- Research tool to derive recommendations concerning crop management and to investigate environmental and sustainability issues.
- Business tool to enhance profitability and improve input marketing.
- Policy tool, for yield and area forecasting and land use planning.

The present version is DSSAT 3.5; a Windows-based version (DSSAT 4) will be released in 2003. This new version will also include banana, cabbage, cotton, cowpea, faba bean, pepper, pineapple, taro, and velvet bean (mucuna).

Date Requirements

1. **Site**—Latitude and longitude.
2. **Weather**—Daily solar radiation, maximum and minimum air temperature, and rainfall.
3. **Soil**—For each layer: depth, texture, bulk density, organic carbon, pH, and aluminum saturation.
4. **Management**—Planting date, dates when soil conditions were measured prior to planting, planting density, row spacing, planting depth, crop variety, irrigation, and fertilizer practices.
5. **Initial Conditions** on soil water, soil ammonium and nitrate, and previous cropping information.

A very lively listserver is available for DSSAT users and others interested in crop model development, crop model applications, and decision-support systems (see the above website).

Further Reading

Alagarswamy, G., P. Singh, G. Hoogenboom, S. P. Wani, P. Pathak, and S. M. Virmani. 2000. "Evaluation and Application of the

CROPGRO-Soybean Simulation Model in a Vertic Inceptisol," *Agricultural Systems,* 63:19-32.

Hoogenboom, G., P. W. Wilkens, and G. Y. Tsuji (Eds.). 1999. DSSAT v3 Volume 4: *A Decision Support System for Agrotechnology Transfer,* 286 p. University of Hawaii, Honolulu, Hawaii, U.S.A.

Jagtap, S. S., F. J. Abamu, and J. G. Kling. 1999. "Long-Term Assessment of Nitrogen and Variety Technologies on Attainable Maize Yields in Nigeria Using CERES-Maize," *Agricultural Systems,* 60:77-86.

Jones, J. W., G. Hoogenboom, C. H. Porter, K. J. Boote, W. D. Batchelor, L. A. Hunt, P. W. Wilkens, U. Singh, A. J. Gijsman, and J. T. Ritchie. 2003. "The DSSAT Cropping System Model," *European Journal of Agronomy,* 18:235-265.

Jones, J. W., G. Y. Tsuji, G. Hoogenboom, L. A. Hunt, P. K. Thornton, P. W. Wilkens, D. T. Imamure, W. T. Bowen, and U. Singh. 1998. "Decision Support System for Agrotechnology Transfer: DSSAT v3," IN *Understanding Options for Agricultural Production*, pp. 157-177, G. Y. Tsuji et al. (Eds.), Kluwer Academic Publishers.

Singh, U., P. K. Thornton, A. R. Saka, and J. B. Dent. 1993. "Maize Modeling in Malawi: A Tool for Soil Fertility Research and Development," IN *Systems Approach for Agriculture Development,* pp. 253-273, F. P. de Vries et al. (Eds.), Proceedings of the International Symposium on Systems Approach for Agriculture Development, December 2-6, 1991, Bangkok, Thailand.

Wafula, B. M. 1995. "Application of Crop Simulation in Agriculture Extension in Kenya," *Agricultural Systems,* 49:399-412.

Appendix 3. APSIM

Name: Agricultural Production Systems Simulator (APSIM)
Authors: Agricultural Production Systems Research Unit (APSRU) is a joint research unit of Queensland Departments of Primary Industries (DPI) and Natural Resources and Mines (DNRM) and CSIRO Divisions of Sustainable Ecosystems (CSE) and Land and Water (CLW).
Address: APSRU, PO Box 102, Toowoomba, Queensland, 4350, Australia
E-Mail: APSIMHelp@tag.sciro.au
Michel.Robertson@tag.csiro.au
Website: http://www.apsru.gov.au/Products/apsim.htm
Availability: APSIM software can only be issued to licensed users, but a demo version can be downloaded from the website

APSIM is a modeling environment that uses various component modules to simulate cropping systems in the semi-arid tropics. Modules can be biological, environmental, managerial, or economic and are linked via the APSIM "engine."

APSIM can simulate the growth and yield of a range of crops in response to a variety of management practices, crop mixtures, and rotation sequences including pastures and livestock. It can do this on a short-term and long-term basis, permitting insight in long-term trends in soil productivity due to fertility depletion and erosion.

It contains modules that permit the simulation of crop-weed interactions, soil organic matter rundown, nutrient leaching, soil erosion, soil structural decline, acidification, and soil phosphorus. There is, however, no current capability to deal directly with effects of salinization, insects, diseases, or biodiversity loss.

Growth of the following crops can be simulated with APSIM:

Maize	Soybean	Chickpea	Lucerne
Sorghum	Barley	Mungbean	Annual medic
Millet	Groundnut	Lupin	Pinus radiata
Wheat	Canola	Mucuna	Eucalyptus sp.
Sugarcane	Cotton	Hemp	Weeds
Fababean	Cowpea	Sunflower	

Data Requirements

1. **Site**—Latitude, soil texture and depth, slope length.
2. **Climate**—Daily maximum and minimum temperatures, solar radiation and rainfall.
3. **Crop Phenology**—Crop type and cultivar, days to flowering, days to maturity.
4. **Soil Water, N, and P**—Soil moisture contents per layer at drained upper limit and lower limit, NO_3-N, soil carbon per layer, total soil N of the top layer, soil bulk density per layer, P extractable and P-sorption for each layer.
5. **Surface Residues**—Crop and manure:type and quantities, C, N, and P contents; NH_4^- and NO_3-N and available P of manures; percentage groundcover for surface-applied materials.
6. **Management**—Dates of all operations, sowing depth, plant density, type and amount of fertilizer, tillage (type, depth, fraction of above ground materials incorporated).

