New Tools, Methods and Approaches in Natural Resource Management

International Crops Research Institute for the Semi-Arid Tropics

Abstract

ICRISAT and its partners have developed a range of new tools, approaches and methods to advance agricultural research in environments characterized by low household and natural resources, high climatic variability and limited infrastructure. These include: applications in simulation modeling, climate forecasting, climate-change and adaptation strategies, economic approaches to food security analyses, market studies, socio-economic analysis of how and why farmers make investment decisions, risk-return trade-offs on such investments, gender-related factors influencing technology choice, extension methods to promote technology adoption, GIS-based mapping and characterization methods, modeling of soil loss and surface water runoff, exploitation of agricultural niches such as fallows. This document provides examples of these successes, and identifies ways to build on them to alleviate poverty and food insecurity among smallholder farm communities in the semi-arid tropics.

Expanding the Legacy of Crop Simulation Modeling

Rationale for the use of models

Erratic rainfall patterns and heterogeneous distribution of soils lead to recurring site- and season-specificity of crop growth environments in the semi-arid tropics (SAT). Systems modeling is a valuable tool under such conditions. It can support field research by evaluating management options for the specific conditions of site and season, and provide a means to extrapolate research results in time and space. A more robust analysis of long-term productivity, climatic risk and environmental sustainability of tested management options becomes possible when we combine field experimentation with simulation modeling. ICRISAT has a long history of contributions to the development and application of systems modeling in the SAT and beyond.

Previous model application and development

Applications of systems modeling at ICRISAT have had a regional focus and have evolved over time as the science of modeling progressed. Most early applications were in West Africa or India. These utilized stand-alone crop models (cereal or legume) designed to characterize the water-related production potentials of environments and evaluate a limited range of crop management options (planting date, population, cultivar selection) to optimize water use. Subsequent developments in modeling the effects of surface management and nutrient constraints (mainly N) allowed analysis of a wider range of production constraints (soil fertility decline, loss of soil and organic matter) and their interaction with water supply, as well as assessment of the long-term effects on productivity and sustainability of production systems. The main focus of these applications was in India. Systems modeling, based on yield gap analysis, made a significant contribution to the broad bed and furrow (BBF) technology at ICRISAT; and to subsequent research on watersheds, that has become the flagship of ICRISAT's natural resource management research in Asia.

The development of cropping systems models (eg DSSAT, APSIM)[1] in the early 1990s greatly expanded the scope of systems modeling applications. The effects of crop rotations, intercrops, organic inputs (eg manure, crop residues) and additional fertility constraints (P), could now be included in the analysis of management options. In India, yield gap analysis and assessment of long-term productivity remains the mainstay for model applications. In southern and eastern Africa, modeling has increasingly been used as an adjunct to participatory on-farm research – to help guide the design of on-farm experimentation, fill gaps in on-farm results, and quantify the climatic risk associated with the technology response so as to help farmers choose low-risk management options to suit household resource constraints.

ICRISAT initiated its work on crop modeling with the development of the sorghum model SORGF, which after several improvements became part of the DSSAT software, CERES-sorghum. DSSAT was developed by IBSNAT,[2] a multi-institutional consortium for model development. ICRISAT has been a major contributor to the consortium – for example, helping to develop the pearl millet model (CERES-pearl millet) that is part of DSSAT. Field evaluation of the groundnut model (PNUTGRO) was carried out from 1987 to 1992 in collaboration with the University of Florida, USA, to calibrate

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and validate this model for Indian conditions. Based on this experience, ICRISAT also contributed to the development of the chickpea model. Both models are now part of the DSSAT software as CROPGRO-peanut and CROPGRO-chickpea. The cereal and legume models have been used in the past to analyze agronomic management effects (sowing date, plant population, variety selection, supplemental irrigation etc), quantify production potentials and yield gaps, and assess water balance and climate variability effects in cropping systems. Cereal models have also been used to assess responses to nitrogen management in different climates and soils, especially in India.

Currently DSSAT has 16 crop models: barley, maize, pearl millet, rice, sorghum, wheat, soybean, dry bean, groundnut, chickpea, cassava, potato, sugarcane, tomato, sunflower, and pasture. Many of these are important SAT crops. DSSAT also has crop sequencing and crop rotation modules, nitrogen and water balance modules, and a crop residue module. Various support modules include weather generators, genetic calculator, soils parameter estimator program, climate modification program, and field database management system.

At the conclusion of the IBSNAT project, DSSAT had limited systems capacity for analysis of long-term organic matter dynamics. ICRISAT explored new opportunities to enhance this capability. In 1996 we began collaboration with the Agricultural Production Systems Research Unit Australia to assimilate the APSIM suite of crop models into ICRISAT research. ICRISAT has contributed to the development and evaluation of the pearl millet and pigeonpea crop models and the farmyard manure module in APSIM. It has also helped develop and evaluate a soil phosphorus module. These developments have significantly enhanced APSIM for analysis of SAT cropping systems, particularly in Africa.

APSIM's suite of models has been used by ICRISAT scientists for various applications in India: for example improved crop management of groundnut in the Pollachi region of Tamil Nadu; assessing productivity, water and N balance of soybean-chickpea sequential and soybean/pigeonpea intercrop systems on Vertic Inceptisols; incorporation of short-duration pigeonpea into the groundnut production system at Anantapur; and for crop intensification studies in Maharashtra.

In southern and eastern Africa, APSIM has been used to measure responses to low rates of N fertilizer application (alone or in combination with manure); to assess the value of crop residues in raising crop productivity; and to quantify the risks and returns of alternative technology investment options in allocating scarce resources (labor, capital and land) to achieve whole-farm production goals. An emerging area of application of APSIM has been adding value to seasonal climate forecasting. Instead of merely providing farmers with the probabilistic rainfall forecast, simulation analysis can enhance this information by including an assessment of the likely risks associated with different crop, cultivar and nutrient management options for a given seasonal forecast, using the historical climate record. With this enhancement, a seasonal climate forecast has a much greater likelihood of significantly changing farmer decision making. This work has been pursued across in India, Ghana, Kenya and Zimbabwe.

Recent research on adaptation to and mitigation of climate change has provided a rationale for further model improvement in West Africa, where biotic and abiotic peculiarities of the cropping systems have long challenged the performance of models focusing on productivity rather than stability. The latest versions of the DSSAT-Century cropping systems model will include new, more universal phenology modules and expanded genotype databases for sorghum and pearl millet, allowing for realistic simulation of highly photoperiod-sensitive landraces and the next generation of improved varieties. Successive carbon sequestration projects have prompted the development of a soil P module as well as improved representations of tillage effects on soil water, soil organic matter, nutrient

dynamics and biomass partitioning in cereals. A CROPGRO-pigeonpea model is in preparation, using ICRISAT data from West Africa. Applications of the model include coupling with GIS to build cultivar-specific regional adaptation maps, and recommendation domains for fertilizer microdoses.

Current Activities and Key Achievements and Impacts since 2000

1. Yield gap analyses

Rainfed crops in Thailand, Vietnam and India. Potential yields and yield gaps of major rainfed crops in Thailand, Vietnam and India were assessed in order to assess the capacity of rainfed environments to meet future food needs. We reviewed research station data in each country, used crop models to estimate potential yields, and compared these with district or province level data on actual yields obtained by farmers to calculate yield gaps for various crops. This helped identify regions/countries and crops where substantial improvements in productivity and production are possible.

Northern Vietnam. Land area in Vietnam is limited, therefore increases in food production must come largely by increasing productivity per unit of land. The major upland crops are maize, groundnut and soybean. In the mountains, legume crops such as groundnut, soybean and mung bean are grown after rice. These are important sources of protein and oil for ethnic peoples, fodder for cattle, and also for improving soil fertility. The major yield constraints for rainfed crops are undulating topography, poor soil fertility, drought and poor adoption of improved soil, water, nutrient, crop and pest management technologies, leading to inefficient use of rainfall and natural resources. Crop yields are low. Simulation analysis showed that soybean yields can be increased 1.5 to 1.7 times, groundnut yields by 2.3 to 2.7 times and maize yields by 2.7 to 3.0 times from their current levels in six selected provinces during the spring and summer or autumn-winter seasons (Table 1). Production can be increased by 0.06 to 0.10 million t for soybean, 0.18-0.32 M t for groundnut and 0.96 M t for maize.

Northeastern Thailand: Northeastern Thailand covers about 17 million ha or one-third of the country. Agriculture is based mainly on upland crops with low water requirements: cassava, upland rice, sugarcane, maize, soybean, groundnut and sunflower. The major constraints are frequent droughts and floods, low soil fertility, soil erosion and land degradation, poor soil water conservation practices, low-yielding crop varieties, and economic limitations of farmers. Current yields are considerably lower than research station yields – by a factor of 1.2 to 1.9 for different crops – indicating large potential for improvement (Table 2). Based on the current area under each crop, we estimate production can be increased by 8.1 Mt for paddy rice, 0.83 Mt for maize, 0.043 Mt for soybean, and 0.012 Mt for groundnut.

Table 1. Yield gap analysis of rainfed crops in northern Vietnam.

Crop	Season	Area (million ha)	Current yield (t ha^{-1})	Research station yield (t ha^{-1})	Rainfed potential yield (t ha^{-1})	Yield gap (t ha^{-1})
Soybean	Spring	0.12	1.36	1.77	2.00	0.40 – 0.68
Soybean	Summer		1.36	1.96	2.35	0.6 – 1.01
Groundnut	Spring	0.14	1.52	3.0	4.17	1.50 – 2.60
Groundnut	Autumn-winter		1.52	2.62	3.53	1.1 – 2.0
Maize	Spring	0.53	3.3		5.0	1.65
Maize	Summer		3.3		5.3	1.99

Table 2. Yield gap analysis of rainfed crops in northeast Thailand.

Crop	Area (million ha)	Current yield (t ha^{-1})	Research station yield (t ha^{-1})	Yield gap (t ha^{-1})
Paddy rice	4.55	1.75	3.53	1.78
Maize	0.37	2.45	4.70	2.25
Soybean	0.06	1.2	1.91	0.71
Groundnut	0.04	1.34	1.73	0.29
Sunflower	0.01	1.47	1.60	0.13

India. The dominant rainfed crops in India are sorghum, pearl millet, pigeonpea, chickpea, soybean and groundnut. There are substantial yield gaps between the current (farmer) and experimental or simulated potential yields. Pearl millet and sorghum yields can be increased 2.7 to 3.0 times with improved management; yields of legumes and oil seeds can be increased by 2.3 to 2.5 times (Table 3). With supplemental irrigation, total production of *kharif* sorghum can be increased by 12.5 Mt, *rabi* sorghum by 4.6 to 9.8 Mt, pearl millet by 12.1-13.3 Mt, pigeonpea by 3.1-3.4 Mt, chickpea by 5.8-7.8 Mt, soybean by 7.4-7.7 Mt and groundnut by 6.6 to 10.8 Mt.

Table 3. Yield gap analysis of crops in India.

Crop	Area (million ha)	Current yield (t ha^{-1})	Research station yield (t ha^{-1})	Rainfed potential yield (t ha^{-1})	Yield gap (t ha^{-1})
Kharif sorghum	5.43	1.14	3.50	3.50	2.31
Rabi sorghum	5.45	0.62	2.40	1.50	0.85 – 1.8
Pearl millet	9.77	0.71	2.07	1.95	1.24 – 1.36
Pigeonpea	3.36	0.61	1.62	1.52	0.91 – 1.01
Chickpea	7.28	0.77*	1.85*	1.08	0.8 – 1.07
Soybean	6.3	0.98	2.16	2.24	1.18 – 1.23
Groundnut	6.6	1.03	2.03	2.66	1.0 – 1.63

* with supplemental irrigation

We also analyzed soil water balance of various agro-ecological zones where major rainfed crops in Thailand, Vietnam and India are grown. This has established the opportunities available for harvesting of surface runoff and groundwater recharging for providing supplemental irrigation or to extend the growing season.

Drought-prone locations in Kenya. Machakos district in Kenya witnessed massive investments on soil and water conservation measures and associated changes in land use between 1948 and 1978. Maize became the key crop, but use of inputs remained very low. The low-input system is leading to declining soil fertility and productivity. Average maize yields declined from 0.8 t ha^{-1} during 1970-74 to 0.4 t ha^{-1} during 1998-2002. We analyzed yield trends in relation to seasonal rainfall. Seasons were classified as below normal (<249 mm rain), normal (250-349 mm) and above normal (>350 mm). According to rainfall data recorded at Katumani research station between 1957 and 2003, nearly 50% of the seasons are below normal, 30% are normal and the remaining 20% are above normal. Yield gap analysis compared the yields currently obtained by farmers with those recorded in a long-term trial at Katumani research station and those simulated using APSIM (Table 4).

Table 4. Yield gap analysis of maize in semi-arid Machakos district, Kenya.

Management	Below normal <250 mm	Normal 250-350 mm	Above normal >350 mm
Farmer yields			
All seasons	222	561	1297
Experimental yields (kg ha^{-1}) (19 seasons)			
Low input management	580	1400	1240
High input management	1570	3220	3890
Yield gap	990	1820	2580
Experimental runoff (mm)			
Rainfall	153	294	571
Runoff	19	53	153
Simulated yields (kg ha^{-1}) (93 seasons)			
Low input management	310	470	450
High input management	1560*	3310	4220
Yield gap	1250	2840	3770
Simulated runoff (mm)			
Rainfall	150	294	487
Runoff	21	52	127

High input: 22,000 plants ha^{-1} with no fertilizer. Low input: 53,000 maize, stubble mulch, 100kg N + 10 kg P
* 22,000 plants ha^{-1} with 50 kg N ha^{-1}

The analysis showed significant yield gains in all seasons. Although average yields under high-input system are significantly higher than those obtained under low-input system in all seasons, it is difficult to bridge the gap during below normal seasons because of the high chance of crop failure (Fig 1).
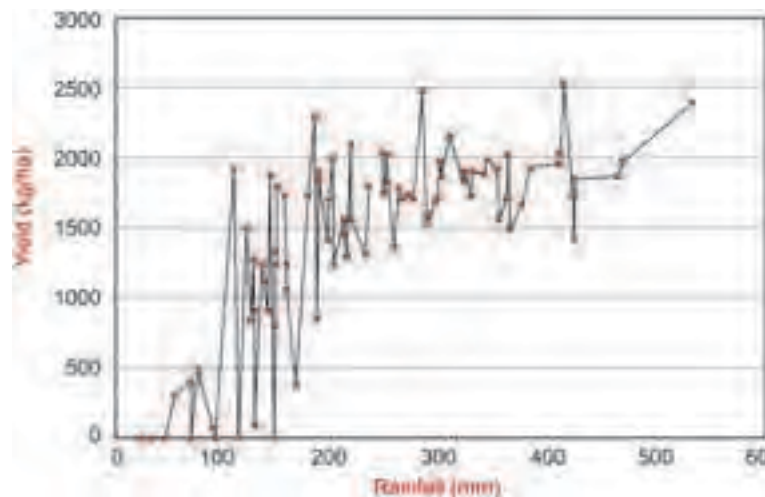

Figure 1. Relationship between seasonal rainfall and maize yield.

To bridge the gap between current and potential yields, it is vital to reduce the risk associated with climate variability. We are now developing tools that assist in tactical decision making. This includes mainly the modeling of impacts of variability in local climatic conditions, and developing decision tools (maps, tables/flow-charts or spreadsheets) based on key decision parameters used by farmers and support agencies, and on economic viability/profitability.

2. Linking *ex ante* and *ex post* risk analyses with participatory approaches in southern Africa

Current research in simulation modeling in southern Africa continues to pursue applications in on-farm participatory research with a focus on fertility and water management technologies. Ex-ante analysis of best bet technologies helps guide on-farm experimentation with farmers; ex-post analysis is used to extrapolate on-farm results in time and space to quantify climatic risks. For example, productivity of various crop management options was analyzed, to help select best bet options for projects in the Water and Food Challenge Program in the Limpopo Basin (see Box 1).

The Limpopo analysis showed that in these environments, rainfall distribution patterns can actually favor long-season cultivars in a high proportion of seasons. This fact has largely been overlooked in breeding and extension programs for drier areas – which tend to concentrate on short-season varieties that escape terminal moisture stress. The analysis also helped to highlight the fact that water productivity increases only really come about with investment in fertility management.

Simulation analysis thus provided the Challenge Program with a cost effective tool for screening technology investment options for improving water productivity (Table 5). The results provide supporting evidence that crop and water productivity in smallholder farming systems can be substantially increased by an integrated genetic, nutrient and water management approach. However, it also separated and quantified the payoffs to incremental uptake of the technology options. This information may be more practical to smallholder farmers facing severe resource constraints by helping to better prioritize their investment choices.

Table 5. Water productivity (WP) calculated from in-crop rainfall and simulated grain yield (Bulawayo, Zimbabwe, 48 seasons) for a range of technology options.

Technology option	WP (kg grain / mm rainfall)
Long season cultivar, zero N	1.5
Short season cultivar, zero N	1.8
Long season cultivar, water conservation, no N	2.0
Short season cultivar, water conservation, no N	2.1
Long season, N applied (17kg/ha)	2.1
Short season, N applied (17 kg/ha)	3.2
Long season, water conservation, N applied	3.7
Short season, water conservation, N applied	4.5

Box 1. Simulation analysis of maize productivity in relation to investment options in Zimbabwe SAT

Simulated maize yield for long and short season cultivars (representing traditional and improved respectively) with no N inputs at Bulawayo is shown in Fig 1. The simulated long-term average grain yield for both cultivars is low (long = 664 kg ha^{-1}, short = 680 kg ha^{-1}) and the year-to-year variability high, although substantially less for the short season cultivar (stdev = 298 vs 436 kg ha^{-1}).

In Fig 2, results in Fig 1 are converted into an annualized difference for the cultivar responses. The effect of applying N fertilizer is also included in figure 2. With no N applied (Fig 2a), the yield advantage of the short season cultivar averages 300kg ha^{-1} and is achieved in 48% of years. In comparison, the long season type has an average yield advantage of 250kg ha^{-1} and is achieved in

52% of years. If a small amount of N is applied (Fig 2b), then there is a considerable shift in favor of the short season cultivar – average yield advantage is 600kg ha^{-1}, and an advantage is seen in 60% of years. But in 40% of years, the long season cultivar still outperforms the short season cultivar, by an average of 390 kg ha^{-1}.
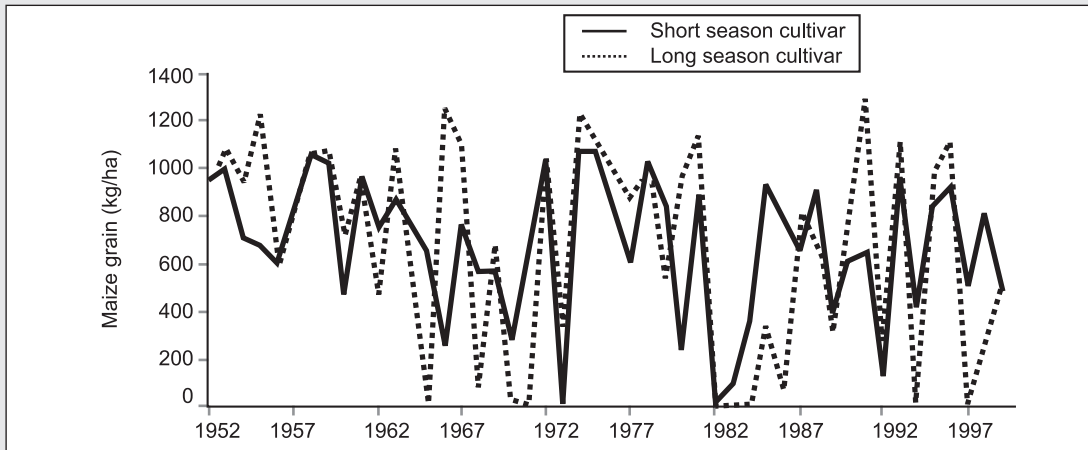

Figure 1. Simulated maize grain yield for long and short season cultivars with no N inputs at Bulawayo for cropping seasons 1951 to 1998.
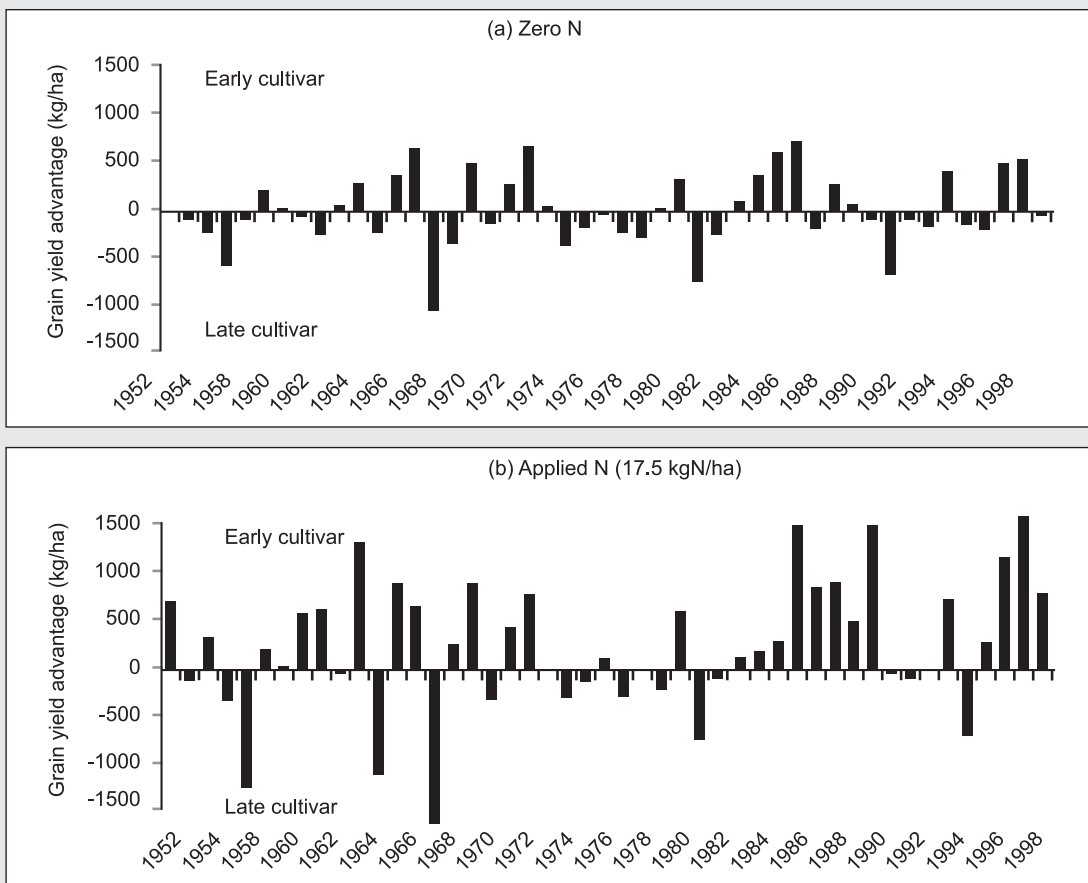

Figure 2. Annual grain yield difference between short and long duration maize cultivars simulated for Bulawayo, (a) without and (b) with N fertilizer applied.

A major outcome of simulation modeling analysis in southern Africa has been the promotion of low doses of N fertilizer with private and public sector agencies. A combination of on-farm experimentation and simulation analysis in South Africa and Zimbabwe has shown that this can substantially increase in productivity (Fig 2), with acceptable risk for farmers in dry regions (Fig 3). For example, in Fig 3, simulated yields are highly variable at Masvingo, especially with higher N inputs, reflecting the variable rainfall in this region. At lower N inputs, the response to N is more stable but almost always substantially higher than the no-fertilizer scenario.
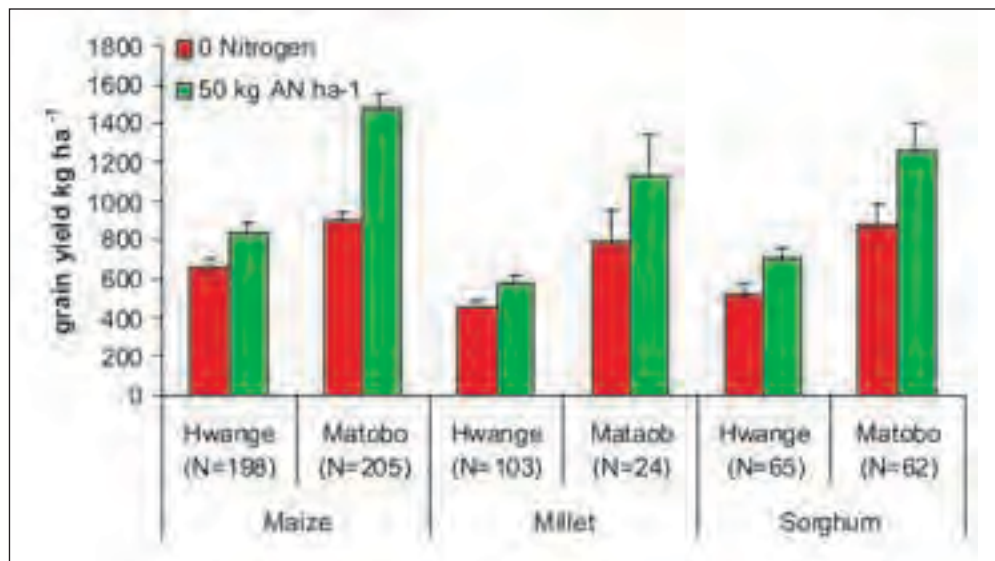

Figure 2. Contribution of small doses of fertilizer to grain yields in Matobo and Hwange districts, Zimbabwe, 2004.
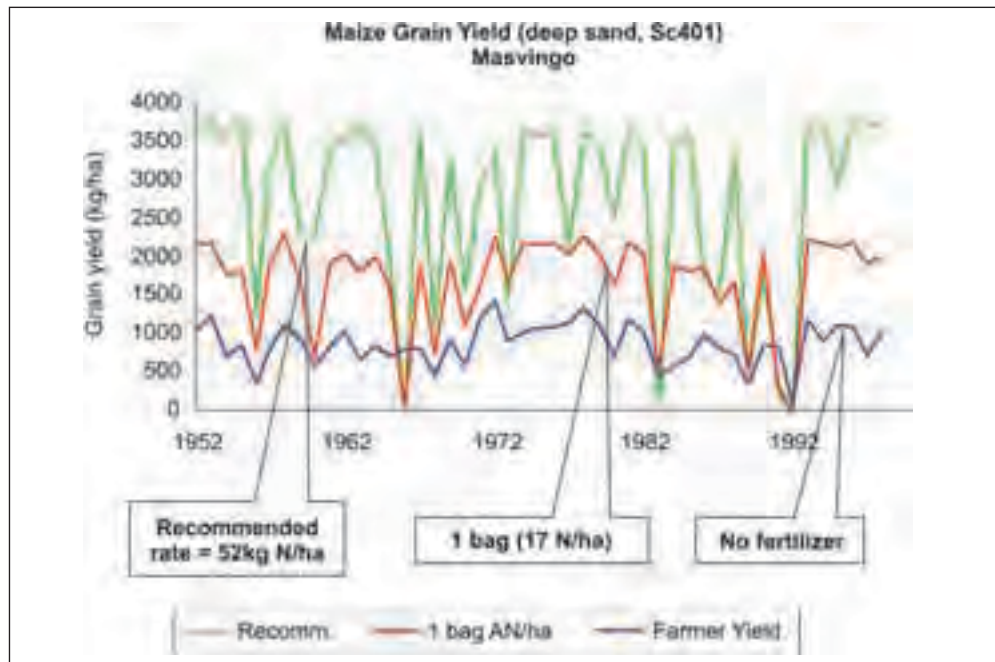

Figure 3. Simulated maize yields for Masvingo, Zimbabwe, for three N fertilizer treatments – no applied fertilizer, the recommended 3 bags/ha (52 kg N/ha) and a smaller investment of 1 bag/ha (17 kg N/ha).

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In Zimbabwe and South Africa, simulation modeling has also been used directly with smallholder farmers to help design on-farm experimentation trials. In South Africa for example, on-farm trials testing 4 different legumes with +/- P and sorghum and maize trials with +/- N were selected by different farmer groups in 2005 following discussions based on simulation modeling outputs (Fig 4).
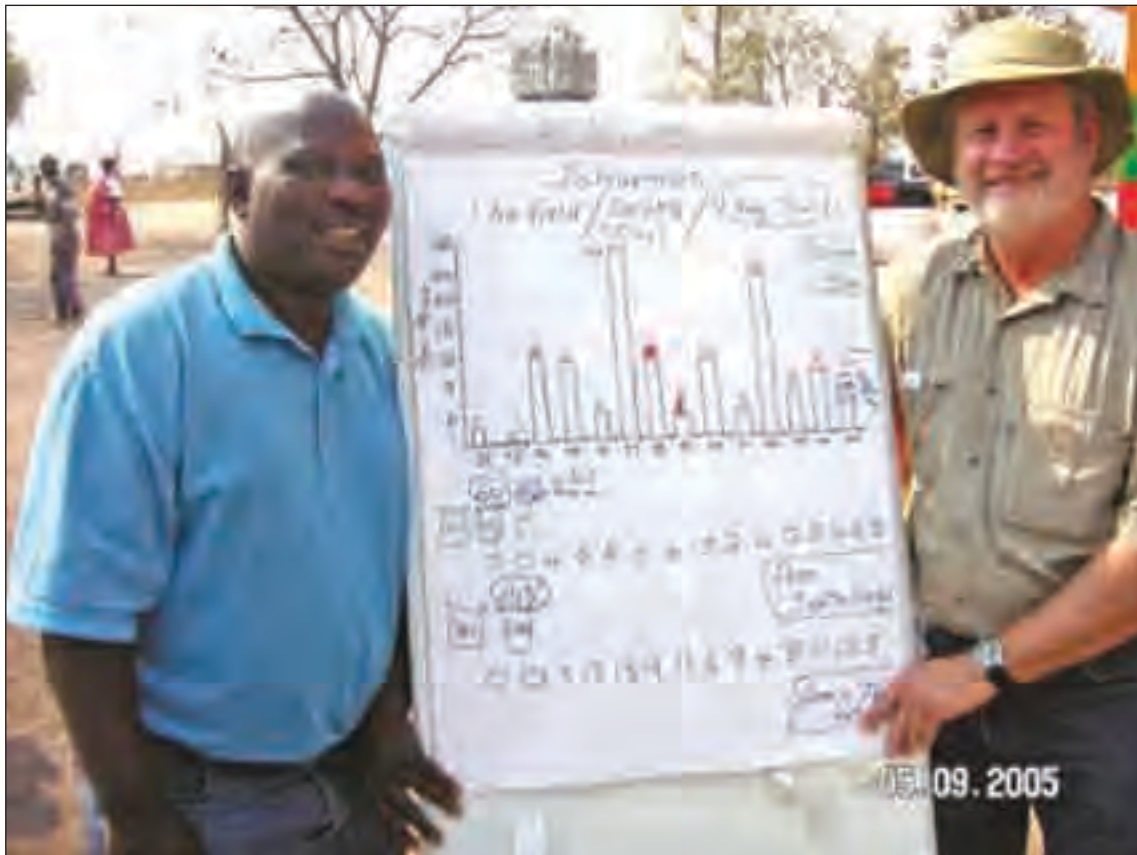

Figure 4. Reviewing model outputs with a collaborating farmer in South Africa.

3. Crop and land management practices and soil carbon sequestration in Asia

Crop models (APSIM and DSSAT v4.0) incorporating soil carbon balance have been used to identify soil and crop management practices that will sequester more carbon in the soil, thereby improving soil fertility and mitigating the impacts of climate change in the long run.

Analysis of crop production and soil organic carbon data from a long-term field experiment on a Vertic Inceptisol (BW7 watershed) showed that, in spite of continuous decline in soil organic carbon (OC) after clearing the fields of natural vegetation and grasses, OC retention in the soil was consistently higher when crop residues were added; and similarly higher in the soybean/pigeonpea intercrop compared to the soybean-chickpea sequential system. The APSIM software was first calibrated against the observed field data and then used to develop scenarios of soil OC changes as influenced by crop residue additions and cropping systems. Long-term simulation analysis showed that addition of crop residues and planting a soybean/pigeonpea intercrop system slowed the rate of decline in soil OC. However, crop residues (C:N ratio 16:1) additions at 8 t ha^{-1} yr^{-1} would be required to maintain soil OC at the initial levels observed at the beginning of the study. Such high amounts of residues are generally not available for incorporation; we need to develop alternate practices for maintaining OC.

4. Pearl millet crop growth model as a component of decision support systems (DSS) in the Sahel

Several crop models are potentially useful for application in semi-arid West Africa. Dynamic process models – such as DSSAT, APSIM, CropSyst, EPIC, CropSys and the 'School of de Wit' family – simulate the dynamic processes of crop growth, development and environmental interaction. Water balance – stress index models, used widely in the target region, simulate water balance dynamics but treat canopy characteristics as an input when calculating stress indices. Pure statistical models have limited applicability due to their insensitivity to crop-weather interactions. Selection of appropriate models should consider appropriateness for the intended purpose, suitability for the environment, and the levels of experience and support available. We are currently evaluating a range of models with respect to these criteria (results not presented).

Among process models, DSSAT and APSIM have the strongest experience, training and support in the West African region and show great promise for the future.

The development and validation of crop growth models within the decision support project aims to simulate complex interactions between water, organic and mineral amendments as well as genetic-management interactions under suboptimal conditions. This will help guide site/season specific intensification recommendations at the household level based on economic return, risk coping capabilities, and access to organic matter. We foresee that after sensitivity analysis, the APSIM model will lead to a simpler meta-model which will be less data intensive and which could be used for spatio-temporal scenario analyses at the field, farm, landscape and regional scales (Fig 5). Once coupled with an animal nutrition model, trade-off analysis could also be performed on the conflicting demands for crop residues.
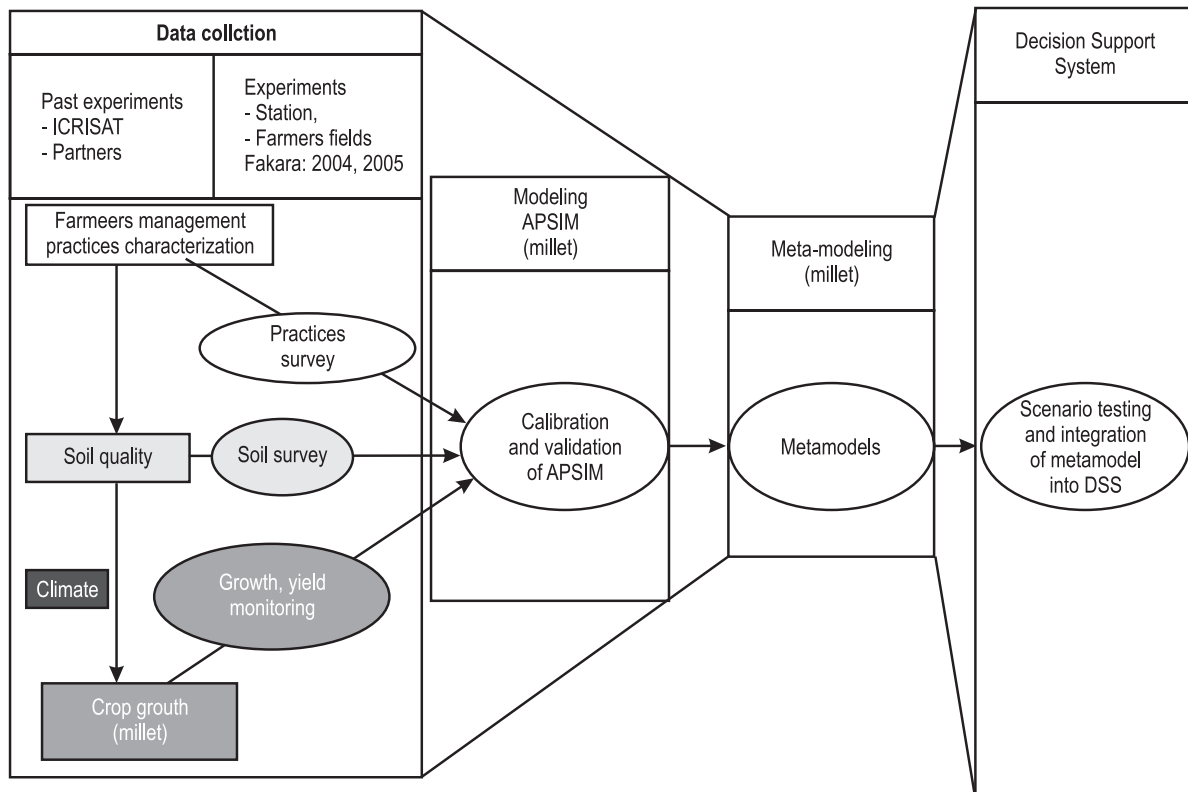

Figure 5. General strategy for crop growth model validation/calibration and its integration in DSS.

Progress made so far on APSIM calibration and validation:

- Calibration of ASPIM with on-station datasets including manure/crop residue/fertilizer treatments for 2 years
- Pearl millet crop parameters including photoperiodism obtained from on-station trial for 7 varieties and Nigerien landraces at four sowing dates (2005 trial)
- On-farm multi-site multi-factorial trial combining mineral and organic amendments and three varieties completed for 3 years. This dataset will serve for the model validation under suboptimal conditions and validation of water balance (weekly soil moisture profiles).

The following modeling issues will need to be addresses for further developments. Recent on-farm trials suggest that mineral fertilizer affects the number of vegetative and non-mature tillers in certain rainfall conditions. Fertilizer also has negative effects on seedling survival. Sahelian farmers manage and maintain high phenotypic variability within their millet population as a risk management strategy. So far crop growth models treat fields as an ensemble of uniform plants. This may be very far from Sahelian reality and models should be further developed to take this factor into account.

5. Spatial weather generation for crop growth simulation models in Kenya

The tremendous value of the type of research described above is constrained to some extent by the fact that it relies on 'point source' climate data collected at specific weather stations, thus making interpolation of the outputs between weather stations problematic. This can be overcome by the use of modern and proven spatial weather generators such as MarkSim, a spatially explicit daily weather generator developed at CIAT and released in 2004. The climate surfaces that are produced use data from 10,000 stations in Latin America, 7000 from Africa and 4500 from Asia. MarkSim relies on climatic data surfaces interpolated from weather stations and generates long-term weather records on a grid basis of 18x18km. MarkSim was evaluated during a week-long exercise in Kenya in 2005 where ICRISAT, CIAT, IMTR, Kenya Met. Department and KARI worked together to assess its reliability as a tool to generate daily climatic data. This was part of a collaborative effort to integrate climate risk management strategies into FAO Farmer Field Schools which are to be established in the SAT of Kenya. The characteristics of the long-term daily weather data generated by MarkSim compares well with existing long-term records for a number of meteorological stations (Figs 6-8).

There is one caveat, however. In simulating runoff, our models tend to get the aggregated annual amounts right, but perform more poorly for individual events (more scatter). This makes simulation of soil loss more problematic given its episodic nature. Similarly, showing that MarkSim can achieve close agreement on the probability of annual rainfall amounts is only part of the equation. Seasons with similar total rainfall can give very different yield response – distribution of rainfall is important. Hence the critical parameter for assessing MarkSim is not so much probability distribution for seasonal rainfall or size of events (although both are very encouraging), but rather the distribution of events within a season (eg number and length of dry spells).