Further Reading

Keating, B.A., P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth, J.N.G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J. P. Dimes, M. Silburn, E. Wang, S. Brown, K. L. Bristow, S. Asseng, S. Chapman, R. L. McCown, D. M. Freebairn, and

C. J. Smith. 2003. “An Overview of APSIM, A Model Designed for Farming Systems Simulation,” *European Journal of Agronomy*, 18:267-288.

McCown, R. L., G. L. Hammer, J.N.G. Hargreaves, D. P. Holzworth, and D. M. Freebairn. 1996. “APSIM: A Novel Software System for Model Development, Model Testing, and Simulation in Agricultural Research,” *Agricultural Systems,* 50:255-271.

Probert, M. E., J. P. Dimes, B. A. Keating, R. C. Dalal, and W. M. Strong. 1998. “APSIM’s Water and Nitrogen Modules and Simulation of the Dynamics of Water and Nitrogen in Fallow Systems,” *Agricultural Systems*, 56:1-28 (353).

Appendix 4. Rothamsted Carbon Model

Name:	RothC-26.3
Authors:	K. Coleman and D. S. Jenkinson, 1999
Address:	IACR - Rothamsted, Harpenden, Herts, AL5 2JQ, United Kingdom
E-Mail:	Coleman@bbsrc.ac.uk
Website:	http://www.iacr.bbrsc.ac.uk/aen/carbon/rothc.htm
Availability:	The model is available free of cost and can be downloaded from the website

The Rothamsted Carbon Model (RothC-26.3) allows calculating the effect of organic resources management on the development of soil organic carbon in non-waterlogged topsoil over a period ranging from a few years to a few centuries. It takes into account the quality and quantity of added organic resources, soil type, temperature, moisture content, and plant cover on turnover processes.

Soil organic carbon (SOC) is split into four active compartments and a small amount of inert organic matter (IOM). The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with its own characteristic rate. The IOM compartment is resistant to decomposition.

The structure of the model is shown here.

Both DPM and RPM decompose to form CO_2, BIO, and HUM. BIO and HUM both decompose to form more CO_2, BIO, and HUM.

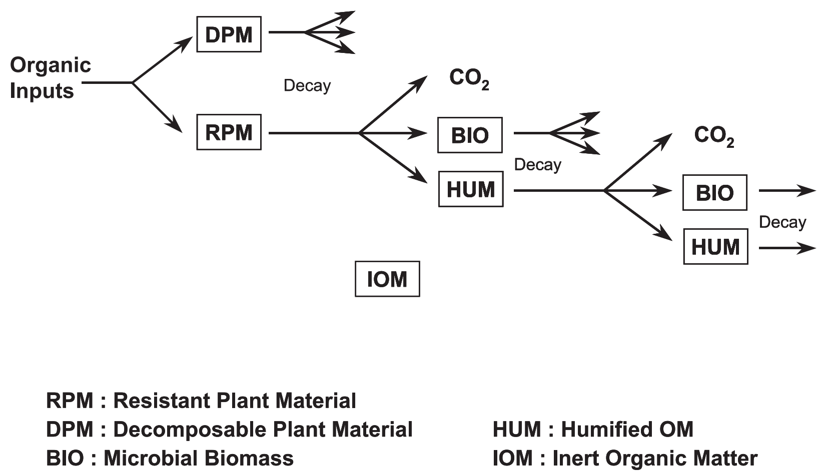


Figure 1. Structure of the Rothamsted Carbon Model

The model uses a monthly time step to calculate total organic carbon (t/ha), microbial biomass carbon (t/ha), and $\Delta^{14}C$ (from which the equivalent radiocarbon age of the soil can be calculated) on a years to centuries time scale. It needs few inputs and those it needs are easily obtainable.

Data requirements

1. Monthly rainfall.
2. Monthly evapotranspiration (mm).
3. Average monthly mean temperature (^{o}C).
4. Percentage clay.
5. An estimate of the decomposability of the incoming plant material – the DPM / RPM ratio.
6. Soil cover – is the soil bare or vegetated.
7. Monthly input of plant residues (t C/ha), including C released from roots during crop growth. This can be calculated by running the model in the “inverse” mode.
8. Monthly input of farmyard manure (t C/ha).
9. Depth of soil layer sampled (cm).

For more information a manual can be downloaded from the website.

Further Reading

Jenkinson, D. S. 1990. "The Turnover of Organic Carbon and Nitrogen in Soil," *Philosophical Transactions of the Royal Society,* B. 329:361-368.

Jenkinson, D. S., and K. Coleman. 1994. "Calculating the Annual Input of Organic Matter to Soil From Measurements of Total Organic Carbon and Radiocarbon," *European Journal of Soil Science*, 45:167-174.

Jenkinson, D. S., D. D. Harkness, E. D. Vance, D. E. Adams, and A. F. Harrison. 1992. "Calculating Net Primary Production and Annual Input of Organic Matter to Soil From the Amount and Radiocarbon Content of Soil Organic Matter," *Soil Biology & Biochem*istry, 24(4):295-308.

Smith, P., J. U. Smith, D. S. Powlson, W. B. McGill, J.R.M. Arah, O. G. Chertov, K. Coleman, U. Franko, S. Frolking, D. S. Jenkinson, L. S. Jensen, R. H. Kelly, Klein-Gunnewiek, A. S. Komarov, C. Li, J.A.E. Molina, T. Mueller, W. J. Parton, J.H.M. Thornley, and A. P. Whitmore. 1997. "A Comparison of the Performance of Nine Soil Organic Matter Models Using Datasets From Seven Long-Term Experiments," *Geoderma,* 81:153-225.

Appendix 5: RFM

Name: RFM: Resource Flow Map

Authors: Toon Defoer, et al., current address: WARDA, The Africa Rice Center, BP 320, Bamako, Mali

E-Mail: T.Defoer@cgiar.org; ToonDefoer@yahoo.fr

Website: www.kit.nl

Availability: The Resource Guide containing examples of RFMs can be requested through the KIT Website for euro 250

The guides to make Response Flow Maps (RFMs) are presented on laminated cards that form Part 3 of a Resource Guide on the Participative Learning and Action Research (PLAR) approach for Integrated Soil Fertility Management (ISFM), developed by Defoer and Budelman (2000). The principal institutes that collaborated in developing this Resource Guide are the Royal Tropical Institute (KIT), Netherlands; the International Institute for Environment and Development (IIED), United Kingdom; and various research and development institutions in Mali, Kenya, Tanzania, Ethiopia, and Benin.

The PLAR approach for ISFM is a process approach that starts with an initial diagnosis and proceeds with a cycle of planning, implementation /experimentation, and evaluation. The cycle is season-based and forms the heart of a long-term engagement between farmer and a field team (i.e., PLAR team) facilitating the process.

The RFM is one of the major PLAR tools during the diagnostic and the planning phases and is generally made by a household head, assisted by at least one of the active household members, and facilitated by one or two PLAR team members.

An RFM presents a picture of the farm and key elements in its soil fertility management and resource flow pattern.

The *diagnostic RFM* is used to discuss and analyze the farmer's crop cultivation practices, use of residues, fertilizers, crop-livestock integration, etc. The analysis intends to assist farmers in considering feasible improvements to the farm system, such as increased recycling of crop residues, limiting resource losses, and rationalizing the use of external inputs.

During the planning phase of PLAR, farmers make a *planning RFM* to visualize their planned improvements and to indicate where they decide to try out alternative techniques over the coming season.

At the end of the cropping season during the evaluation phase of PLAR, farmers evaluate planned activities using their planning RFM by indicating the activities they actually implemented, thereby transforming the planning RFM into a *RFM of implemented activities*.

Guides have been developed for change agents to assist farmers in making RFMs. The guides first present the objectives, expected outputs, participants involved, preparations, materials, and time required. Thereafter the step-wise procedure is presented as well as a topic list (data requirements) to assist farmers in making the RFM.

Data Requirements

1. General characteristics of the household and the farm—Household members, active members, external labor, off-farm income, agricultural equipment, decision-making processes, etc.
2. Fields, plots, and crops—Inventory of field/plots, plot areas, soil types and status, crops, rotations, etc.
3. Livestock and household—Inventory of cattle, kraals, food and feed stores, manure and compost storage, etc.

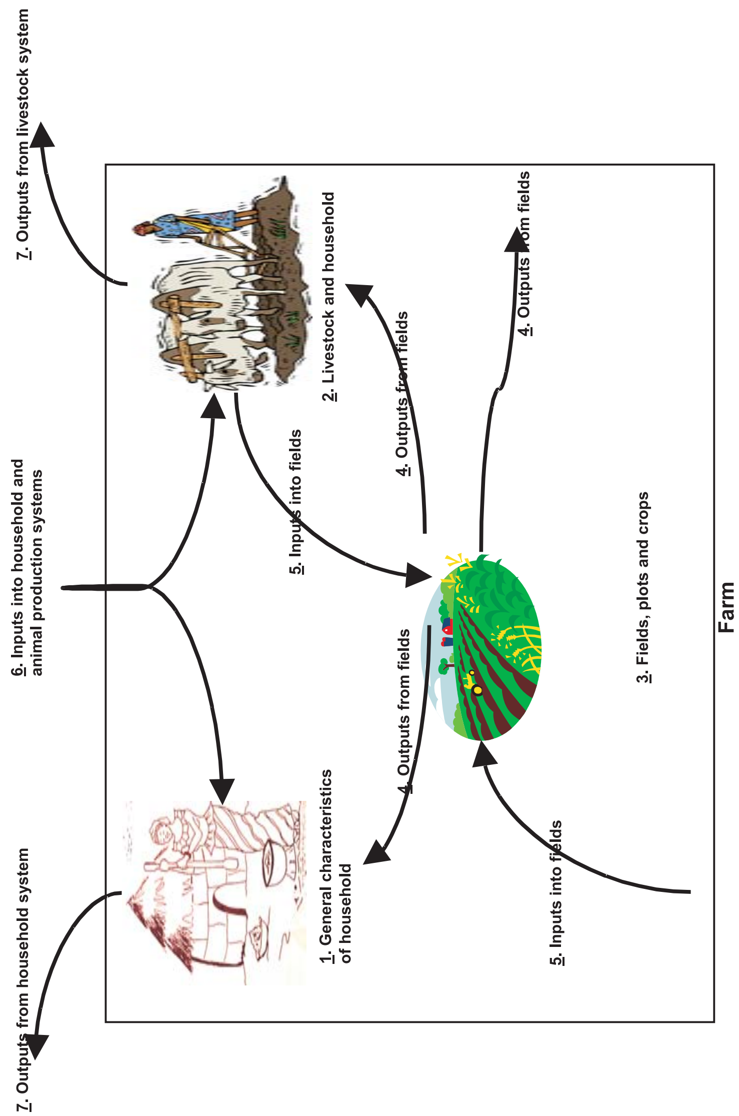


Figure 1. Resource Flows Within a Farm

4. Output from fields—Last season's crop production (quantities harvested and destinations) and use of residues (quantities, destinations, and proportional uses).
5. Inputs into fields—Organic and mineral fertilizers (types/quantities, sources).
6. Off-farm inputs to household and animal production systems (other than to the fields represented in step 5)—Animal feed, grasses/biomass, human food, etc.
7. Outputs from households and animal production systems (other than from the fields represented in step 4) leaving the farm—Marketed crop and animal produce, organic fertilizers, etc.

All information contained in RFMs can be transferred onto recording forms that can be entered into the ResourceKIT software (see description of this tool).

Further Reading

Defoer, T., and A. Budelman (Eds.) 2000. *Managing Soil Fertility in the Tropics: A Resource Guide for Participatory Learning and Action Research*, Composed of Five Parts, Amsterdam, Netherlands: Royal Tropical Institute.