The combined use of crop growth simulation models, historic records and weather generators such as MarkSim allows both characterization and subsequent mapping of the agricultural implications of climatic variability (Jones and Thornton 2002). It is also possible to integrate different climate change scenarios into MarkSim and, through crop growth simulation models, assess their impact on agricultural production.
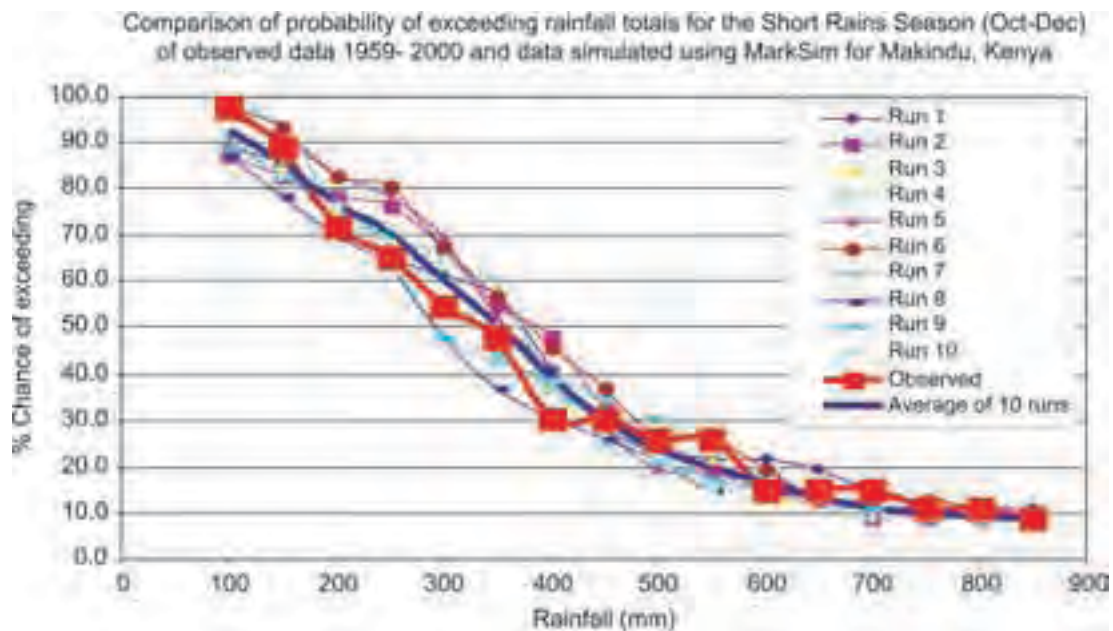
Figure 6. Rainfall probabilities during the short rains (Oct-Dec) at Makindu in the SAT of Kenya.
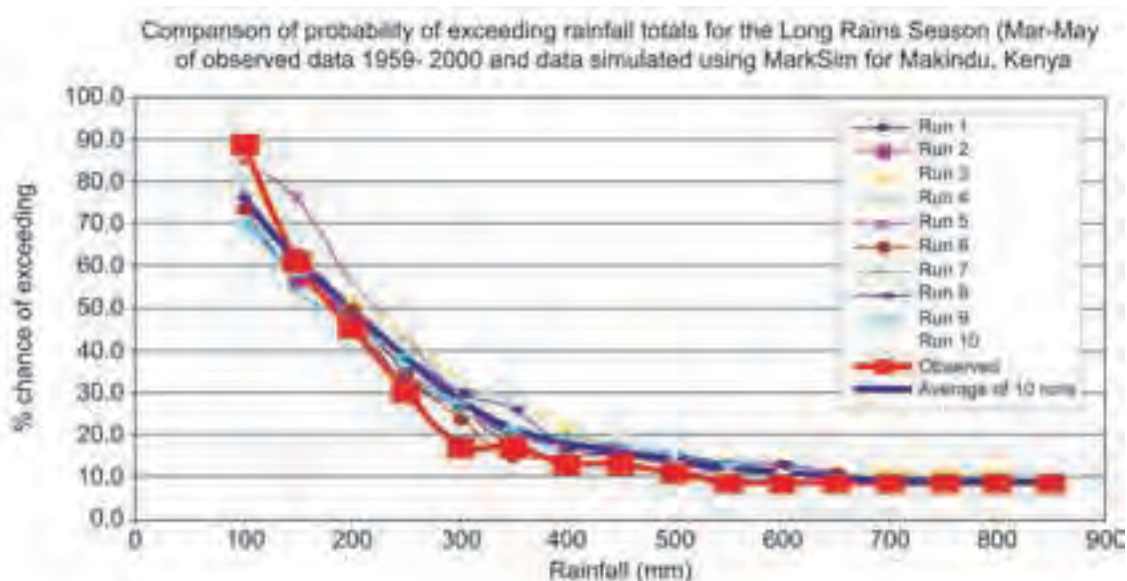
Figure 7. Rainfall probabilities during the long rains (March- May) at Makindu in the SAT of Kenya.

6. Adaptating cropping systems models for West African landraces: photoperiod sensitivity

To identify profitable technologies and practices, a key prerequisite is that crop simulation models first be able to effectively reproduce the characteristics of local cropping systems (Phillips et al 1998). In West Africa, this presents difficult challenges for the available models, because of peculiarities such as surface crusting, low planting densities, heterogeneous canopies, specific adaptation traits etc.
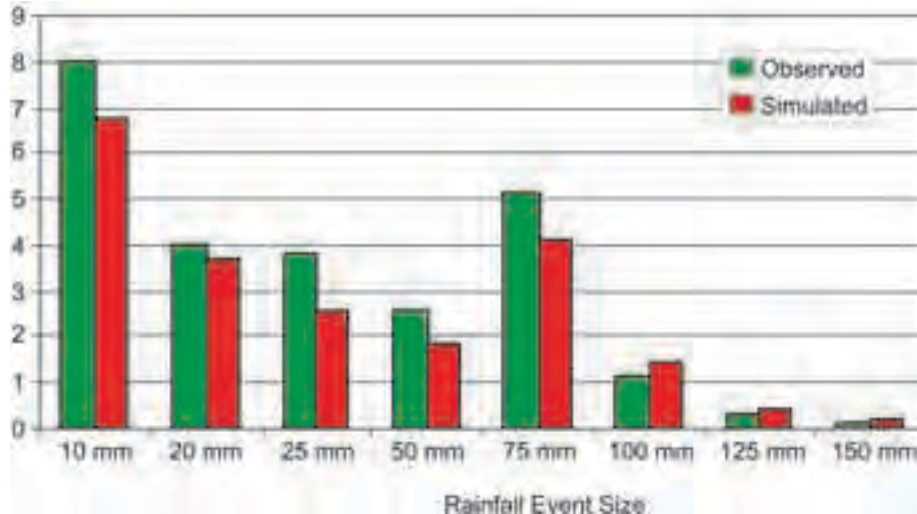
Figure 8. Observed and predicted (MarkSim) annual frequency of rainfall events of different magnitudes at Katumani, Kenya.

Critical advances have been made by ICRISAT and collaborators in the adaptation of photoperiod response in the CERES sorghum and millet modules of the DSSAT-Century cropping systems model. In its original form, a linear photothermal response resulted in underestimates of crop cycle duration for late-maturing landraces (Fig 9). A threshold-hyperbolic function was shown to simulate cycle duration for both photoperiod sensitive and insensitive material (Folliard et al 2004). This work allowed us to revisit the popular but incorrect photothermal approach widely used in modeling crop development (Robertson 1973).
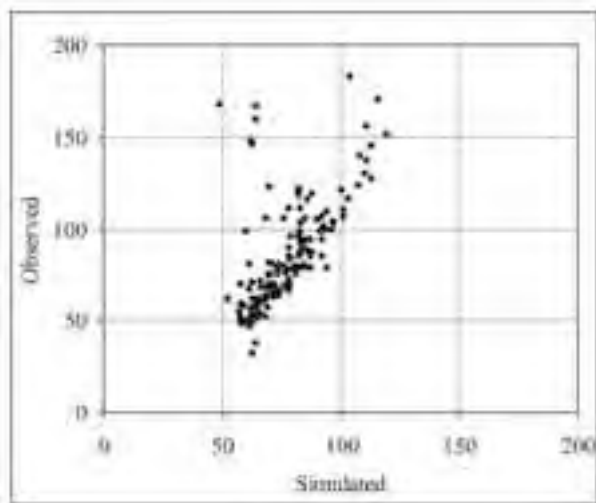
(a) PP response: Cumulative linear (CERES original). $R^2 = 0.37$, RMSE = 25.7.
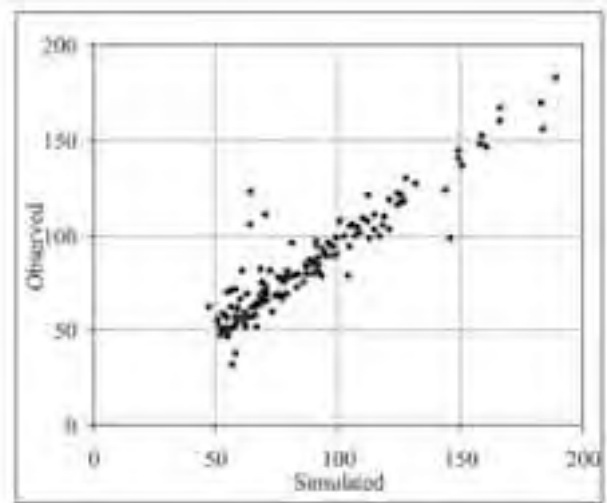
(b) PP response: Threshold hyperbolic (Folliard et al 2004). $R^2 = 0.88$, RMSE = 11.6.

Figure 9. Days to anthesis computed over a sample size of 146 from planting date experiments conducted between 1992 and 2003 in six locations (Cinzana, Koporo-Pen, Katibougou, Samanko, Sikasso, Sotuba) covering a latitudinal gradient in Mali. Sorghum and millet varieties: CSM219, CSM388, Jebana, M9D3, Nazongala, Sanioba-03, Sanioba-B, Surukuku, W33, Wasulu.

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Other ongoing work seeks to improve models' poor ability to simulate yield components because of flaws in the timing of stem elongation (occurring after panicle initiation in CERES) and the inadequate partitioning of assimilates resulting in inflated harvest indices for sudano-sahelian landraces. The characteristic effect of photoperiod sensitivity and partitioning traits on biomass production is illustrated in Fig 10. Improvements in models' ability to simulate yield components will have important applications, *inter alia* for future ecosystem services (eg carbon sequestration by dual-purpose photoperiod-sensitive cultivars) and in supporting the developing regional seed sector (through spatial analysis of GxE interactions, phenotyping and varietal adaptation mapping: see page 44).

Planted on 20 June.

Planted on 20 July.

Figure 10. Sorghum landrace at flag leaf stage.

Taking Account of Market and Policy Drivers with Bio-Economic Models

Food aid and famines in Niger

The market price of staple foods is a major indicator of food availability and accessibility; the study of its dynamics is therefore an essential tool in the fight against starvation. Prices trajectories in Niger between 1990 and 2003 showed an unexpected phenomenon. (Fig 11). Even if prices in October and November are fairly continuously distributed, this is not the case for prices in the period April to July. Indeed, during these months, prices never seem to take intermediary values. Furthermore, note that knowing the post-harvest prices, we can predict quite well the April-July process only if prices during the first period prices are either high or low. If October prices are at intermediate levels, the future trajectory is unpredictable. In short, two trajectories are possible if post-harvest prices are at intermediate levels. The first trajectory leads prices upwards to worrying high levels while the second maintains prices at reasonable levels.

Figure 11. Millet grain price fluctuations as recorded by SIMA (Système d'information sur les marchés agricoles), Gaya market, Niger.

To clarify this phenomenon, we built a theoretical model that shows the existence of two price trajectory equilibriums in intermediate-harvest years. This can be explained by uncertainties about future food aid. (Fig 12). Note the equilibrium indetermination in the model only appears for intermediate-harvest years. Thanks to the formal framework used, we can identify the conditions under which it happens. The model suggests that only some kinds of food aid can generate this double equilibrium. On one hand, we have fixed intervention costs that we interpret in two different ways: (i) direct fixed expenditures on logistics and bribes; (ii) a 'propaganda' strategy where the intervening organization provides food aid only in regions where the situation is extremely serious; and provides

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massive quantities of grain in order to completely 'solve' the problem. This case is illustrated in the graphs bellow for a good production year and an intermediate production year. Starting in the upper right quadrant and reading clockwise we have Hotelling's law, the demand function for the staple good in the first period, the identity relationship for millet quantity available in the second period, and the second period price function taking into account the kind of intervention. In the last quadrant, we also represent the locus L of all possible equilibriums between P_b and Q_h given by the first three quadrants, regardless of the quantities harvested.

On the other hand, we have food aid determined not only by local needs but also by cereal production in other regions of the world, or the interest a specific country has to intervene in a specific region in a particular year.

The model is a theoretical justification of the existence of the Famine Early Warning System (FEWS) and pleads for the creation of an Early Commitment System by which the intervening organizations publicly announce in April or May (when the price trajectories diverge) whether or not they will intervene. Furthermore, it shows the importance of cereal banks for food security and invites international organizations to review their intervention systems (to prevent arbitrary interventions) as well as the tools used to evaluate an intervention.
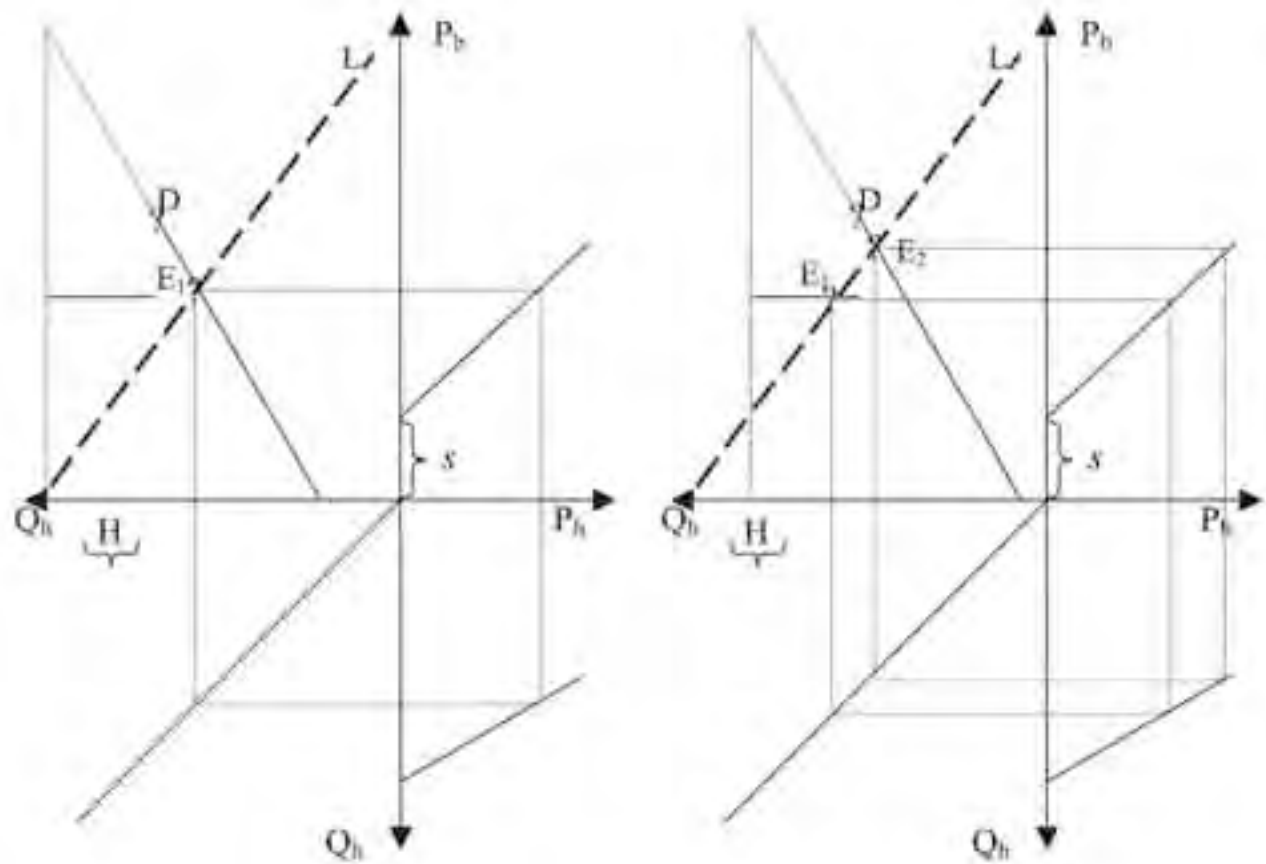
Figure 12. Model equilibrium (fixed intervention costs): (i) simple equilibrium in a good harvest year; (ii) multiple equilibriums in an intermediate-harvest year.

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Analysis of millet market integration in Niger

One prerequisite to achieving food security in Niger is to understand the factors promoting market integration. Using the monthly millet prices data collected since 1990 by SIMA (Système d'Information sur les Marchés Agricoles), we analyzed the integration between 10 different markets in Niger: Niamey, Maradi, Gaya, Dosso, Konni, Diffa, Agadez, Dungass, Bakin'Birgi and Bande. We use a VAR (Vector Auto-Regressive) model that aims to explain contemporary prices in all markets on the basis of past prices and seasonal variations. As a preliminary result, we can simulate the impact of an exogenous shock in a specific market, on the other markets (Fig 13).
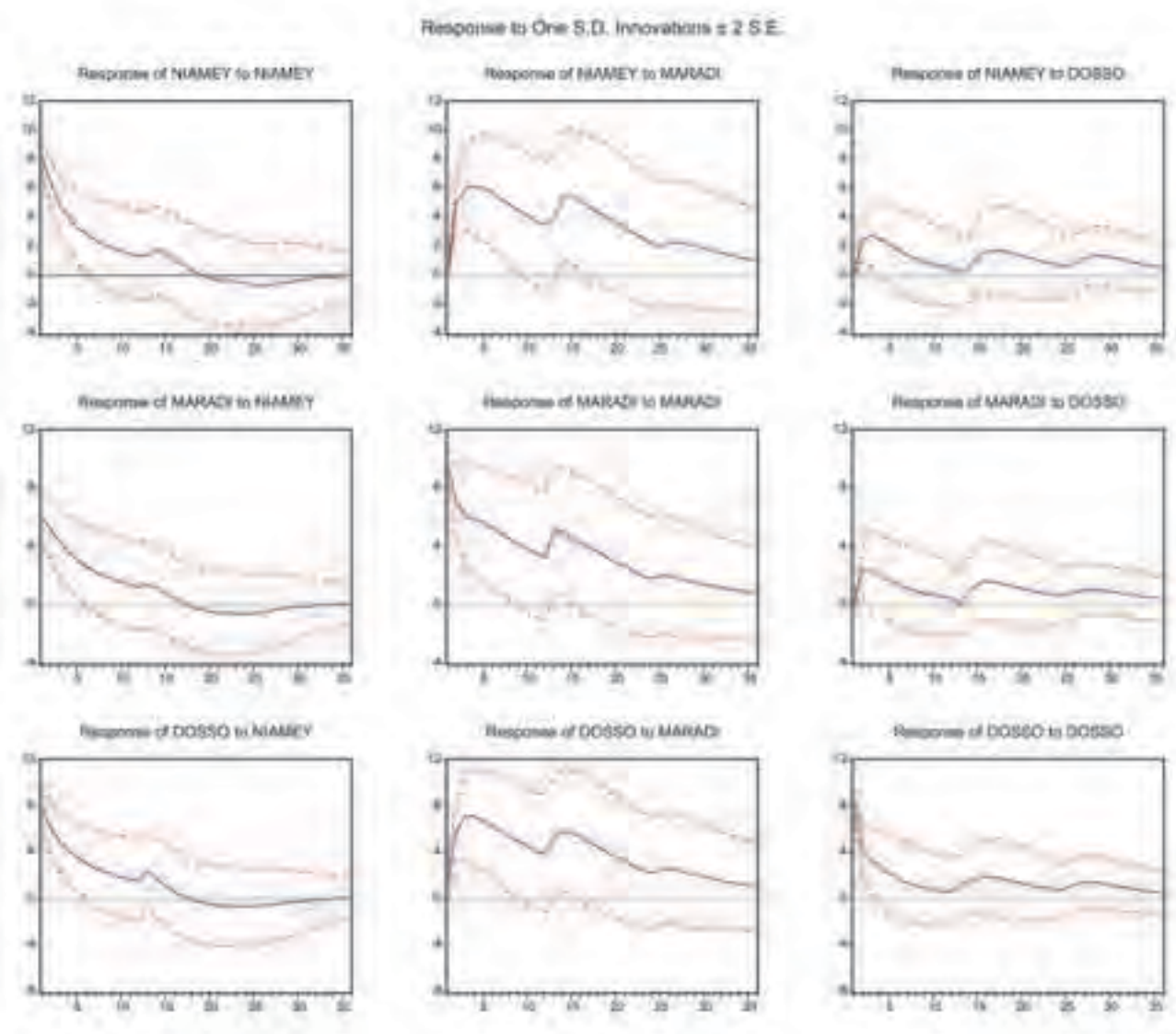
Figure 13. Exogenous shocks and market responses in Niger.

Fig 13 illustrates these simulations for three different markets (Niamey, Maradi and Dosso) where prices deviated from equilibrium during 25 months after the initial shock. The blue line shows predicted impact, the red shows the confidence interval. For example, the second graph (response of Niamey to Maradi) shows how prices in Niamey deviate from equilibrium following an exogenous shock in prices in Maradi.