Appendix 6. ResourceKIT

Name: ResourceKIT
Authors : Toon Defoer, et al., current address: WARDA, The Africa Rice Center, BP 320, Bamako, Mali
E-Mail: T.Defoer@cgiar.org; ToonDefoer@yahoo.fr
Website: www.kit.nl
Availability: The Resource Guide containing ResourceKIT can be requested through the KIT Website for euro 250

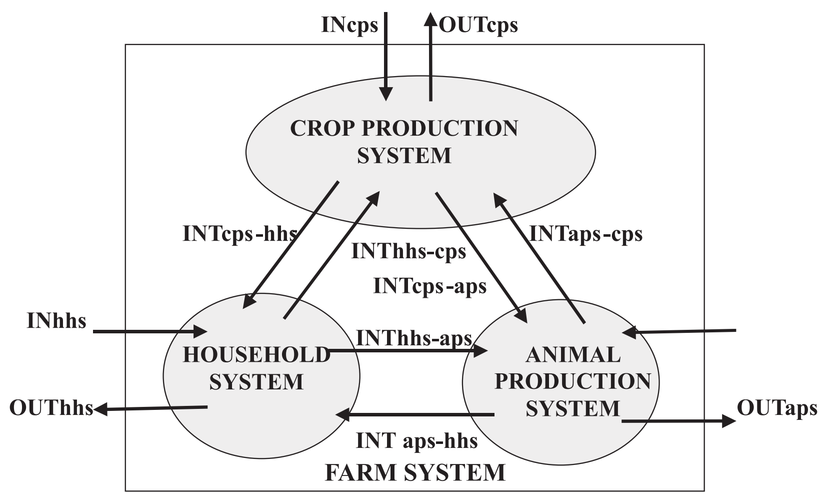
ResourceKIT is directly linked to the PLAR (Participatory Learning and Action Research) approach, and RFMs (Resource Flow Maps) (Appendix 5). ResourceKIT is a software that allows the transfer of information of the RFMs (captured in the recording forms) into nutrient flows and balances. ResourceKIT only deals with visible flows directly linked to management practices as presented on farmers' RFMs. Consequently, calculated nutrient balances are "partial."

The principles of the transformation are explained in Chapters 4 and 7 of Part 1 of the Resource Guide (Defoer et al, 2000) while Parts 4 and 5 of the Resource Guide present the details of the ResourceKIT (Defoer and Budelman, 2000). The principal collaborating institutes in developing the ResourceKIT are: the Royal Tropical Institute (KIT), Netherlands, the International Institute for Environment and Development (IIED), UK, and various research and development institutions in Mali, Kenya, Tanzania, Ethiopia, and Benin.

The transformation process comprises the following steps:

1. Build the picture of the basic elements of the farm system and its sub-systems (the crop production system, the animal production system, and the household system), including details on the total cultivated area, livestock, household, kraals, feed and food store, etc.

2. Present all possible resource flows between the elements or sub-systems of the farm system, grouped into three types of input flows (IN), three types of output flows (OUT), and six types of internal flows (INT).
3. Translate the resource flows into nutrient flows, using estimates of the nutrient composition of major crops and residues. ResourceKIT is limited to N, P, and K. Measured nutrient data can be entered.



IN_{cps}	Flows entering the crop production system from outside the farm system
OUT_{cps}	Flows leaving the crop production system and farm system
IN_{aps}	Flows entering the animal production system from outside the farm system
OUT_{aps}	Flows leaving the animal production system and farm system
IN_{hhs}	Flows entering the household system from outside the farm system
OUT_{hhs}	Flows leaving the household system and farm system
$INT_{cps\text{-}aps}$	Flows from the crop production system to the animal production system
$INT_{aps\text{-}cps}$	Flows from the animal production system to the crop production system
$INT_{cps\text{-}hhs}$	Flows from the crop production system to the household system
$INT_{hhs\text{-}cps}$	Flows from the household system to the crop production system
$INT_{aps\text{-}hhs}$	Flows from the animal production system to the household system
$INT_{hhs\text{-}aps}$	Flows from the household system to the animal production system

4. Calculate "partial" nutrient balances for different units of analysis—the farm system as a whole, the crop production system, the animal production system, and the household system. Partial balances can be calculated for the system as a whole or on a hectare basis.

Date Requirements

ResourceKIT requires data from RFMs, basic elements of the sub-systems of the farm system, sources and directions of flows, quantities of produce, proportional uses of crop residues, quantities of fertilizers and other inputs, and quantities of farm outputs.

ResourceKIT contains default values of N, P, and K contents of crops, residues, feeds, compost, household waste, manures, etc. ResourceKIT also includes default values of produce-to-residue conversion factors and of nitrogen fixation by deep-rooted trees, soil nutrient data, livestock management factors related to residue grazing under open access, etc.

Further Reading

Defoer, T., and A. Budelman (Eds.) 2000. *Managing Soil Fertility in the Tropics: A Resource Guide for Participatory Learning and Action Research*, Composed of Five Parts, Amsterdam, Netherlands: Royal Tropical Institute

Defoer, T., A. Budelman, C. Toulmin, and S. Carter. 2000. "Building Common Knowledge: Participatory Learning and Action Research," Part 1 IN *Managing Soil Fertility in the Tropics: A Resource Guide for Participatory Learning and Action Research*, Composed of Five Parts, T. Defoer and A. Budelman (Eds.), Amsterdam, Netherlands: Royal Tropical Institute.

Appendix 7. NUTMON

Name:	Monitoring Nutrient Flows and Economic Performance in Tropical Farming Systems
Authors:	J. Vlaming, H. van den Bosch, M. S. van Wijk, A. de Jager, A. Bannink, and H. van Keulen
Address:	Alterra, Green World Research. P.O. Box 47, NL-6700 AA Wageningen, Netherlands/Agricultural Economics Research Institute, LEI, P.O. Box 29703, 2502 LS, The Hague, Netherlands
E-Mail:	NUTMON-support@alterra.wag-ur.nl
Website:	http://www.nutmon.org
Availability:	Copies of NUTMON—Toolbox can be requested through the website for euro 250. The toolbox is available at no cost for universities, national research institutes, and NGOs in developing countries.

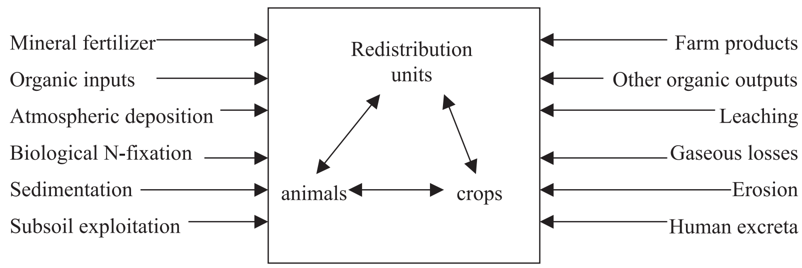
The NUTMON toolbox was developed as a model at the Wageningen University and Research Center during the 1990s in close collaboration with national research and development institutions in Kenya, Uganda, and Burkina Faso.

NUTMON is an integrated, multidisciplinary methodology, which targets different factors in the process of managing natural resources in general and plant nutrients in particular.

The NUTMON-Toolbox consists of a questionnaire, a manual, and several software modules that are specifically designed to facilitate monitoring and analysis of nutrient flows and economic performance at farm level.

The software makes possible a quantitative analysis, which generates important indicators such as nutrient flows, nutrient balances, cash flows, gross margins, and farm income.

NUTMON considers the following nutrient flows:



Data Requirements

1. **Soil**—C, N, P, and K contents; bulk density; slope; mineralization rate; rootable depth; enrichment factor; erodibility.
2. **Weather**—Monthly rainfall, rainfall erosivity (USLE R-factor).
3. **Crop**—Crop type, area, yield (grain, straw), destination of products, crop calendar.
4. **Animals**—Type, growth and composition, production, livestock confinement per month.
5. **Redistribution Units**—Size and quality of latrines, compost pits, manure heaps, etc.
6. **Management**—Internal and external inputs per field, animal and redistribution units.

In addition, information is required about nutrient contents of all products, prices, feed requirement, production of human and animal excreta, production of household waste, losses through burning, etc., for which NUTMON provides default values.

Further Reading

De Jager, A., S. M. Nandwa, and P. F. Okoth. 1998. "Monitoring Nutrient Flows and Economic Performance in African Farming Systems (NUTMON). I. Concepts and Methods," *Agriculture, Ecosystems, and Environment*, 71:37-48.

De Jager, A., F. M. Kariuki, M. Matiri, M. Odendo, and J. M. Wanyama. 1998. "Monitoring Nutrient Flows and Economic Performance in African Farming Systems (NUTMON). IV. Monitoring of Farm Economic Performance in Three Districts in Kenya," *Agriculture, Ecosystems and Environment,* 71:81-92.

Van den Bosch, H., A. De Jager, and J. Vlaming. 1998. "Monitoring Nutrient Flows and Economic Performance in African Farming Systems (NUTMON). II. Tool Development," *Agriculture, Ecosystems and Environment,* 71:49-62.

Vlaming, J., H. Van den Bosch, M. S. Van Wijk, A. De Jager, A. Bannink, and H. Van Keulen. 2001. "Monitoring Nutrient Flows and Economic Performance in Tropical Farming Systems (NUTMON), Part 1: Manual for the NUTMON Toolbox," Wageningen, Netherlands.

Vlaming, J., H. Van den Bosch, M. S. Van Wijk, A. De Jager, A. Bannink, and H. Van Keulen. 2001. "Monitoring Nutrient Flows and Economic Performance in Tropical Farming Systems (NUTMON), Annex," Wageningen, Netherlands.

Appendix 8. COTONS

Name: CotonSimbad
Authors: Eric Jallas, Philip Bauch, San Turner, Pierre Martin, Michel Cretenet, and Ron Sequiera
Address: Cirad, Avenue d'Agropolis, 34398 Montpellier Cedex 5, France
E-Mail: jallas@cirad.fr , cretenet@cirad.fr
Website: http://www.cirad.fr/presentation/programmes/coton.shtml

COTONS is a physiologically detailed simulation model of the growth and the development of the cotton plant that runs under Windows. It is based on GOSSYM, a cotton model developed in the 1970s. It consists of a plant model and a soil model. Weather information, crop management practices, and genetic characteristics drive the plant model. Plant development is limited by water and nitrogen supply and also by soil water potential. The model runs on a daily basis.

A special feature of the model is that the development of one or more plants is visualized on the screen, showing the development of branches, leaves, flowers, and roots. This can be done for an average plant, but it can also introduce variability between plants.

The model can be used for various purposes, e.g., to:

- Evaluate the adaptability of a variety to well-defined agro-ecological conditions.
- Evaluate the reaction of the variety to damage of the leaves or fruits caused by insects.
- Identify production-limiting factors, such as nutrients, water supply, or plant density.
- Evaluate the effects of impediments to root growth.
- Predict crop yields.

Data requirements

1. **Site**—Latitude.
2. **Weather**—Daily rainfall, solar radiation, minimum and maximum temperatures, and wind speed.
3. **Soil**—Depth of soil layers, texture, bulk density, available water at field capacity, saturation and wilting point, levels of nitrate, ammonia, organic matter, and water per layer.
4. **Management**—Variety, spacing, dates and quantities of fertilizer, irrigation, and growth regulators.

Further Reading

Jallas, E. 1998. "Improved Model-Based Decision Support by Modeling Cotton Variability and Using Evolutionary Algorithms," Ph.D. Dissertation, Mississippi State, Mississippi, U.S.A.

Jallas, E., R. A. Sequeira, P. Martin, S. Turner, and M. Cretenet. 1998. "COTONS, a Cotton Simulation Model for the Next Century," Second World Cotton Research Conference, Athens, Greece, September 1998.