In the next phase of the study, we will try to explain the coefficients obtained in these regressions by the distance between the different markets, the existence of roads linking then, and the proximity to borders with other countries. The same methodology will be applied at a local scale (project sites) in order to test the impact of cereal banks, inventory credit systems and local radios on market integration and price stabilization.

Linking bio-physical and bio-economic models: risk-return tradeoffs of smallholder investments in improved soil fertility management technologies in the semi-arid areas of Zimbabwe

Understanding the factors that influence the adoption of improved soil fertility management options is key to increasing crop production in the drier areas of southern Africa. Using the results of participatory soil fertility management trials carried out in Zimbabwe for two seasons, 1999/2000 and 2000/01, the APSIM model was used to extrapolate results to different management conditions and years. Based on a series of focus group discussions and panel data collected from communities in Gwanda, Tsholotsho and Zimuto Communal Areas, the @RISK model was used to analyze returns and risks associated with each technology, drawing on historical price movements and the probability density functions from crop simulation. The analysis assessed whether or not the soil fertility technologies offer significant benefits, how their risk-return characteristics compared to other farm and non-farm investments, adoption patterns when farmers are exposed to these technologies through farmer-participatory research, constraints to wider adoption, and institutional innovations that can help target different technologies to the investment objectives and capabilities of households with different resource levels.

Tables 6-8 present the returns and risks per hectare above fixed costs for maize and sorghum for 11 years from 1990/91 to 2000/01, for alternative soil fertility technologies and for different household categories. The tables also include the annual return and risk of investing funds in a risk-free asset, the POSB savings account. For male-headed households with resident husband and higher resource endowments (labor and draft animals), the most profitable technologies are, in decreasing order, maize with 9 kg N ha^{-1}, maize with kraal manure + 18 kg N ha^{-1}, maize-groundnut rotation, and maize-cowpea rotation. The ranking is similar in the lower rainfall sites (Gwanda and Zimuto). But at wetter sites (Tsholotsho) groundnut and cowpea rotations give the highest expected annual returns. For *de facto* female-headed households with intermediate resource endowments but better access to off-farm cash, the order in the drier sites was maize with kraal manure plus 18 kg N ha^{-1}, maize with 9 kg N, maize with kraal manure + 9 kg N, maize-cowpea rotation, and maize-groundnut rotation. But maize-cowpea rotation, sorghum-cowpea rotation, and sorghum-cowpea intercrop give the best returns at wetter sites. For *de jure* female-headed households – the most resource-constrained group – the most profitable technologies are the same as for *de facto* female-headed households for both drier and wetter sites, with some exceptions. At all sites, legume rotations and intercrops are more profitable for *de jure* households than for *de facto* households. For all household categories at all sites, higher expected returns are associated with higher risks and lower expected returns with lower risks. This shows that the Capital Asset Pricing Model approximates the risk-return characteristics estimated for soil fertility management investment options.

Table 6. Expected annual returns and risk (Zimbabwe$ per ha) of alternative maize and sorghum soil fertility management technologies for male-headed households, Gwanda, Tsholotsho and Zimuto, Zimbabwe, 1990/91 to 2000/01.

Activity	Gwanda		Tsholotsho		Zimuto	
	Return	Risk	Return	Risk	Return	Risk
POSB savings account	289	328	289	328	289	328
Sorghum + kraal manure	−15272	3948	−13793	5310		
Sorghum + 0 kraal manure + 0N	−2440	4350	−156	6347		
Maize + 0 kraal manure + 0N	3286	4526	5046	5759	4249	7688
Sorghum + 9N	−849	5856	1911	7642		
Maize groundnut intercrop	1738	6302	1260	8213	−2285	5969
Sorghum groundnut intercrop	−3486	6403	−4383	8872		
Sorghum + pit manure	−1888	6752	542	8752		
Sorghum groundnut rotation	554	7033	2914	8054		
Sorghum + cowpea rotation	−319	7422	8769	11024		
Maize + 9N	4286	7450	7188	7160	6860	7913
Maize groundnut rotation	3888	7535	6800	8902	5764	7862
Maize cowpea rotation	3412	7545	12743	10542	8591	10656
Sorghum + 18N	−2330	7703	788	9718		
Sorghum + kraal + 18N	−154	7759	3314	10160		
Maize + kraal manure + 9N	2629	8296	6547	7984	6127	8498
Maize + pit manure	2414	8723	6417	7768	6281	9132
Maize cowpea intercrop	−1179	9006	6875	10783	168	9807
Maize + kraal manure	3717	9220	5557	9774	4303	9785
Sorghum cowpea intercrop	−5177	9306	3498	13359		
Sorghum + kraal manure + 9N	−450	9765	2711	11107		
Maize + 18N	1614	9804	5588	8436	6081	10255
Maize + kraal manure + 18N	3894	10286	8293	8874	8951	10480

Figs 14-16 show trade-offs between expected returns and risks of several alternative soil fertility technologies. The dominating technologies are reflected by the set of points on the frontier. Options that lie inside the frontier are inferior because they give lower expected returns for the same risk, compared to options on the frontier. These inferior options can be eliminated from further analysis. The efficiency frontier is different for different household categories at different locations. Male-headed households in Gwanda face a frontier which includes, in increasing order of risks and returns, POSB savings account, sorghum + kraal manure, traditional maize production without manure or nitrogen fertilizer, traditional sorghum, maize with 9 kg N ha^{-1}, maize with pit manure, maize with kraal manure + 9 kg N, maize with 18 kg N, and maize with kraal manure + 18 kg N. The frontier for male-headed households in Tsholotsho includes the POSB, traditional maize, maize + 9 kg N, maize-cowpea rotation, maize with kraal manure, maize with kraal manure + 18 kg N. Male-headed households in Zimuto have a smaller available set of risk-efficient technologies: POSB, traditional maize, maize-groundnut rotation, maize with 9 kg N, maize with kraal manure + 18 kg N.

Table 7. Expected annual returns and risk (Zimbabwe$ per ha) of alternative maize and sorghum soil fertility management technologies for *de facto* female-headed households, Gwanda, Tsholotsho and Zimuto, Zimbabwe, 1990/91 to 2000/01.

Activity	Gwanda		Tsholotsho		Zimuto	
	Return	Risk	Return	Risk	Return	Risk
POSB savings account	289	328	289	328	289	328
Sorghum + kraal manure	−12801	3654	−10128	4911		
Sorghum + 0 kraal manure + 0N	62	4366	3177	6334		
Maize + 0 kraal manure + 0N	3378	4422	5042	5965	3200	7619
Sorghum + 9N	2203	6042	4874	7642		
Maize groundnut intercrop	2007	6352	1417	8479	−11012	7138
Sorghum + pit manure	344	6435	4908	8839		
Sorghum groundnut intercrop	−1151	6542	−843	8883		
Maize + 9N	5591	6699	6657	7505	−1802	22751
Sorghum groundnut rotation	1886	7039	5374	8204		
Sorghum cowpea rotation	1509	7264	11369	11236		
Maize cowpea rotation	4456	7470	13524	10753	6449	10686
Maize groundnut rotation	4422	7564	7563	9056	427	8424
Maize + kraal manure + 9N	4505	7767	5937	7952	−1924	22736
Sorghum + 18N	697	7863	3548	9749		
Sorghum + kraal manure + 18N	2873	7911	6205	10293		
Maize + pit manure	3884	8166	5791	8155	4974	9054
Maize cowpea intercrop	−482	9005	7217	11232	−896	9912
Sorghum cowpea intercrop	−1860	9220	8243	13643		
Maize + 18N	3491	9286	4625	8780	−10118	40691
Maize + kraal manure	4031	9334	4946	9764	3170	9678
Maize + kraal manure + 18N	5770	9611	7682	8839	−6049	39594
Sorghum + kraal manure + 9N	2577	9980	3890	8759		

The results show that differently resourced households will invest in different technologies (Table 9). There are three major implications. First, revolutionary changes are required in agricultural extension. Rather than the current emphasis on a few 'ideal' recommendations, extension agents must offer a basket of options including targeting of small quantities of manure, inorganic fertilizer, and manure-fertilizer combinations. They could use multiple extension approaches, media and messages to target different technologies to different households. Second, linking research-extension with markets can help stimulate adoption of fertility technologies by providing farmers opportunities to earn cash, which they can use to purchase inputs. Groundnut, cowpea and pigeonpea could potentially serve: they are high-value cash crops with low nitrogen requirements; and in addition to the income they generate, they also provide residual fertility benefits that can improve cereal production. Third, input and output markets must be strengthened, especially for legumes. This will enhance incentives for farmers to adopt improved soil fertility and water technologies and generate cash returns to pay for external nutrient inputs.

Table 8. Expected annual returns and risk (Zimbabwe$ per ha) of alternative maize and sorghum soil fertility management technologies for *de jure* female-headed households, Gwanda, Tsholotsho and Zimuto, Zimbabwe, 1990/91 to 2000/01.

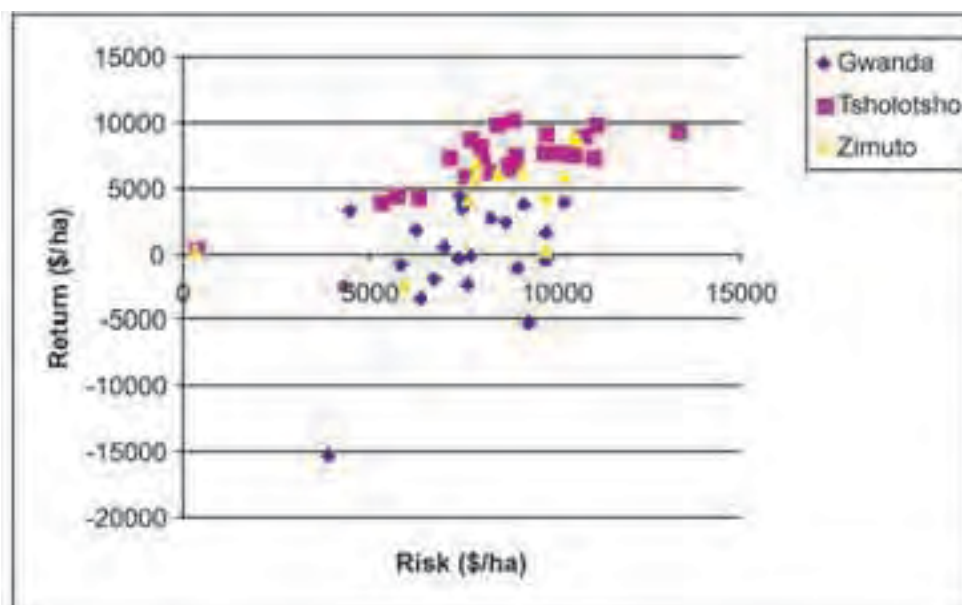| Activity	Gwanda		Tsholotsho		Zimuto	
	Return	Risk	Return	Risk	Return	Risk
POSB savings account savings account	289	328	289	328	289	328
Sorghum + kraal manure	–13023	3668	–7821	4410		
Sorghum + 0 kraal manure + 0N	1704	8129	5419	6018		
Maize + 0 kraal manure + 0N	3692	4422	5375	5986	5560	7518
Sorghum + 9N	1981	5994	7181	7347		
Maize groundnut intercrop	1976	6364	4721	8216	–15949	6092
Sorghum + pit manure	122	6398	6405	8531		
Sorghum groundnut intercrop	–1795	6476	3966	8355		
Maize + 9N	5954	6714	7759	7529	–1997	22645
Sorghum groundnut rotation	1696	7024	7986	7992		
Sorghum cowpea rotation	2296	7278	12735	11081		
Maize cowpea rotation	5534	7482	14288	10698	6349	10647
Maize groundnut rotation	4524	7571	9573	8990	–1777	7727
Maize + kraal manure + 9N	4869	7796	7044	7976	–2111	22647
Sorghum + 18N	475	7814	5855	9464		
Sorghum + kraal manure + 18N	2650	7861	8512	9992		
Maize + pit manure	4247	8185	6893	8175	4779	8970
Maize cowpea intercrop	800	9076	8291	11151	–1108	9812
Sorghum cowpea intercrop	–545	9171	10167	13431		
Maize + 18N	3855	9310	5727	8796	2983	9632
Maize + kraal manure	4394	9397	6053	9785	–6237	39510
Maize + kraal manure + 18N	6134	9632	8789	8865	–10313	40600
Sorghum + kraal manure + 9N	2355	9926	6197	8470		

Figure 14. Risk-return tradeoffs of alternative maize and sorghum soil fertility management technologies for male-headed households, Gwanda, Tsholotsho and Zimuto, Zimbabwe, 1990/91 to 2000/01.
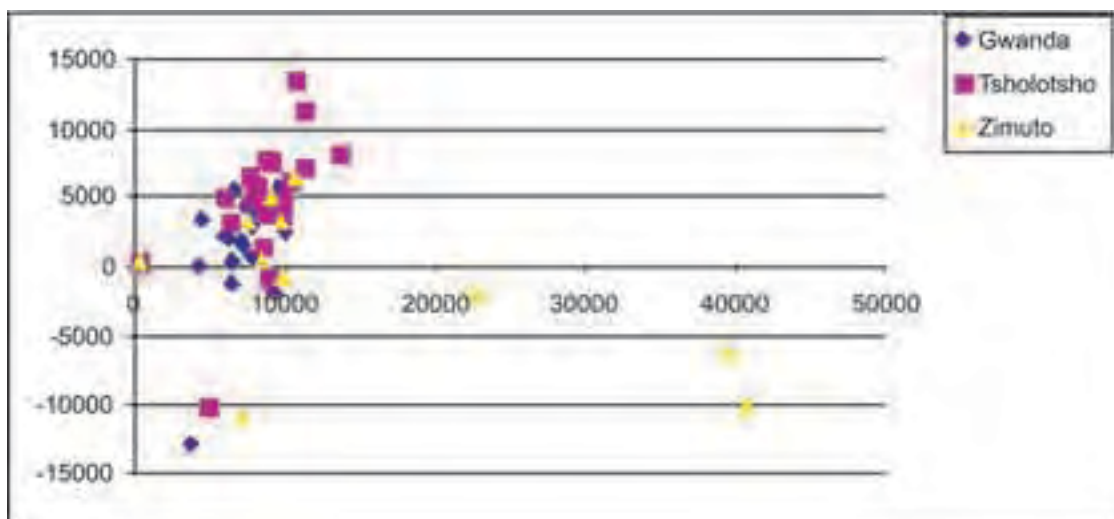
Figure 15. Risk-return tradeoffs of alternative maize and sorghum soil fertility management technologies for de facto female-headed households, Gwanda, Tsholotsho and Zimuto, Zimbabwe, 1990/91 to 2000/01.
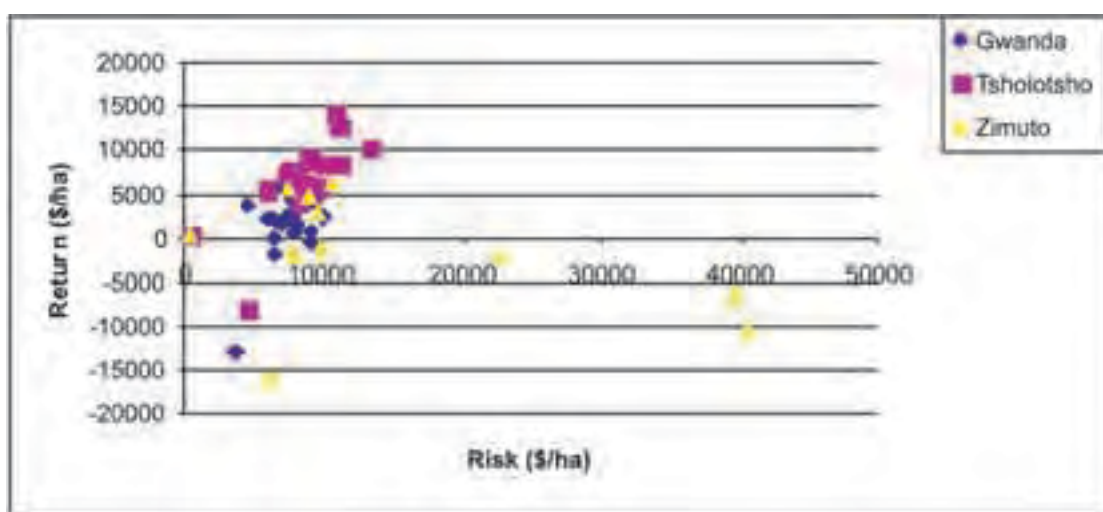

Figure 16. Risk-return tradeoffs of alternative maize and sorghum soil fertility management technologies for de jure female-headed households, Gwanda, Tsholotsho and Zimuto, Zimbabwe, 1990/91 to 2000/01.

Table 9. Practices taken up by farmers onto main fields by gender of household head, Zimbabwe, 2000/01.

Practice	Status of household-head			
	Male head (%)	De facto female head (%)	De jure female head (%)	All(%)
New cereal varieties	31.5	37.8	16.6	32.3
Legumes rotations/intercrops	20.8	10.2	13.3	18.7
Seed priming, planting methods, spacing	16.1	20.5	16.6	16.8
Small fertilizer/weeding/manure	8.6	13.8	0	7.7
Treated manure	16.7	30.9	26.7	19.9
Water harvesting	14.8	0	20	13.6
Reduced tillage/compost	0.6	0	6.6	1.4

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Strengthening the Spatial Dimension in Modeling Work

Landscape and Watershed-Level Studies

Landscapes are to communities what farms are to individuals – they provide a familiar, recognizable physical setting for the execution of daily activities and mold significant portions of human life spans. Yet the distribution of resources and diversity of interests that impinge on livelihoods are far more complex at landscape level than at the farm level.

Landscapes harbor a range of competing, often conflicting processes that affect ecological sustainability, livelihood security, resource productivity and social well-being. This intricacy is exacerbated in poverty-stricken areas in semi-arid regions characterized by heterogeneous agro-ecosystems, disparate endowments, and where local and external forces like population growth, climate variability and the global economy result in a scarcity of land, water, forest and other resources.

1. In-situ evaluation of technologies at the landscape scale: case study of the hill-placed application of mineral fertilizer in the Fakara in SW Niger

Hill-placed application of small quantities of mineral fertilizer at the time of pearl millet sowing has shown promising results in on-station and on-farm trials conducted over the last seven years. This technology, developed jointly by IFDC, University of Hohenheim and ICRISAT, has attracted the interest of several development projects in Niger. The FAO Projet Intrants hosted by the Ministère Nigérien du Développement Agricole was particularly interested by the diffusion of the technology across agricultural regions of Niger. Since 1999, hill-placed application of mineral fertilizer (NPK 15-15-15 or DAP) at a rate of 4 kg P ha^{-1} (9 kg P$_2$O$_5$ ha^{-1}) has been promoted by the FAO Projet Intrants and partners through over 5000 demonstrations in the regions of Niamey, Maradi and Zinder.

The objectives of the study were to:

- Evaluate *in-situ* the agronomic and economic performance of hill-placed application of different formulations of mineral fertilizer and confirm the on-station and on-farm experiments showing a net yield increase
- Asses yield response variability to mineral fertilizer under a range of biophysical conditions and management practices
- Draw recommendations for mineral fertilizer use considering soils, drought risk, and manure availability
- Monitor the adoption of this technology.

During three consecutive rainy seasons (2000-2002), a series of simple demonstrations was established in collaboration with farmers in the Fakara region of southwestern Niger, 80 km east of the capital Niamey. The site was selected because of the abundance of biophysical and socio-economic data packaged in spatial database, including rainfall spatio-temporal distribution obtained from a network of 60 rain gauges (Figs 17-20, Table 10). Demonstration fields were selected to cover the range of organic manure management practices followed by farmers in the area (corralling, transported manure, unmanured fields).