Jallas, E., M. Cretenet, R. Sequeira, S. Turner, E. Gerardeaux, P. Martin, J. Jean, and P. Clouvel. 1999. "COTONS, Une Nouvelle Génération de Modèles de Simulation des Cultures," *Agriculture et Développement,* 22:35-46.

Appendix 9. NuMaSS

Name:	Nutrient Management Support System (v. 2.0)
Authors:	D. L. Osmond, T. J. Smyth, R. S. Yost, D. L. Hoag, W. S. Reid, W. Branch, X. Wang, and H. Li. 2002
Address:	Soil Science Department, Box 7619, North Carolina State University, Raleigh, North Carolina 27695
E-Mail:	numass@ncsu.edu
Website:	http://intdss.soil.ncsu.edu/
Availability:	NuMaSS 2 can be downloaded free of charge from the website

NuMaSS is Windows 9x/NT/XP-compatible software that helps in soil acidity, nitrogen, and phosphorus management decisions for crops in tropical regions of Africa, Asia, and Latin America. Assistance in nutrient management decisions to grow a crop under user-specified field conditions is provided through three software modules.

The *Diagnosis* module addresses the question of whether acidity, nitrogen, or phosphorus problems exist based on observations provided about geographical location, climatic conditions, soil type, previous crop yield and nutrient management, nutrient deficiency symptoms, and indicator plants. Soil and plant analytical data are considered if available but are not required.

The *Prediction* module recommends lime and nutrient inputs to correct identified acidity, nitrogen, and phosphorus problems that could limit achievement of the yield level specified by the user for the selected crop. Lime and fertilizer recommendations provided by NuMaSS account for differences in available nutrient sources and nutrient requirements among crop species and cultivars, but user input of a minimum soil analytical dataset is required. The soil analysis data are restricted to measurements routinely determined by soil-testing laboratories.

With user input of commodity prices and lime/fertilizer costs, the *Economics* module estimates net returns to applied nutrients. Users can compare different types of elemental fertilizers, available commercial blends, and organic sources. For each combination of nutrient sources, NuMaSS will estimate amounts of inputs for either the best profit or the best yield. Economic estimates can also be constrained by specifying a maximum amount of fertilizers to be applied or a given amount of cash to be invested in fertilizers and application costs. For each of the various user-selected scenarios, NuMaSS estimates whether there will be a surplus or deficit in applied nitrogen and phosphorus.

The integration of nutrient diagnosis, prediction and economics in NuMaSS empowers users to compare and make choices among different field conditions, cropping strategies, and nutrient source alternatives. The software contains an extensive database assembled from published and gray literature on field and laboratory investigations conducted throughout Africa, Asia, and Latin America for the following crops: bambarra groundnut, cassava, cotton, cowpea, peanut, phaseolus bean, maize, mung bean, pearl millet, potato, sorghum, soybean, upland rice, wheat, yam, forage grasses, and legumes. A module for tree crops is also included, using peach palm for heart-of-palm production as the test crop. Additional details on software development are available from the project's website.

Data Requirements

The minimum input requirements vary with module and soil nutrient constraint:

	Soil Nutrient Constraint		
Module	Nitrogen	Acidity	Phosphorus
Diagnosis	Location and climatic range Intended crop		
		Crop critical % Al saturation	
Prediction	Target yield Bulk density Fertilizer application depth		
	Grain stover ratio	% clay or textural class	
	Grain stover and % N	Exchangeable Al	Soil test P-value
	Fertilizer N-use efficiency	Effective cation exchange capacity (CEC)	Soil test P method
	Amount of organic inputs		Fertilizer application method
Economics	Maximum achievable yield for region Crop price N and P fertilizer resource; lime, N, and P fertilizer prices Lime and fertilizer application costs		

Further Reading—See website

Appendix 10. RIDEV

Name: Rice Development (RIDEV)
Authors: West Africa Rice Development Association (WARDA)
Address: Abdoulaye Sow, WARDA, BP 96 St. Louis, Senegal
E-Mail: warda-sahel@cgiar.org / warda-sahel@sentoo.sn
Availability: RIDEV software can be obtained free of charge from WARDA

RIDEV is a simple decision-support tool for irrigated rice systems in the Sahel. It simulates rice phenology, providing a time axis from germination to maturity depending on daily minimum and maximum temperatures and varietal constants. Furthermore, the percentage of spikelet sterility resulting from extreme temperatures is estimated. Based on the cultivar used, the sowing date, and weather data, RIDEV simulates optimal sowing dates (avoiding spikelet sterility), timing of N applications, timing of weeding, timing of last drainage before harvest, and timing of harvest. The model assists, therefore, with timing of important crop management interventions in irrigated rice-based systems.

The original version was programmed in GWBASIC. User-interface and outputs are in English. A newer version is also available, which runs under Windows. User-interface and outputs of this version are in French.

Photothermal constants of 95 rice genotypes, including 9 cultivars widely used by farmers in the Sahel, are provided with the model. Weather data of 38 meteorological stations are also available, covering important rice production systems in the Sahel.

Data Requirements

1. **Site**—Latitude.
2. **Climate**—Daily maximum and minimum temperatures.

3. **Crop Phenology**—Cultivar name—linked to a database with photothermal constants.
4. **Management**—Date(s) of sowing.

Further Reading

Dingkuhn, M. 1995. "Climatic Determinants of Irrigated Rice Performance in the Sahel. III. Characterizing Environments by Simulating the Crop's Photothermal Responses," *Agricultural Systems,* 48:435-456.

Dingkuhn, M. 1997. "Characterizing Irrigated Rice Environments Using the Rice Phenology Model RIDEV," IN K. M. Miézan, M.C.S. Wopereis, M. Dingkuhn, J. Deckers, and T. F. Randolph (Eds.), *Irrigated Rice in the Sahel: Prospects for Sustainable Development*, pp. 327-342. WARDA, Côte d'Ivoire.

Haefele, S. M., M.C.S. Wopereis, and C. Donovan. 2002. "Farmers' Perceptions, Practices and Performance in a Sahelian Irrigated Rice Scheme," *Journal of Experimental Agriculture*, 38(02):197-210.

Poussin, J. C., M.C.S. Wopereis, D. Debouzie, and J. L. Maeght. 2003. "Determinants of Irrigated Rice Yield in the Senegal River Valley," *European Journal of Agronomy*, 19:341-356.

Appendix 11. PRDSS

Name: Phosphate Rock Decision Support System (PRDSS)
Authors: U. Singh, P. W. Wilkens, J. Henao, S. H. Chien, D. T. Hellums, and L. L. Hammond
Address: IFDC, PO Box 2040, Muscle Shoals, AL 35662, U.S.A.
E-Mail: usingh@ifdc.org; pwilkens@ifdc.org

PRDSS is an expert system for estimating agronomic efficiency of freshly applied phosphate rock. It is a database that includes a large number of sources of phosphate rock and evaluates their feasibility under diverse soils, crops, and climatic conditions. It predicts the relative agronomic effectiveness (RAE) of phosphate rock with respect to soluble P fertilizers (e.g., TSP) in the first year of application. The current version of PRDSS does not estimate residual effect of phosphate rock.

Data Requirements

1. **Site**—Latitude, longitude.
2. **Climate**—Annual rainfall and rainfall during the growing season.
3. **Soil**—pH, texture, P-BrayI, organic matter, and CEC.

Further Reading

Singh, U., P. W. Wilkins, J. Henao, S. H. Chien, D. T. Hellums, and L. L. Hammond. 2003. “An Expert System for Estimating Agronomic Effectiveness of Freshly Applied Phosphate Rock,” IN *Proceedings of the International Workshop on Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences*, Kuala Lumpur, Malaysia.

Appendix 12. ORD

Name: Organic Resource Database
Authors: Tropical Soil Biology and Fertility Program and Wye College, University of London
Address: TSBF, PO Box 30592 Nairobi, Kenya
E-Mail: tsbfinfo@tsbf.unon.org
Website: http://www.wye.ac.uk/BioSciences/soil/
Availability: The database can be downloaded from the website and is free of charge

The ORD contains information on organic resource quality parameters including macronutrient, lignin, and polyphenol contents of fresh leaves, litter, stems, and/or roots from almost 300 species found in tropical agro-ecosystems. Data on the soil and climate from where the material was collected are also included as are decomposition and nutrient release rates of many of the organic inputs.

Examples of its uses are:

- Help select organic resources for a particular purpose.
- Develop hypotheses on the decomposition rates of organic resources based upon C/N ratios, lignin, and polyphenol contents.
- Use it as a database in conjunction with models and decision-support tools.

Further Reading

Palm, C. A., C. N. Gachengo, R. J. Delve, G. Cadisch, and K. E. Giller. 2001. "Organic Inputs for Soil Fertility Management in Tropical Agro-Ecosystems: Application of an Organic Resource Database," *Agriculture, Ecosystems and Environment*, 83:27-42.

Appendix 13. SOILPAR

Name: Soil Parameters Estimate
Authors: Marcello Donatelli and Marco Acutis
Address: Research Institute for Industrial Crops, Via di Corticella 133, 40128 Bologna, Italy; Tel +39 051 6316843; Fax +39 051 37485
E-Mail: isci-crop@iol.it
Website: www.isci.it
Availability: The software is available free of charge for non-profit organizations

SOILPAR 2.00 is a Win 98/2000/XP program to estimate physical and hydrological parameters of soil using various methods. Hydrological parameters can be estimated from a variable number of commonly available soil parameters (according to the method of estimate) such as soil texture, organic carbon, soil pH, and CEC. A geo-referenced soil database is maintained, including soil profile information and measured and estimated data. Soil profile sites can be visualized on a ArcView/ArcInfo shape file.

Data Requirements

Commonly available soil parameters, such as soil texture, organic carbon, soil pH, and CEC.

Appendix 14. Soil-Water Characteristics

Name: Soil-Water Characteristics
Author: K. E. Saxton
Address: USDA/ARS, Pullman, WA 99164-6120
E-Mail: ksaxton@wsu.edu
Website: http://www.bsyse.wsu.edu/saxton/soilwater/
Availability: The software can be downloaded from the website free of charge

This graphic computer program is used to estimate the hydraulic conductivity and water retention characteristics of a soil horizon. Using only the soil texture selected from within the ranges shown on the graphical soil texture triangle, the variation of soil water tension and conductivity with water content and the related water-holding characteristics are estimated. The water-holding characteristics are estimated by equations derived and published by Saxon et al., 1986.

Further Reading

Saxton, K. E., et al. 1986. "Estimating Generalized Soil-Water Characteristics From Texture," *Soil Science Society of America Journal,* 50(4):1031-1036.

Appendix 15. DST Legumes

Name: A Decision Tree on the Feasibility of the Use of Legumes in Africa
Authors: H. Breman and H. van Reuler
Address: IFDC, Africa Division, BP 4483, Lomé, Togo
E-Mail: hbreman@ifdc.org
Website: www.ifdc.org
Availability: The DST can be obtained free of charge from the authors.

This decision tree assesses the feasibility of legume use under biophysical and socioeconomic conditions prevalent in sub-Saharan Africa. The decision tree takes factors into account such as prevalence of N-deficiency in soils, protein deficiency, price ratio between N and P fertilizer, and intended use of legumes.

Further Reading

Breman, H., and H. van Reuler. 2002. "Legumes: When and Where An Option?" IN *Integrated Plant Nutrient Management in Sub-Saharan Africa: From Concept to Practice,* pp. 285-298, B. Vanlauwe, J. Diels, N. Sanginga, and R. Merckx (Eds.), CAB International, Wallingford, Oxon, United Kingdom.