No significant yield differences were detected between 15-15-15 and DAP fertilizer, suggesting a much better economic return on DAP – which is only one-third as expensive, per unit of P (Fig 21).
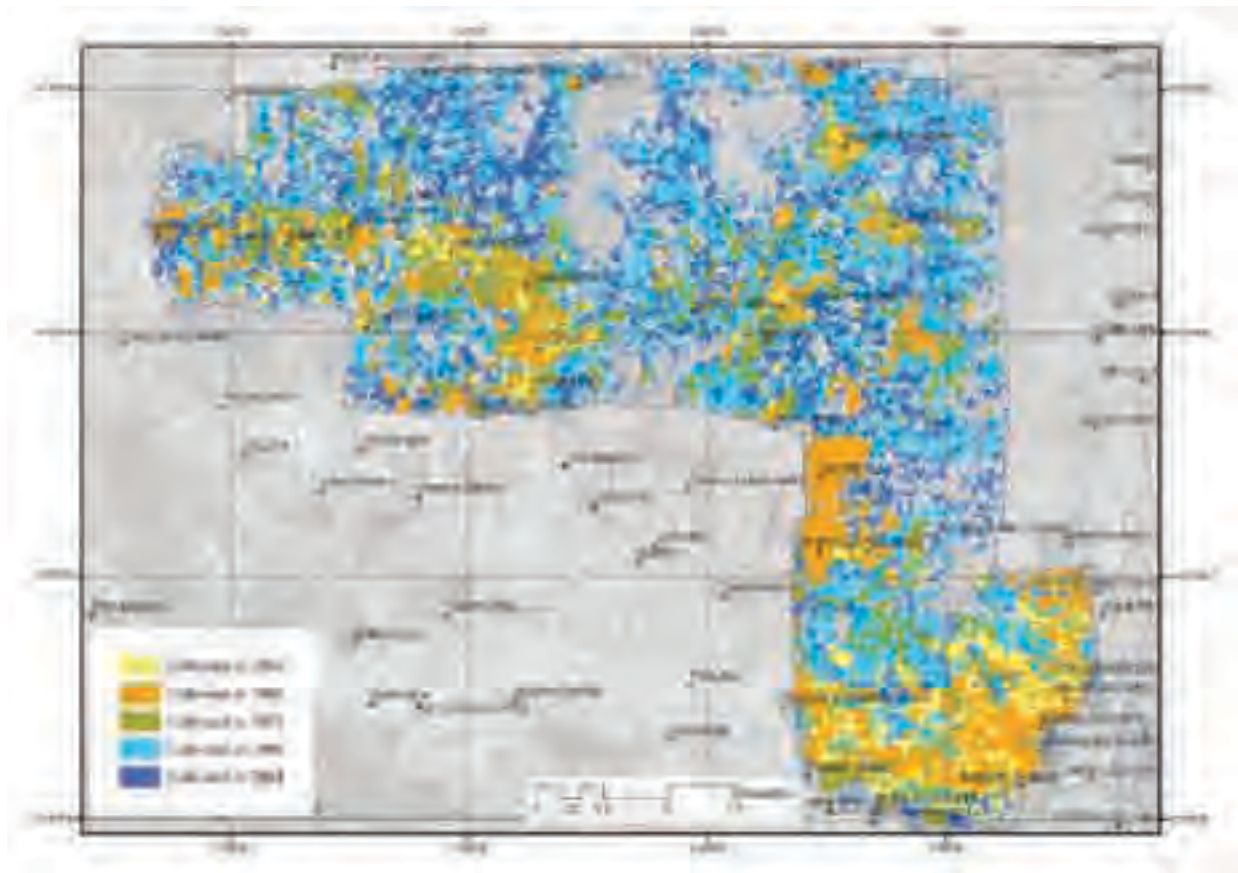
Figure 17. Extension of crop land in the Fakara region from 1950 to 2005 (data source: ILRI for 1950, 1975, 1996 from aerial photograph. ICRISAT: Segmentation and object based classification of geo-referenced Corona images for 1965 and Spot 5 image for 2004).
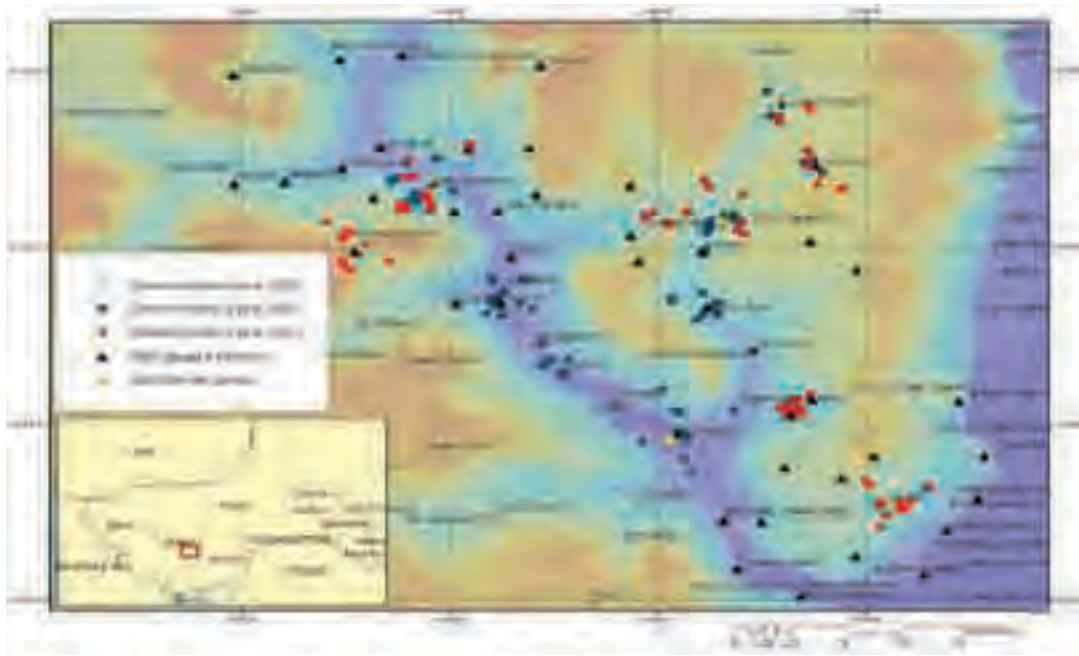
Figure 18. FAO/ICRISAT demonstrations monitored between 2000 and 2002 to evaluate in-situ the variability of millet yield response to mineral fertilizer. SRTM Digital elevation model shows valley systems in blue and plateaux in light brown.

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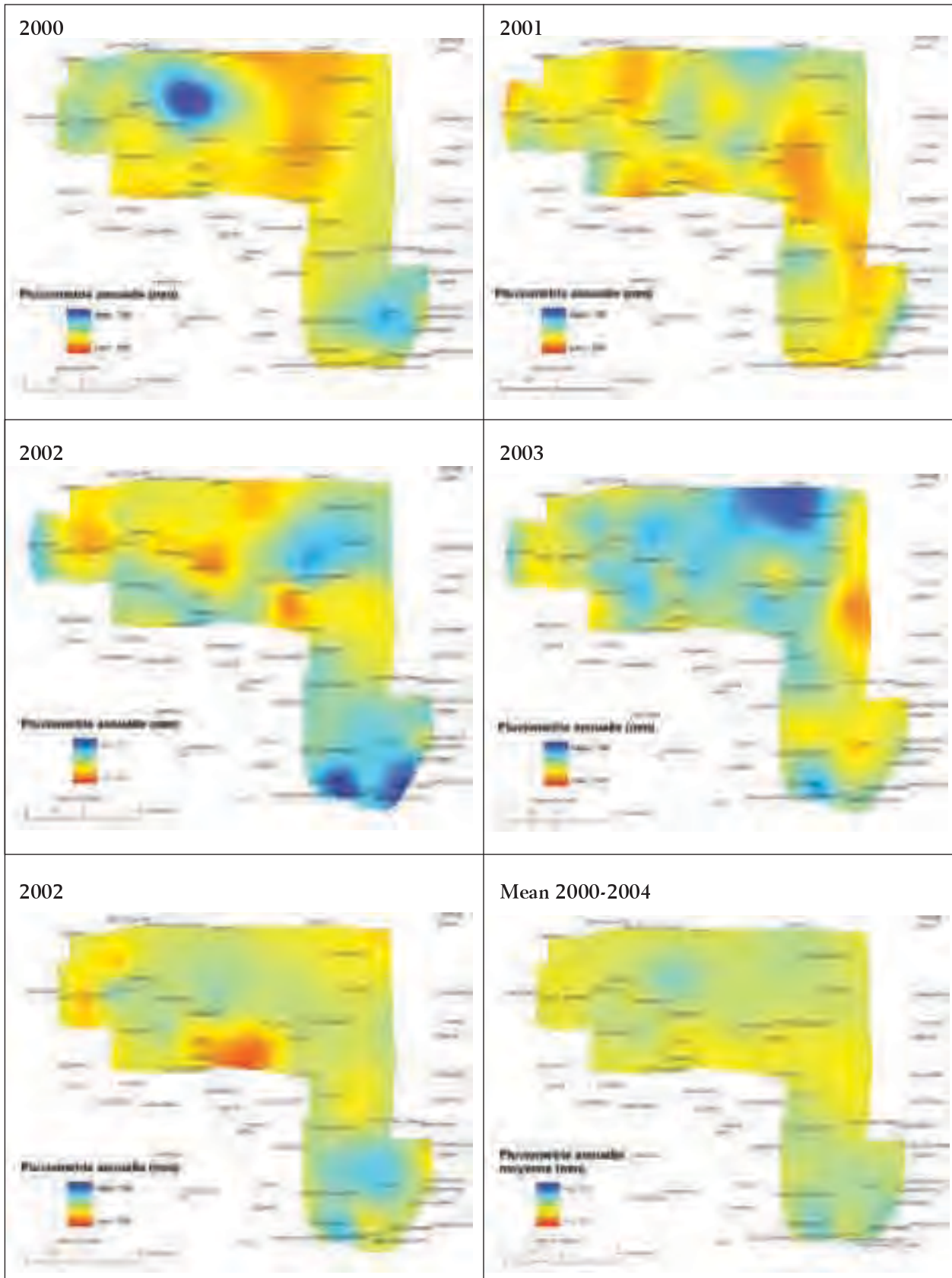
Figure 19. Seasonal rainfall distribution over the Fakara site, 2000 to 2004.

Figure 20. Changes in the Fakara region between (a) 1966 Corona image, (b) 2004 Spot 5 panchromatic image, showing the anthropization and structuring of the landscape into clearly delimited fields and cattle paths.

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Table 10. Land use changes in three village clusters in the Fakara. Figures show area in ha.

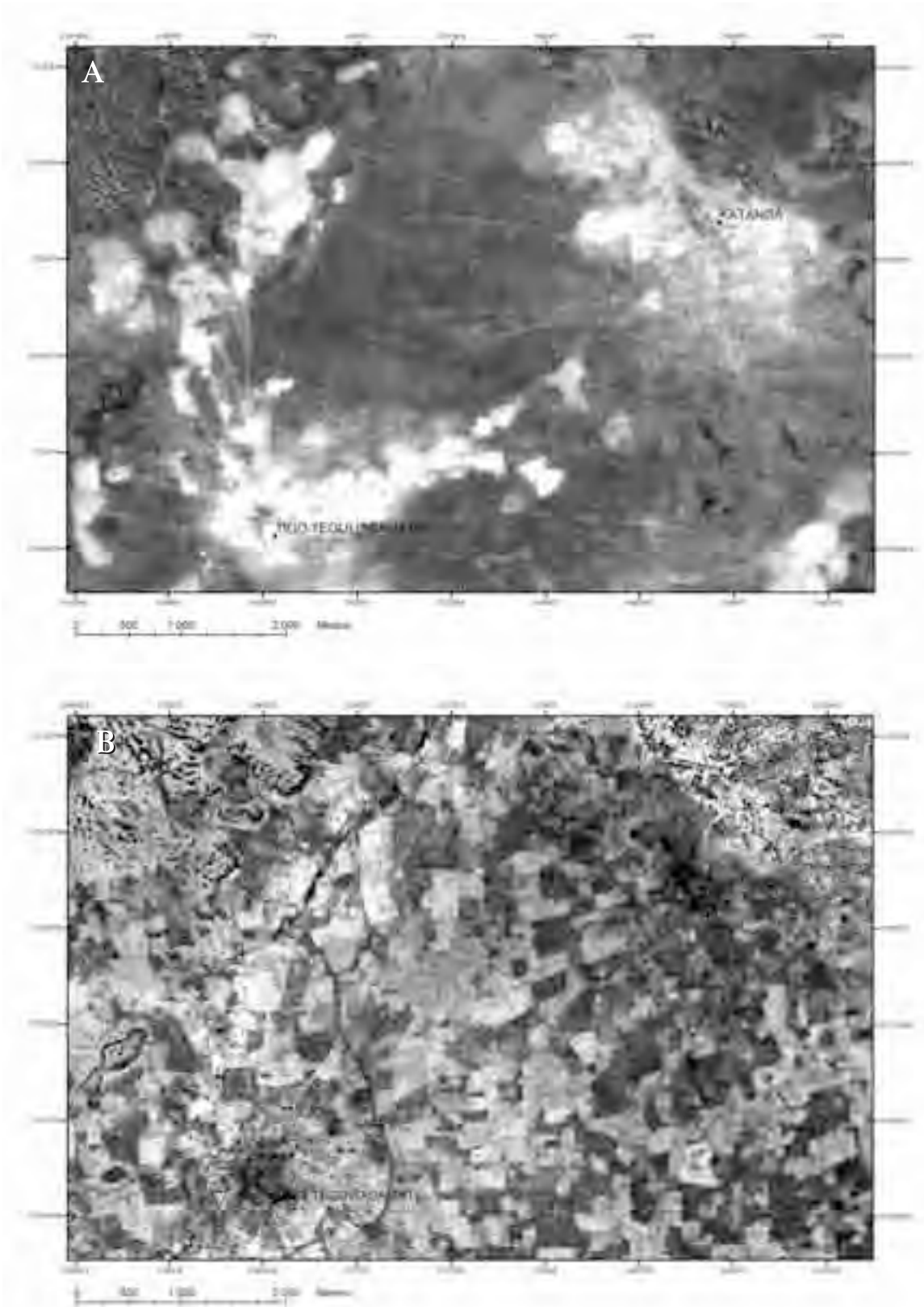|	Crop	Fallow	Long fallow	Plateaux	Degraded soils
Banizoumbou					
1950	470.8	597.7	8784.1	1624.8	
1975	2385.6	4402.1	2906.3	1886.5	
1994	3109.6	4801.6	1701.1	1999.4	
1996	3305.8	5726.2	435.9	2110.6	
2002	4277.8	4072.2	243.6	1680.3	1353.7
2004	4737.7	5028.2	145.7	1710.8	
Tigo-Tegui					
1950	262.4	772.5	6937.3	1496.2	
1975	1465.7	5387.1	2261.8	1783.5	
1994	4441.6	3638.1	1345.5	1626.7	
1996	3821.1	4693.1	789.2	1745.2	
2002	4346.3	4445.2	750.8	1339.7	180.7
2004	5208.1	4473.8	168.3	1210.3	
Kodey					
1950	1513.4	1811.7	3053.4	627.3	
1975	2903.8	4032.3	57.5	551.8	
1994	4837.1	1851.8	460.3	424.1	
1996	4777.8	1574.2	231.6	579.1	
2002	4630.0	2203.9	227.3	481.6	32.3
2004	3722.4	3380.0	116.8	358.9	

1950, 1975, 1994, 1996 data from interpretation of aerial photographs by ILRI
2002 and 2004 data estimated after object segmentation and supervised classification (eCognition software) Spot 4 scene taken on 22 Sep 2002 and a Spot 5 scene on 28 Sep 2004
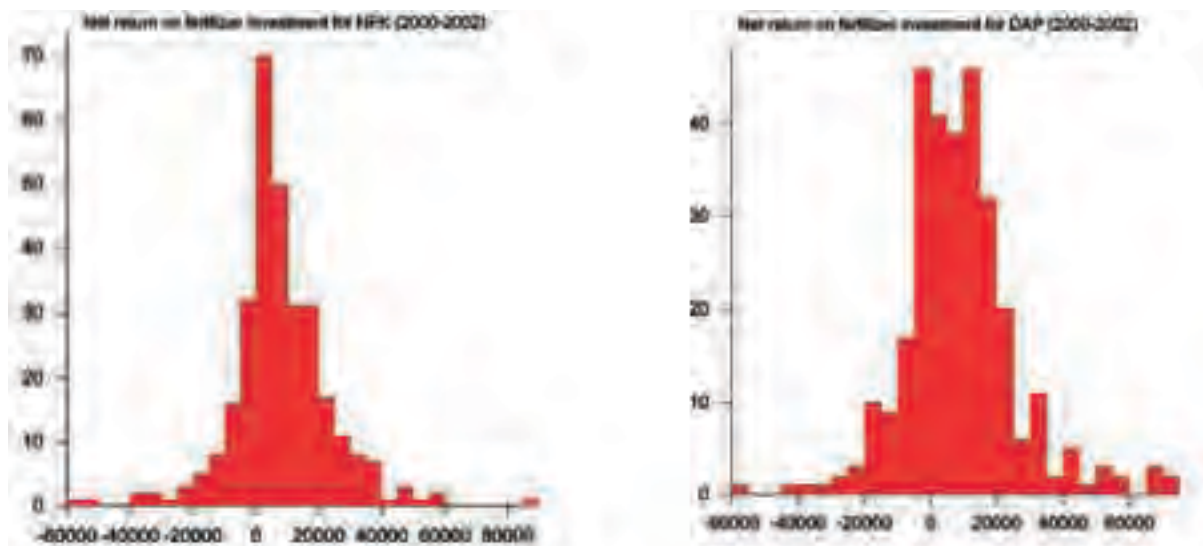
Figure 21. Distribution of net return on fertilizer investment (CFA per ha) for the Fakara demonstrations, using NPK 15-15-15 and DAP.

Yield analysis using the Generalized Linear Model (GLM) allowed us to identify several factors influencing grain yield (Table 11). Management practices such as planting density and time of weeding significantly affect yields. Although used in limited quantities, manure has a large impact on production and a good residual effect for up to three years. Seasonal rainfall amounts introduced as a factor in the GLM analysis of grain yield is not significantly different from zero but there are

significant differences between village and years, implicitly suggesting the importance of rainfall distribution during the season. Water balance and stress analysis at the landscape scale (by researcher students from Texas A&M University and Université catholique de Louvain) and analysis of water stress index should further improve the statistical model.

Table 11. Generalized linear model to explain grain yield of FAO/ICRISAT demonstrations as function of fertilizer treatment, organic matter management, farmer practice and landscape characteristics obtained from SRTM Digital Elevation Model.

	Grain yield (kg ha^{-1})
Variance accounted for (%)	32.6
d.f residuals	1029
Factors	
Constant	104.1 (<.001)
Year 2001	–80.5 (<.001)
Year 2002	–21.9 (0.157)
Corralled previous dry season	239.3 (<.001)
Second cropping season after corralling	168.2 (<.001)
Third cropping season after corralling	186.5 (<.001)
Transported manure	78.5 (<.001)
DAP	70.0 (<.001)
DAP+Urea	83.4 (<.001)
NPK 15-15-15	60.7 (<.001)
Density	0.02213 (<.001)
No. of days between sowing and 1st weeding	–2.656 (<.001)
No. of days between 1st and 2nd weeding	0.454 (0.030)
Distance to village (in meters)	–0.04101 (<.001)
Field slope	11.12 (0.037)
Reference levels for factors	Year 2000, no manure, control (no mineral fertilizer)

2. Remote sensing and GIS-based model for estimating soil loss from watersheds

Remote sensing and GIS-based techniques are essential for large-scale implementation and monitoring of watershed management programs. A soil erosion model based on remote sensing data was used to estimate sediment yield and runoff from an agricultural watershed at Medak district, Andhra Pradesh, India. The basic data were derived from panchromatic sensor (PAN) stereo data of Indian Remote Sensing Satellite IRS-1C as well as aerial photographs. The input parameters required for the model were also derived through visual interpretation of aerial photographs. The slope factor was derived from a digital elevation model (DEM) generated from the aerial photographs and PAN stereo images. Comparison of elevation and slope derived from PAN stereo images and aerial photographs reveal that aerial photographs provides more accurate information on elevation, and agrees well with *in-situ* measurements. The GIS and remote sensing based technique has yielded good preliminary results for topographic survey and estimation of runoff and soil loss. Further testing and validation is in progress for various topographic conditions.

3. Spatial water balance modeling of watersheds

In partnership with the Michigan State University, USA, we have attempted to integrate the topographic features of the watersheds into hydrological models. The automation of terrain analysis and the use of digital elevation models have made it possible to quantify the topographic attributes of the landscape for hydrological models. These topographic models, commonly called digital terrain models (DTMs), partition the landscape into series of interconnected elements, based on the topographic characteristics of the landscape; and are usually coupled to a mechanistic soil-water balance model. Partitioning between vertical and lateral movement at field scale helps predict the complete soil-water balance and consequently the water available to plants over space and time.

Data generated in the black soil watershed (BW7) on-station experiment at ICRISAT Patancheru, was used for validating the model developed at Michigan State University. This led to the development of SALUS-TERRAE, a DTM for predicting the spatial and temporal variability of soil-water balance. A regular grid digital elevation model (DEM) provided the elevation data for SALUS-TERRAE. We have successfully applied SALUS-TERRAE at the field scale to simulate the spatial soil-water balance and identify how the terrain affects the water routing across the landscape. The model provided excellent results, comparable with field measurements of soil water content (Fig 22).
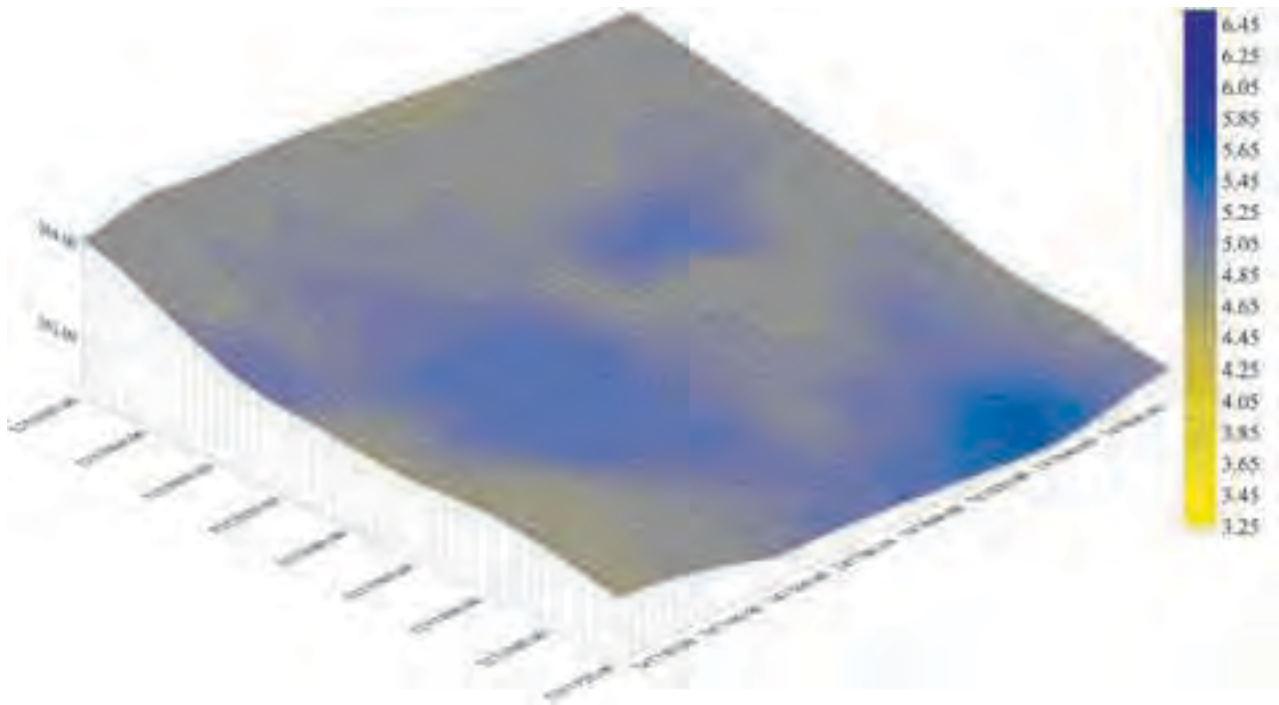

Figure 22a. Soil water content (cm) in the top 0-26 cm soil depth on day-2 for scenario 1 (uniform soil type, high rainfall, no restricting soil layer).
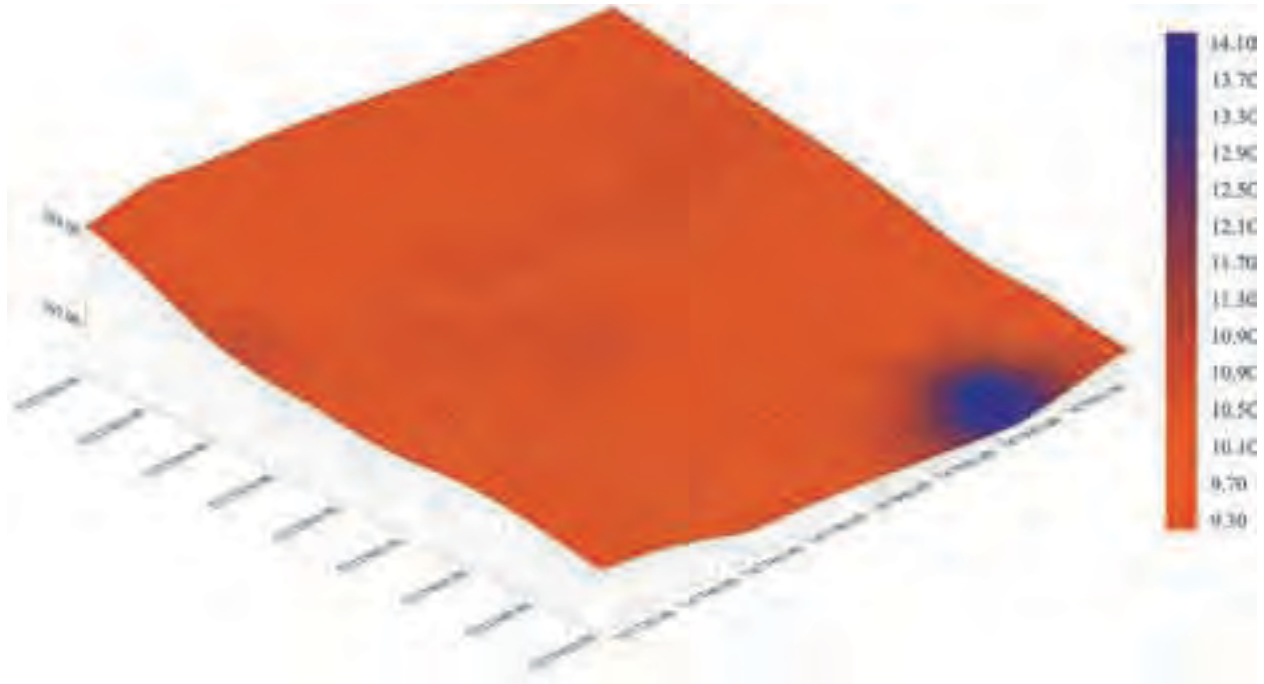
Figure 22b. Soil water content (cm) in the 26-77 cm soil depth on day-2 for scenario 1 (uniform soil type, high rainfall, no restricting soil layer).

4. Environmental risk assessment of genetically enhanced sorghums in Mali and Kenya: a landscape genetics approach in contrasted African settings

Landscape genetics has recently emerged at the interface of molecular population genetics and landscape ecology, and aims at exploiting existing or new statistical tools (geostatistics, maximum likelihood and Bayesian approaches) to provide information about the interaction between landscape features and microevolutionary processes, such as gene flow, genetic drift and selection (Manel et al 2003). ICRISAT's work relates to a project under USAID's Biotechnology and Biodiversity Interface (BBI) Program. This approach is used to test two broad hypotheses:

- Inter- and intra-specific crop diversity is not randomly distributed within the agroecosystem. Traditional agricultural systems are agro-ecologically and socially structured
- The distribution of wild sorghums in the agroecosystem is not random. Their spatial distribution is determined to a significant extent by farmer practices (land use, agricultural/livestock management) and to a lesser extent by environmental factors (wind regimes, temperature/ moisture regimes, surface hydrology).

Two intensive study sites were selected in Mali and Kenya based on (i) significant occurrence of both wild and cultivated sorghum in the agroecosystem, (ii) presence of wild/weedy relatives of sorghum outside cultivated cereal fields, (iii) presence of farmer knowledge and management practices related to wild/weedy sorghums, (iv) sites accessibility, (v) combinations of human and environmental incentives related to the project: Karamokola in the Mande Plateau physiographic region of Mali

(12°25'N, 8°37'W), and Mara River across the 900m contour line on the eastern slopes of Mount Kenya (Kenya: 0°20'S, 37°48'E). Over each 8x8km site, a QuickBird satellite subscene has been acquired (Kenya: in progress) to speed up landscape characterization: digitization of field boundaries, human habitat, quick identification of potential cryptic boundaries etc. Advanced differential GPS technology is used for comprehensive surveys of the cropping system: cropping history for each field, presence of wild sorghums, land ownership etc; which are then combined with background images to map the agroecosystem mosaic as a first appraisal of the environmental and anthropic determinants of gene flow.

Figs 23-26 provide some initial support to the hypotheses above. In these figures, field survey information is overlayed on a natural color composite of the QuickBird scene draped on top of a digital elevation model for the Karamokola site in Mali. Figs 23 and 24 show that wild/weedy sorghum relatives are not randomly distributed within the agroecosystem mosaic. Fig 25 illustrates the significant presence of women-managed fields that generally exhibit important crop diversity at both species and variety levels. Women generally cultivate fields less than 0.5 ha in area, where more wild/weedy sorghums can be observed. Spatial point pattern analyses are being performed to identify the processes responsible for the observed diversity distribution, and the underlying anthropic and environmental determinants. Fig 26 illustrates the diversity of production units in terms of size and compactness.

The overall project rationale and methodology are illustrated in Fig 27, which was developed as a poster for technical audiences.
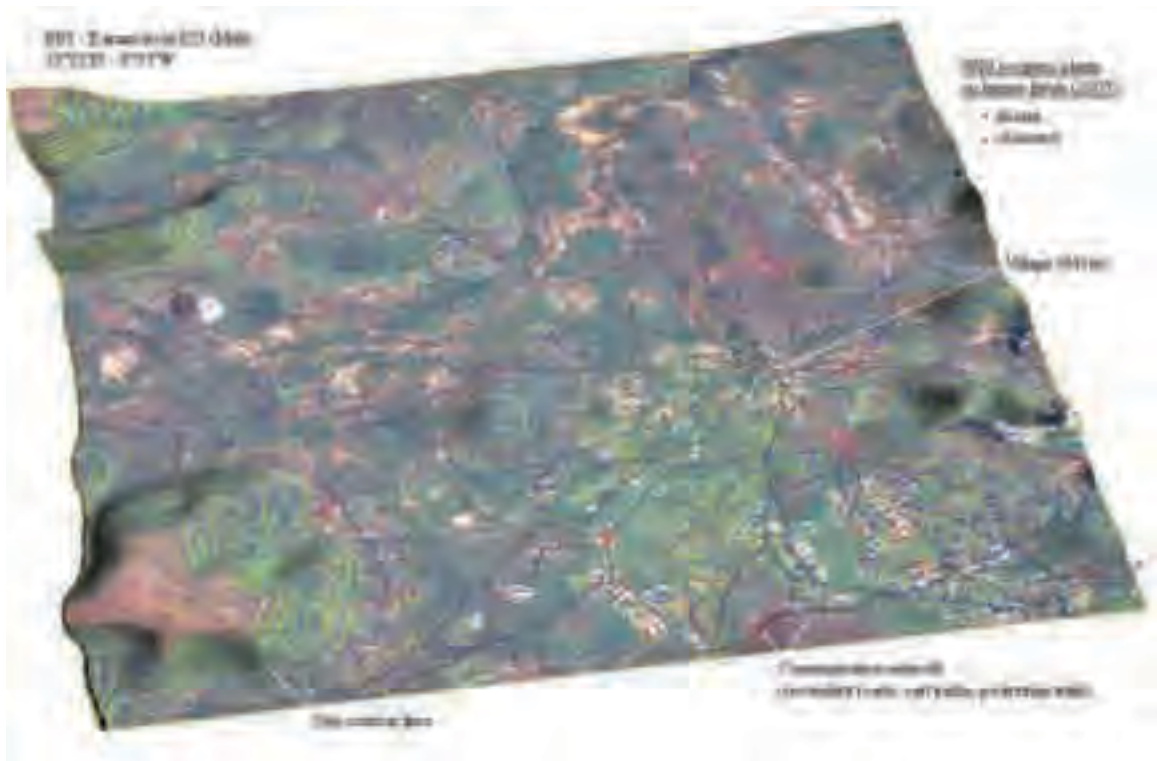

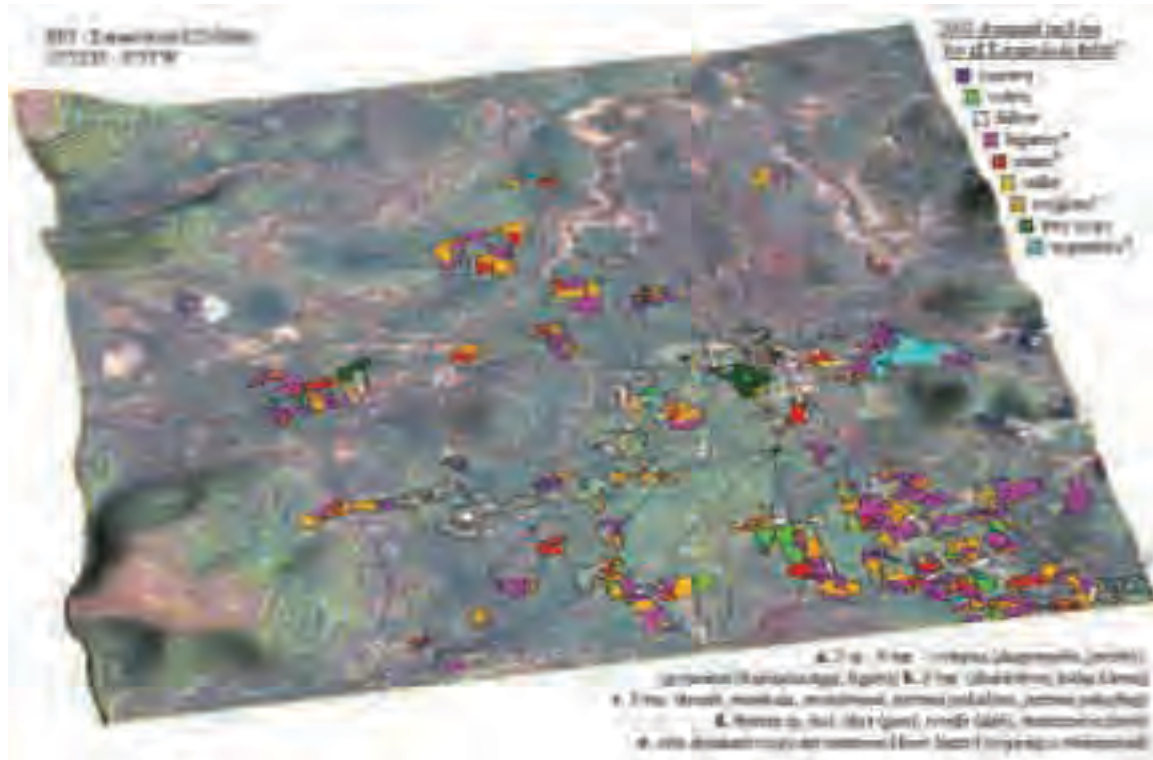*Figure 23. Distribution of wild/weedy sorghum at the Mali intensive study site, 2005.*

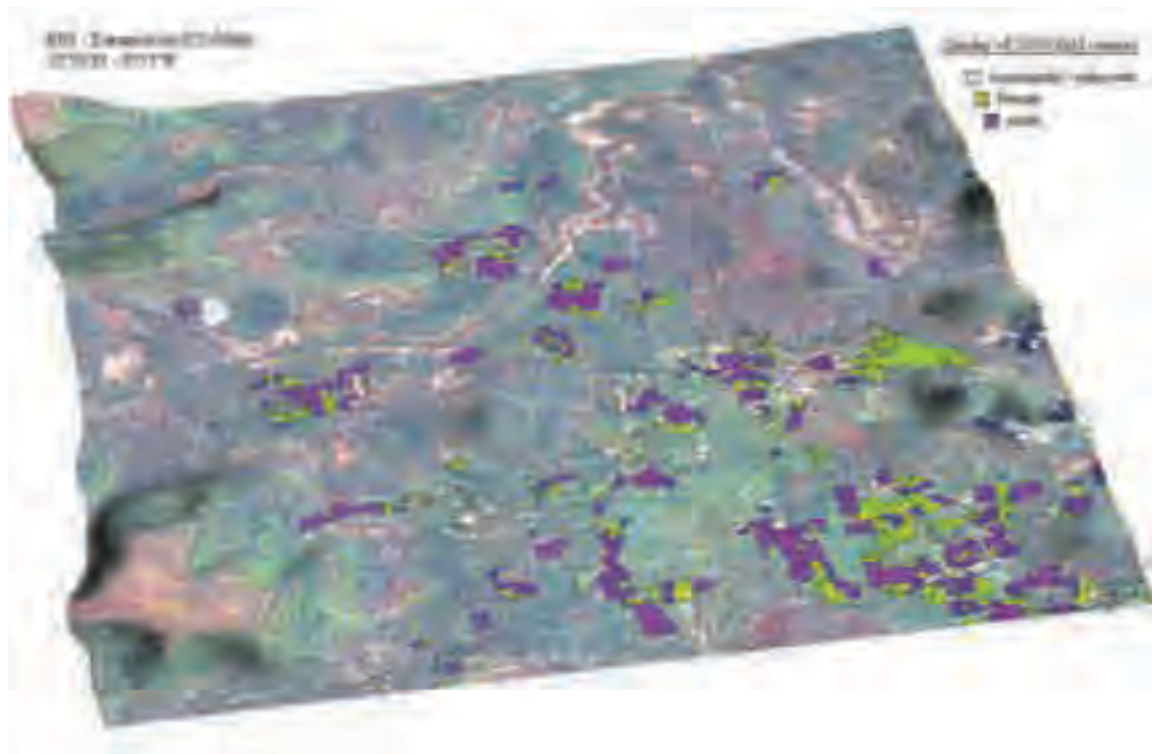*Figure 24. Crop distribution at the Mali intensive study site, 2005.*

Figure 25. Gender distribution of field managers at the Mali intensive study site, 2005.
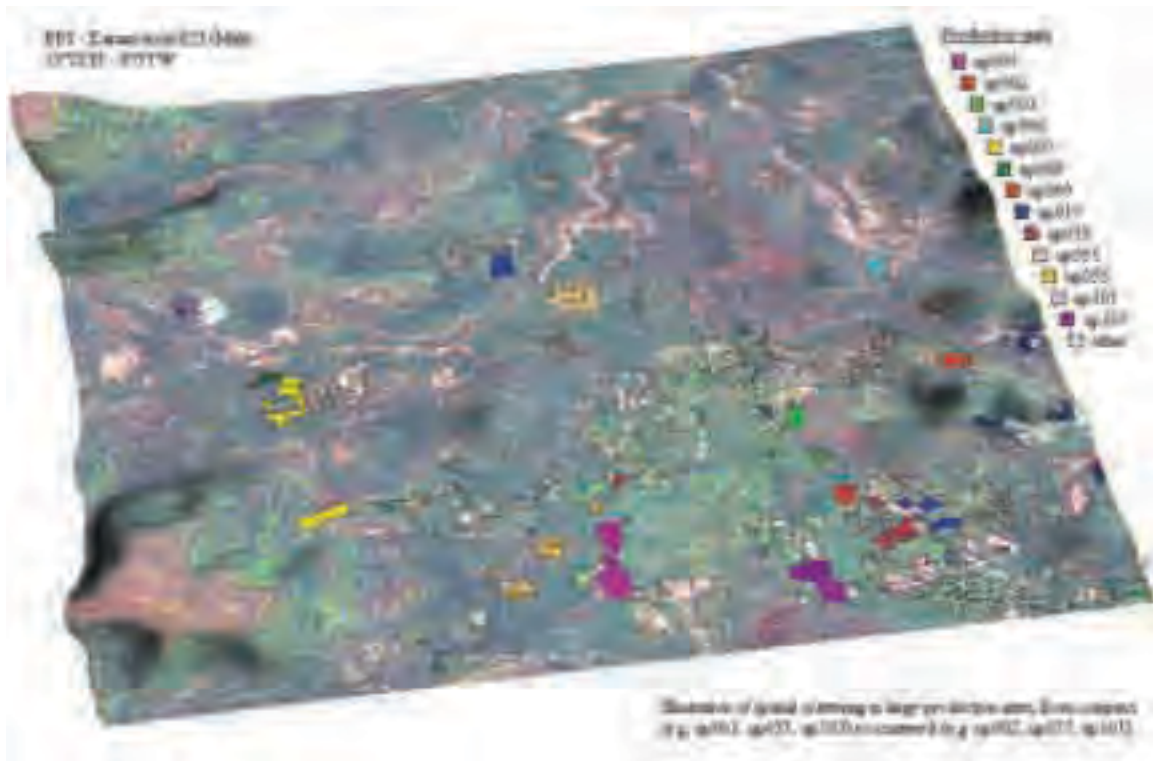
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Figure 26. Distribution of production units (households) at the Mali intensive study site, 2005.