Appendix 16. SARRA-H

Name:	Système d'Analyse Régional des Risques Agro-climatiques-Habillé (System for Regional Analysis of Agro-Climatic Risks)
Authors:	C. Baron, V. Bonnal, M. Dingkuhn, F. Maraux (CIRAD), and M. Sarr (AGRHYMET)
E-Mail:	vincent.bonnal@cirad.fr .
Website:	Currently not available on-line
Availability:	SARRA-H is available on a collaborative basis subject to license agreement, and training courses are conducted annually at CIRAD. The model is so far only available in French (documentation on CD-ROM upon request).

SARRA-H is a crop model that simulates water and radiation limited biomass production and yield, and is sensitive to sowing density and photoperiod. It has been developed for the drier areas of West Africa. The MS-Windows compatible software, written in DELPHI language, combines models and database management, and offers an extensive graphic interface. It offers the possibility of simulated sowing dates.

The currently available version is for rainfed cereals, but prototype versions exist already for groundnut and oil palm, and a broader range of crops is ultimately envisaged, including cotton and aquatic rice. This model is being used to evaluate the impact of climatic variations at various temporal and physical scales, but it can also be used at the plot scale to measure yield gaps (on-farm versus attainable, attainable versus potential yield), to test decision rules for sowing dates (based on locally observed rains, regional signals for the onset of monsoon, or any other type of forcing), and the choice of varietal types (e.g., degree of photoperiod sensitivity).

SARRA-H is the amended version (Habillé or "dressed") of SARRA, a much simpler crop-water balance model used for agro-ecological zoning and plot level characterization of crop stress history.

Data Requirements (SARRA crop water balance model)

- Daily rainfall, potential evapotranspiration.
- Duration of various growth phases in days.
- Maximal value for crop coefficient Kc(max).

Data Requirements (SARRA-H)

- Daily rainfall, potential evapotranspiration, solar radiation, and temperature.
- The volume of water-holding capacity in the root zone of the soil.
- Initial plant population or seeding rate.
- Crop parameters as appropriate for crops/varieties differing from preset calibration (e.g., cardinal temperatures, photoperiod sensitivity, thermal duration of juvenile phase, minimal and maximal specific leaf area [SLA], and maximal radiation use efficiency [RUE]).

Further Reading

Affholder, F. 1997. "Empirically Modeling the Interaction Between Intensification and Climatic Risk in Semi-Arid Regions," *Field Crops Research*, 52:79-93.

Baron, C., F. N. Reyniers, A. Clopes, and F. Forest. 1999. "Applications du Logiciel SARRA à l'Etude de Risques Climatiques," *Agriculture et Développement*, 24:89-97.

Baron, C., A. Clopes, P. Perez, B. Muller, and F. Maraux. 1996. *Manuels d'Utilisation de: SARRAMET 45 p, SARRABIL 35 p., et SARRAZON 29 p*, CIRAD, Montpellier, France.

Maraux F., C. Baron, F. Forest, J. Imbernon, and H. Ouaidrari. 1994. *Prévisions de rendement du mil en Afrique Sahélienne; l'expérience du CIRAD,* FAO, Colloque Villefranche sur mer, 24-27 Octobre 1994.

Samba, A. 1998. "Les Logiciels Dhc de Diagnostic Hydrique des Cultures. Prévision des Rendements du Mil en Zones Soudano-Sahéliennes de l'Afrique de l'Ouest," *Sécheresse,* 9(4):281-288.

Ecoregional Fund

The Fund for Methodological Support to Eco-regional Programs (Eco-regional Fund) stimulates eco-regional initiatives within or outside the CGIAR that aim at the development and implementation of sustainable, productive agriculture, rural development, and natural resource management. This is implemented by supporting methodologies (1) for research that is eco-regional in scope and (2) for enhancing the implementation of new approaches to natural resource management and rural development in eco-regions. Since its establishment in 1995 it has supported 10 projects in South America, Africa and Asia. The Eco-regional Fund is managed by the International Service for National Agricultural Research (ISNAR) and can be accessed through www.cgiar.isnar.org.

IFDC

IFDC—An International Center for Soil Fertility and Agricultural Development—is a public, international organization (PIO), which was founded in 1974 to assist in the quest for global food security. The nonprofit Center's mission is to increase agricultural productivity through the development and transfer of effective, environmentally sound plant nutrient technology and agricultural marketing expertise.

CTA

The Technical Center for Agricultural and Rural Cooperation (CTA) was established in 1983 under the Lomé Convention between the ACP (African, Caribbean, and Pacific) Group of States and the European Union Member States. Since 2000, it has operated within the framework of the ACP-EC Cotonou Agreement.

CTA's tasks are to develop and provide services that improve access to information for agricultural and rural development, and to strengthen the capacity of ACP countries to produce, acquire, exchange, and utilize information in this area. CTA's programs are designed to provide a wide range of information products and services and enhance awareness of relevant information sources; promote the integrated use of appropriate communication channels and intensify contacts and information exchange (particularly intra-ACP); and develop ACP capacity to generate and manage agricultural information and to formulate ICM strategies, including those relevant to science and technology. CTA's work incorporates new developments in methodologies and cross-cutting issues such as gender and social capital.

This book is meant to help agricultural researchers and extension staff in the selection and application of tools that facilitate decision-making to improve soil fertility management and agricultural productivity. These tools provide valuable additions to traditional approaches in research and development because they better capture the diversity and dynamics of farming systems and can readily be applied to provide site-specific diagnoses, analyses, and best-bet management options.

A large variety of tools are presented, ranging from relatively simple nutrient-flow mapping to more complex crop growth-simulation modeling. Case studies mostly set in sub-Saharan Africa provide practical examples of the use of these tools. An introductory chapter helps the reader to find the appropriate tool for a particular topic. In the appendixes, more detailed information is provided on each tool, such as a brief description and contact addresses of the developers of the tool.

This book is a result of the COSTBOX project (A Client-Oriented Systems Tool Box for Technology Transfer Related to Soil Fertility Improvement and Sustainable Agriculture in West Africa), managed by IFDC during 1999-2002 and funded by the Ecoregional Fund to Support Methodological Initiatives. The publication of this book was co-funded by CTA.

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