Region and Basin-Scale Studies

Understanding the distribution and magnitude of biophysical resources of watersheds is a prerequisite to developing technology interventions to better manage natural resources and increase agricultural productivity. During the past 5 years we have characterized the agroclimatic conditions and biophysical resources (soils and vegetation resources) of pilot watersheds in India. This has helped in planning project interventions as well as quantifying their impacts.

1. Delineation of fallow lands in the black soil region of India

In Madhya Pradesh in central India, Vertisols are traditionally left fallow during the rainy season (*kharif*) and crops are grown on residual soil moisture thereafter (postrainy season or *rabi*). After the successful introduction of soybean (Madhya Pradesh accounts for 87% of national soybean production), the area under rainy season fallow has substantially declined. We analyzed the remote sensing data obtained from the Indian Remote Sensing Satellite to delineate the current status of rainy season fallows in the state, as a preliminary to introduction land and water management technologies.

A deductive approach was used, including delineation of agricultural land and forests from temporal satellite data, to identify *kharif* fallows. Three sets of satellite data were used, corresponding to three periods, mid *kharif*, late *kharif* and *rabi* season. Satellite data for the *kharif* season provided information on cropped versus fallow area. Data for the *rabi* season provides the spatial distribution pattern of land cropped in this season – including areas which were left fallow in *kharif*.

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Figure 27. Overview of the ICRISAT-BBI project.

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An estimated 2.02 million ha (6.57% of the total area of the state) were under *kharif* fallow. Madhya Pradesh is endowed with well-distributed rainfall ranging from 700 to 1200 mm. Vertisols, with their good moisture-holding capacity, can be planted with short-duration soybean provided sound land management practices are used. This will increase farmers' incomes and also prevent land degradation due to runoff erosion during the fallow period.

2. Delineation of rice fallows in India

Rice is the most extensively grown crop in South Asia, occupying 50 million ha in Bangladesh, India, Nepal and Pakistan. Much of it is grown in the *kharif* season. A substantial part of this area remains fallow during the *rabi* season because of several limitations, chiefly lack of sufficient soil moisture in the top soil layer to establish a second crop after rice. Precise estimates of rice-fallows and their spatial distribution were not available. Since rice is grown on some of the most productive land, there is substantial scope to increase cropping intensity by introducing a second crop during the *rabi* season. In the project, we used satellite imagery to estimate the area and spatial distribution of rice-fallows in South Asia. Using GIS tools, we overlaid the spatial distribution of the rice-fallows onto the climatic and soil information data, in order to identify appropriate short-season crops – for example legumes such as chickpea, *kesari*, lentil, mung bean and black gram that could be grown in rice-fallows.

Analysis of satellite images shows that rice area during 1999 *kharif* season was about 50.4 million ha; while rice fallows in 1999/2000 *rabi* were 14.29 million ha in Bangladesh, India, Nepal and Pakistan. This amounts to nearly 30% of the rice-growing area. Nearly 82% of the rice-fallows are located in the Indian states of Bihar, Madhya Pradesh, West Bengal, Orissa and Assam. The GIS analysis of these fallow lands shows a range of soil types and climatic conditions; thus a variety of warm-season legumes (soybean, mungbean, black gram, pigeonpea, groundnut) and cool-season legumes (chickpea, lentil, kesari, faba bean and pea) can be grown in this region.

Economic analysis has shown that cultivation of legumes in rice-fallows is highly profitable, with a benefit-cost ratio >3 for many legumes. Such cultivation could also generate 584 million person-days of employment. Appropriate technologies for *rabi* rainfed cropping, especially for chickpea, have been identified. They include:

- use of short-duration chickpea varieties
- block planting so as to protect the crop from grazing animals
- sowing using rapid minimum tillage as soon as possible after harvesting rice
- seed priming for 4-6 hours with the addition of sodium molybdate to the priming water at a rate of 0.5 g litre^{-1} (kg^{-1} seed) and *Rhizobium* inoculum at the rate of 5 g litre^{-1} (kg^{-1} seed)
- application of manure and single superphosphate.

This technology is now being widely promoted. In eastern India, over 6000 farmers have been exposed to this technology; and obtained chickpea yields of 0.4 to 3 t ha^{-1} in different areas, planting without irrigation on rice fallows. Similar results have been obtained in the Barind region in Bangladesh.

3. Regional scale water budgeting for SAT India and basins of China, Thailand and Vietnam

First-order water budgeting using a GIS-linked water balance model was used to select target regions for watershed development in central and peninsular India. The simulation model, using monthly rainfall and soils data, has been shown to be an effective tool for prioritizing target regions and

strategies for improved rainwater management (Fig 28). Once a target region is selected, benchmark sites can then be selected using second-order water budgeting using more detailed simulation models. The GIS map produced using this methodology shows the potential of various regions in central and peninsular India in terms of the amount of water surplus available for water harvesting and groundwater recharging.
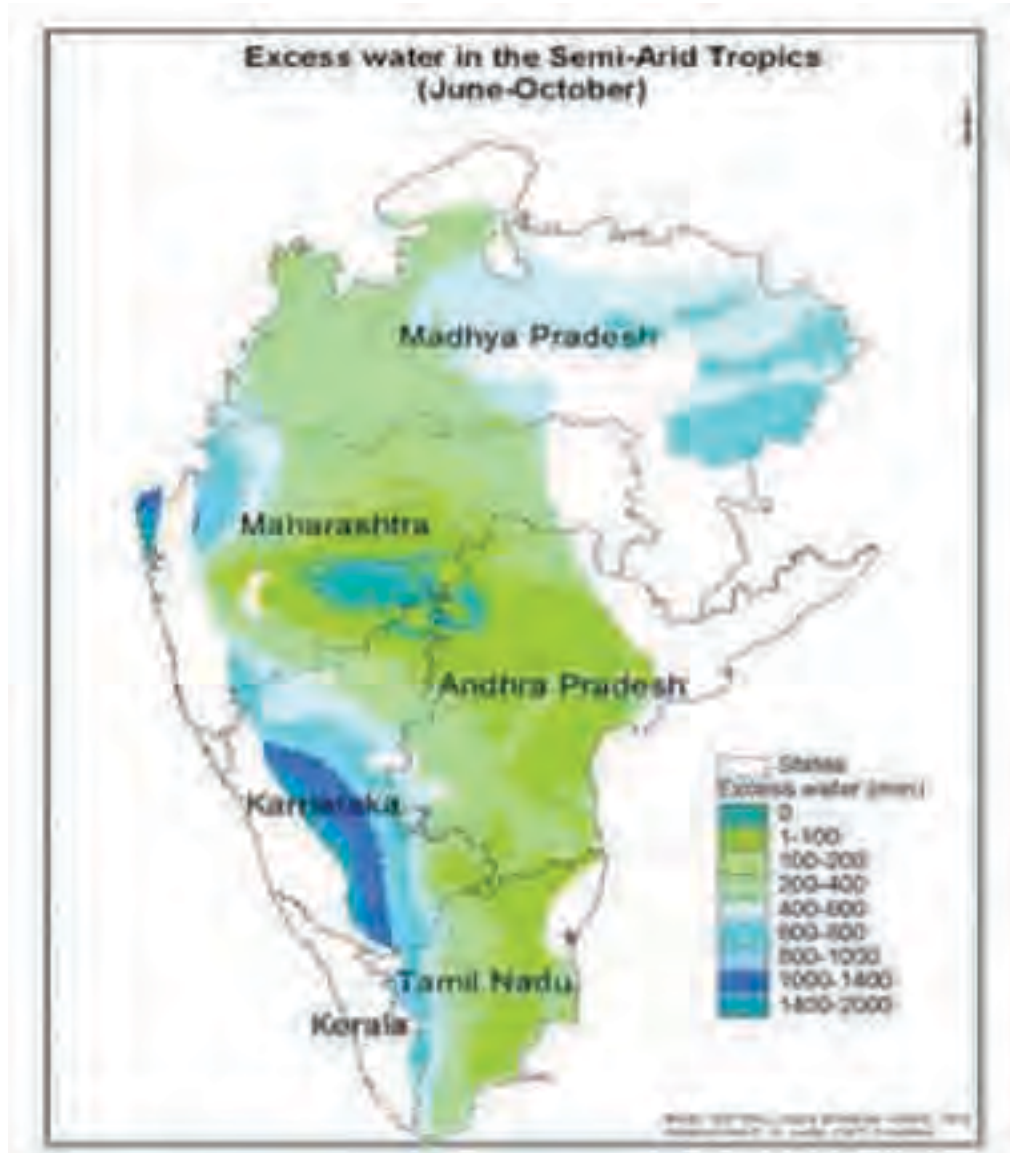
Figure. 28. Excess water available for harvesting as runoff in the states of SAT India.

Weekly water balances of selected watersheds in China, Thailand and Vietnam were estimated based on long-term agrometeorological data and soil type. The water balance components included potential evapotranspiration (PET), actual evapotranspiration (AET), water surplus and water deficit. PET varied from about 890 mm at Lucheba in China to 1890 mm at Tirunelveli in South India (Table 12). AET values are relatively lower at the watersheds in China and India compared to those in Thailand and Vietnam. Varying levels of water surplus and deficit were found. Tirunelveli in India has the

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largest water deficit (1347 mm) and no water surplus. Chine in Vietnam has the largest water surplus of 907 mm. These analyses defined the dependability for moisture availability for crop production and opportunities for water harvesting and groundwater recharge.

Table 12. Annual water balance characters (all values in mm).

Country	Location	Rainfall	PET	AET	Water surplus	Water deficit
China	Xiaoxingcun	641	1464	641	Nil	815
	Lucheba	1284	891	831	384	60
Thailand	Wang Chai	1171	1315	1031	138	284
	Tad Fa	1220	1511	1081	147	430
Vietnam	Chine	2028	1246	1124	907	122
	Vinh Phuc	1585	1138	1076	508	62
India	Bundi	755	1641	570	186	1071
	Guna	1091	1643	681	396	962
	Junagadh	868	1764	524	354	1240
	Nemmikal	816	1740	735	89	1001
	Tirunelveli	568	1890	542	Nil	1347

4. Varietal adaptation mapping to spot landrace niches and spread adoption of targeted, promising cultivars

For several decades, breeding research in West Africa's sudano-sahelian zone has focused on developing daylength-insensitive, short-duration varieties – while neglecting important pools of adaptation such as photoperiod sensitivity. This focus was due to incomplete understanding of climatic variation in the region, and the urgency triggered by droughts in the 1970-80s. But today, there is a growing agreement that photoperiod (PP) sensitivity, which actually 'encapsulates' variability management inside the plant's genome, needs to be fully incorporated in new germplasm to ensure better plasticity, yield stability, adaptation to the high unpredictability of the local agro-climate, and higher adoption levels (Traoré et al 2006).

This in turn requires us to revisit traditional adaptation mapping techniques. ICRISAT used West Africa as an illustration of the need to shift from classical crop adaptation concepts based on the sole 'normal' length of growing period to a dynamic, hierarchical analysis of environmental constraints (abiotic, biotic and socio-economic) to varietal adaptation. The rapidly increasing quantities of phenotypic and genotypic data available from conventional and marker-assisted selection will help make the transition from what used to be a merely academic exercise (mapping crop mega-environments, of little use to farmers) to an operational genotype x environment interaction mapping framework with numerous concrete outcomes for the local and commercial seed sectors – such as improved targeting of germplasm to proper niches in the production systems.

We used the same hierarchical approach used successfully in crop modeling to simulate plant growth – starting with simple mapping based on phenology only, refining the method by introducing water and nutrient constraints to biomass accretion, and eventually followed by higher-level mapping representation of pests, diseases and socio-economic constraints (eg

farmer preferences). As a first step, appropriate date of maturity is the key determinant of adaptation of sorghum and pearl millet in West and Central Africa. This is a key factor for maximizing productivity; reducing risks of yield and quality loss due to grain molds, insects and bird damage; and minimizing post-harvest problems associated with moldy and/or insect-damaged grains. Although appropriate maturity is universally accepted as essential, there is still lack of capacity in the region to effectively predict zone(s) of adaptation of new PP-sensitive sorghum and millet varieties, based on their maturity responses across a range of sowing dates, and latitudes.

Varietal adaptation maps in Figs 29-31 illustrate new adaptation mapping from a phenology perspective. Here, the cultivar is considered adapted when the average flowering date occurs 20 (±10) days before end of season. End of season occurs when a moving 10-day average of daily rainfall drops below the ETP line (~end of humid period, adapted from Cochemé and Franquin 1967). The two planting periods, so-called 'optimal' (shortly after onset of humid period) and delayed, reflect the traditional spread of sowing dates. For example the adaptation strip for early-maturing, non-PP sensitive CSM63 is thinner than that of late-maturing, PP sensitive CSM335 on any given date. It rapidly migrates southwards for delayed sowing, with relatively small latitudinal overlap for a 15-day delay, in contrast to CSM335. CSM63 can be considered to have wide geographic adaptation if, and only if, there is a shift in sowing dates. CSM335 demonstrates both large temporal adaptation (small latitudinal shift, large overlap) and large geographic coverage. PP insensitive germplasm (like CSM63) is more likely to benefit from improved climate forecasts, but PP sensitive cultivars could remain very competitive in a context of increased inter-annual variability and limited predictability, as is the case in West Africa. Table 13 illustrates the potential impacts of such technologies.

Table 13. Potential impacts and benefits – human populations (millions) in the adaptation zones of six sorghum cultivars, in CILSS countries (based on 2001 Landscan Population Database).

	CSM335	CSM63e	CGM19	CSM207	IRAT174	IRAT204
Early 'optimal' sowing	12.16 m	9.43 m	15.29 m	16.65 m	14.03 m	6.74 m
15-day delayed sowing	12.74 m	7.80 m	14.62 m	12.45 m	18.73 m	6.29 m

CILSS = Comite Inter-Etats de Lutte contre la Sécheresse au Sahel

Starting in 2006 the scope and breadth of this initial work will be expanded: (i) variety-wise to cover a full range of representative sorghum and millet varieties (landraces and improved), (ii) country-wise over the SAT areas of Nigeria, Sudan and beyond, (iii) time-wise to investigate the effects of climate change (by changing the 30-year normal climatological periods of reference). For this purpose, ICRISAT has entered a joint venture with the Agrhymet Regional Centre in Niamey, to gain restricted access to comprehensive daily weather databases for the WCA region. Contacts have been made with RCMRD (Nairobi, Kenya) and SADC-RRSU (Gaborone, Botswana) to undertake similar work in Eastern and Southern Africa.
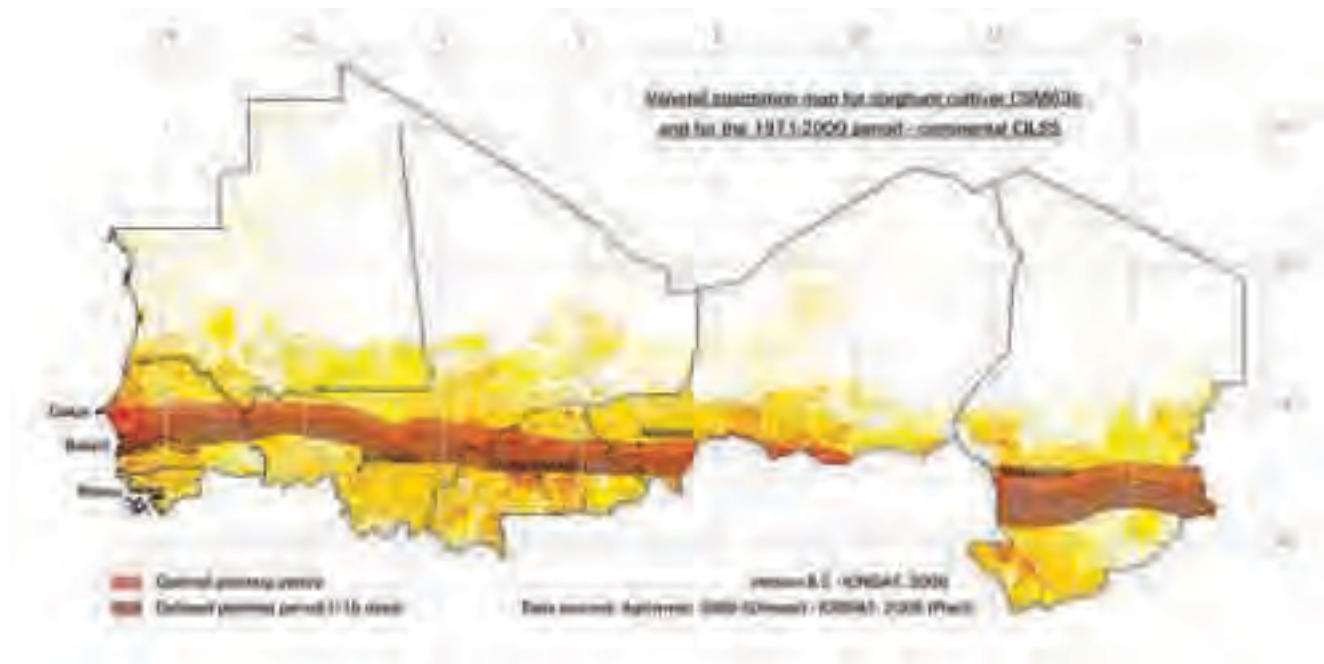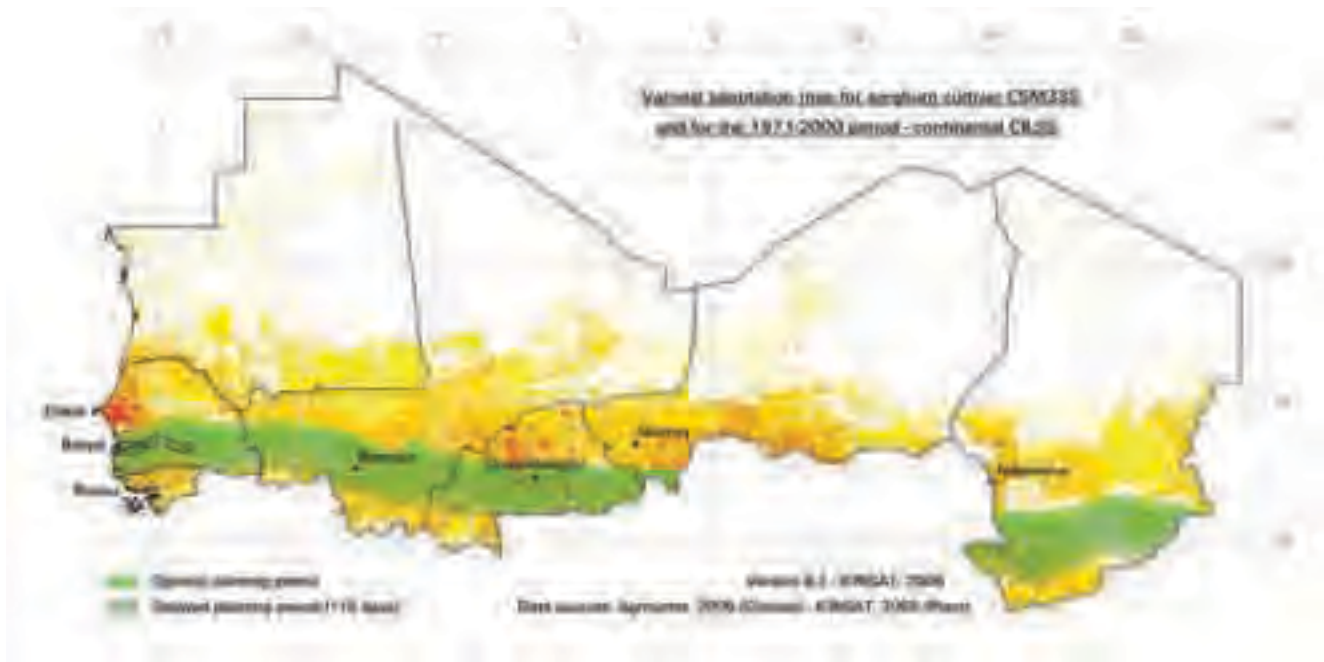
Figure 29. Varietal adaptation maps for sorghum cultivars CSM335 and CSM63.
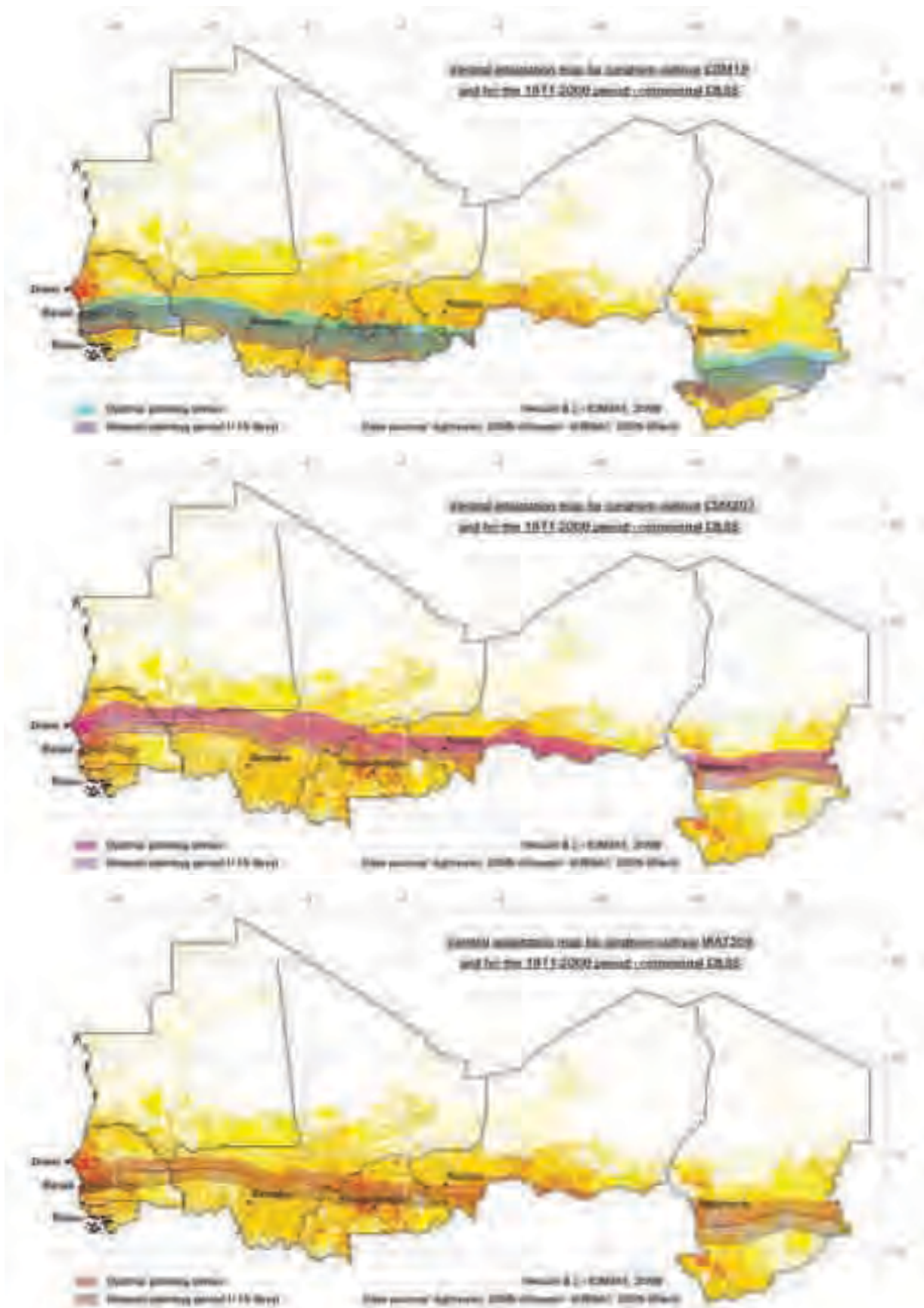
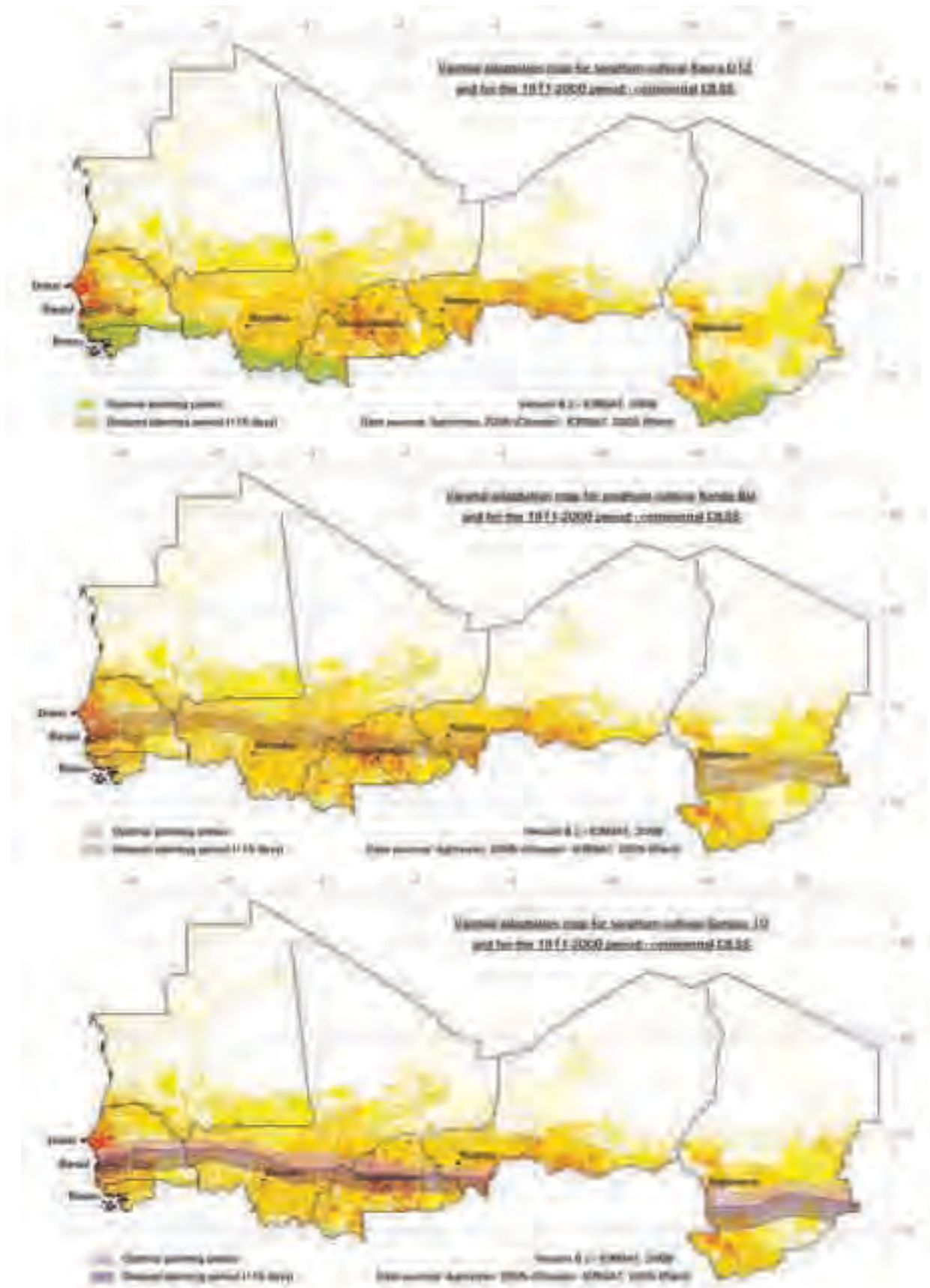*Figure 30. Varietal adaptation maps for sorghum cultivars CGM19, CSM207 and IRAT204.*

Figure 31. Varietal adaptation maps for sorghum cultivars Kaura D12, Kendebla and Sariaso10.

Harnessing Advances in Climate Science: Constraints and Opportunities from Variability and Seasonal Forecasting

Seasonal rainfall forecasting and climate risk management options for peninsular India

Uncertainty about the climate and weather has adverse effects on crop production and farmers' incomes throughout the SAT. They are traditionally risk averse and conservative in adopting high-input improved technologies because of the uncertainties in production associated with variable climate. Seasonal climate prediction in advance of the season could help them take appropriate decisions to minimize losses in low-rainfall years and harness the full potential in normal or high-rainfall years. With technical input from the International Research Institute on Climate and Society (IRI), a pilot project was carried out in Nandyala and Anantapur districts of Andhra Pradesh to assess the value to farmers, of seasonal climate prediction at district scale. Using a GCM predictor based model output statistical (MOS) technique, the probabilistic seasonal rainfall prediction for year 2003 was communicated to farmers more than a month in advance, enabling them to make appropriate cropping decisions. The prediction for Nandyala district proved accurate, and farmers derived significant benefits by adopting double cropping rather than a single crop. Farmers in Anantapur had mixed experiences because the rains started late. Those who intercropped groundnut with short-duration pigeonpea (rather than sole groundnut) benefited; while those who intercropped groundnut with medium-duration pigeonpea made losses as compared to the sole groundnut system. This work will be further strengthened in the next five years.

Pilot studies on seasonal climate forecasting in the SAT of Kenya

While the potential predictability of climate anomalies for some parts of Africa is among the highest anywhere in the world, currently the predictability of seasonal rainfall remains variable within Africa (Table 14) The high level of predictability of the Oct-Dec rains in East Africa are illustrated by the results of a study undertaken at Machakos in Kenya (Fig 32).

Surveys and pilot studies at Machakos in Kenya in collaboration with IRI and the Kenya Agricultural Research Institute (KARI) show that farmers see opportunities to benefit from seasonal forecasts (Table 15). However, such studies have also shown that farmers are often constrained by the timing, scale and format of available forecasts, lack of trust or comprehension of the forecasts, and need for competent guidance in order to use seasonal forecasts effectively. Effective agrometeorology

Table 14. Qualitative assessment of potential predictability of seasonal forecasts in Africa.

Region	Rainfall period	Potential predictability
West Africa	July-Sep	High
East Africa	Oct-Dec	High
East Africa	March-May	Low to medium
Southern Africa	Jan-March	Medium
North Africa		Low
DR Congo, Mozambique, Angola		Unknown

extension can address these challenges and facilitate the effective use of forecast information by supporting dissemination, interpretation, education, technical guidance, and feedback to forecast providers. This will require close collaboration between agricultural and meteorological institutions.
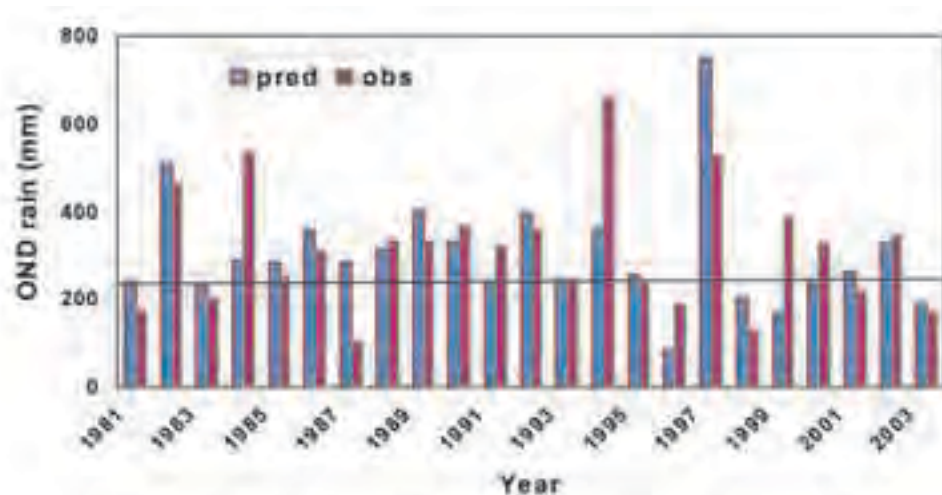

Figure 32. IRI Weather forecasts and observed rainfall for October, November and December at Machakos, Kenya (1981-2003).

Table 15. Some farmer identified management options for below normal and normal to above normal seasons at Machakos, Kenya.

Dry season	Normal to wet season
Use low plant density (2.2 plants/m^2) Reduce labor and other input useIncreased use of drought tolerant crops, eg sorghum, millet, greengram, cassava Plow and plant early before onset of rains Adopt water conservation measures Reduce area under cultivation	Use higher plant density (3.5-4.5 plants/m^2) Apply fertilizer Plant hybrid maize varieties, eg Pioneer Adopt intercropping Strengthen terraces Increase area under cultivation

Farmers are most likely to trust and act on information and advice when it comes from sources that they already know and trust. The trusted source will depend on circumstances – and may be agricultural extension services, meteorological services, development NGOs, agribusiness, farmer associations or community leaders. Hence the need for a multi-stakeholder approach to disseminate agrometeorologial information, that can help farmers cope with seasonal climatic variability.

Seasonal forecasts can also be linked with simulation models that provide probabilistic crop yield and production estimates well in advance of harvest – thus strengthening disaster preparedness. However, ICRISAT has yet to become engaged in such work.

Regional synthesis on climate prediction and agriculture: what is different about West Africa?

In 2003-05 ICRISAT conducted a START-funded pilot project entitled 'Bytes for Bites: translating climate forecasts into enhanced food security for the Sahel'. Little did we realize then that sudano-

sahelian farmers (and their crops) still are, in many ways, experts in resilience (Batterbury and Warren 2001, National Research Council 1996) and that our early assumption of *human vulnerability* could be challenged by generations of trusted kinship networks (Roncoli et al 2001) and sophisticated practices including selective management of plant genetic resources. West African farmers, partly thanks to biodiversity in sorghum, millet and other crops, were able to ride the stochasticity of climate, and manage their way out of dramatic droughts as in the 1970s and 80s.

A thorough review of current knowledge on regional climate revealed that in sudano-sahelian West Africa, *climate predictability* remains limited and very likely constrains the beneficial use of current forecasts. Unique combinations of external and internal forcings make West Africa one of the most climatically sensitive regions worldwide, and perhaps the most challenging to model. Linkages between local climate and relatively predictable ocean drivers are less clear-cut and strongly modulated by intricate effects of continentality – leading to high, distinctive seasonal climatic uncertainty and the importance of the peculiar adaptation traits found in the region (Traoré et al 2006).

ICRISAT's synthesis work strongly indicates that regional climate prediction skill at various time scales remains modest (earlier pointed out by IPCC 2001); and that at local spatial scales, low skill dominates in spite of an understandable urge to demonstrate the value of seasonal forecasts through more attractive scores at the aggregate level. For example, 'high degrees of skill' for the JAS period (IRI 2005) should be carefully interpreted in terms of scale-compatible applications (such as large watershed management), because any space-time downscaling will irremediably result in a loss of skill as suggested by Gong et al (2003). The inability of dynamic models to correctly reproduce the succession of sub-grid scale convective events severely limits their applicability in hydrology (Lebel et al 2000) and even more so in smallholder agriculture. This has special implications for West Africa, where IRI's own priority agenda focuses on health (meningitis etc) and not agricultural applications.

These problems, plus severe resource constraints and poorly developed information systems in small-scale agriculture, hamper farmers' decision capacity by reducing the options available to take advantage of forecasts. In sum, the prerequisites for successful application of seasonal forecasts in sudano-sahelian smallholder agriculture are not being met. This is in contrast to several other regions of Africa.

This will change over the next decade, as (i) progress on the implementation of retroactive land-atmosphere interactions in dynamic climate models reduces the uncertainty levels, thus facilitating uptake by farmers, (ii) production systems intensify under growing population pressure, increase in sedentary agriculture and fallow reduction. Meanwhile, a range of preparatory activities can be pursued with benefits in the shorter term: the ongoing adaptation of crop models to simulate local crops and farming systems (page 17), their coupling with GIS technologies to target regional breeding programs (page 38), and a 'rejuvenation' of early agrometeorological crop yield assessment techniques using the latest stochastic data assimilation approaches within the rapidly expanding spectrum of data sources (page 50). The latter offers timely prospects for the use of within-season, intermediate timescale forecasts in operational early warning systems and, possibly, selective response farming by sudano-sahelian smallholders. In a few years, progress achieved on these fronts will combine with improved predictability of climate variability trends to investigate agricultural impacts of global and regional change, and specifically the sustainability of existing and alternate patterns of adaptation (Sivakumar et al 2005).

Next Generation IGNRM Research: New Synergies for Development of Stochastic Simulation and Monitoring Frameworks

The last few decades have seen tremendous improvements in information and communication technologies (ICT), computing power and access thereto. For example, technological advances have allowed double-digit increases in the spatial resolution of earth observation systems, opening prospects for an ever growing range of applications increasingly relevant to agricultural scales. Twenty years from now, reasonable expectations call for spaceborne hyperspectral sensors with submeter spatial resolution to monitor intra-field variations in groundnut leaf spot disease, operational separation of GM/non-GM germplasm, etc across entire landscapes. With similar advances in bio-informatics, we are on the brink of important changes in applied research paradigms. In the future, work will be less constrained by data scarcity and computer power than by the operational ability to assimilate (and assess the quality of) large amounts of data in models that are more holistic and trans-disciplinary in nature.

From a remote sensing standpoint, the synergistic benefits of spaceborne observations, in-situ measurements and process-based models have already been illustrated for a variety of applications, including soil moisture monitoring (Crow et al 2003), estuarine hydrodynamics (Bertino et al 2002), and ecophysiological modeling (Inoue 2003). On the one hand, process-based models expand the usefulness of remote sensing by increasing vertical penetration and, in some cases, horizontal resolution. They effectively downscale the remote sensing signal to a wider range of system states of interest (Walker et al 2003) beyond the limited number of directly measurable variables (Dowd and Meyer 2003). Conversely, satellite observations can help estimate model parameters and mitigate errors arising from poor model initialization (Crow et al 2003).

The effective translation of increased data and processing power into useful outcomes through on-the-fly knowledge adaptation requires a shift from the traditional, deterministic research approach to information extraction from satellite data towards probabilistic paradigms that make full quantitative use of uncertainty in observations (eg satellite signals) and predictions (eg GCM outputs). The same applies to the interpretation of field and lab data which will gain from a full statistical characterization of the error therein, instead of outcomes stated as a single value, or set of values. Today the ability to predict outcomes of a given scenario in probabilistic terms is best illustrated by climate science, because of the uncertainty inherent to the climate system. The novel extension of such stochastic data assimilation frameworks to agricultural technologies is introduced below for carbon sequestration and agrometeorological yield applications. We believe that such approaches will greatly increase the convergence between farmer and scientist analyses of production systems and opportunities, facilitate communication and technology exchange.

Inter-annual data assimilation for ecosystem services: carbon sequestration

Participation in carbon (C) markets could provide farmers in developing countries incentives for improving soil fertility. However, carbon traders need assurances that contract levels of C are being achieved. Thus, methods are needed to monitor and verify soil C changes over time and space to

determine whether target levels of carbon storage are being met. Because direct measurement over the large areas needed to sequester contract amounts of carbon in soil is not practical, other approaches are necessary. ICRISAT works with University of Florida, IER-Mali and SARI-Ghana to develop an Ensemble Kalman Filter (EnKF) used to assimilate *in situ* soil carbon measurements into a stochastic soil C model to estimate soil C changes over time and space. The approach takes into account errors in *in situ* measurements and uncertainties in the model to estimate mean and variance of soil C for each land unit within a larger land area (Fig 33). The approach requires initial estimates of soil carbon over space along with uncertainties in these estimates. Model predictions are made to estimate soil C for the next year, *in situ* soil C measurements update these predictions using maximum likelihood methods, and the spatial pattern of soil C mean, variance, and covariance thus evolve over time. This approach can also be used to provide yearly estimates of the changes in soil C over multiple fields, the variance in those estimates, and aggregate soil carbon mean and variance values each year.
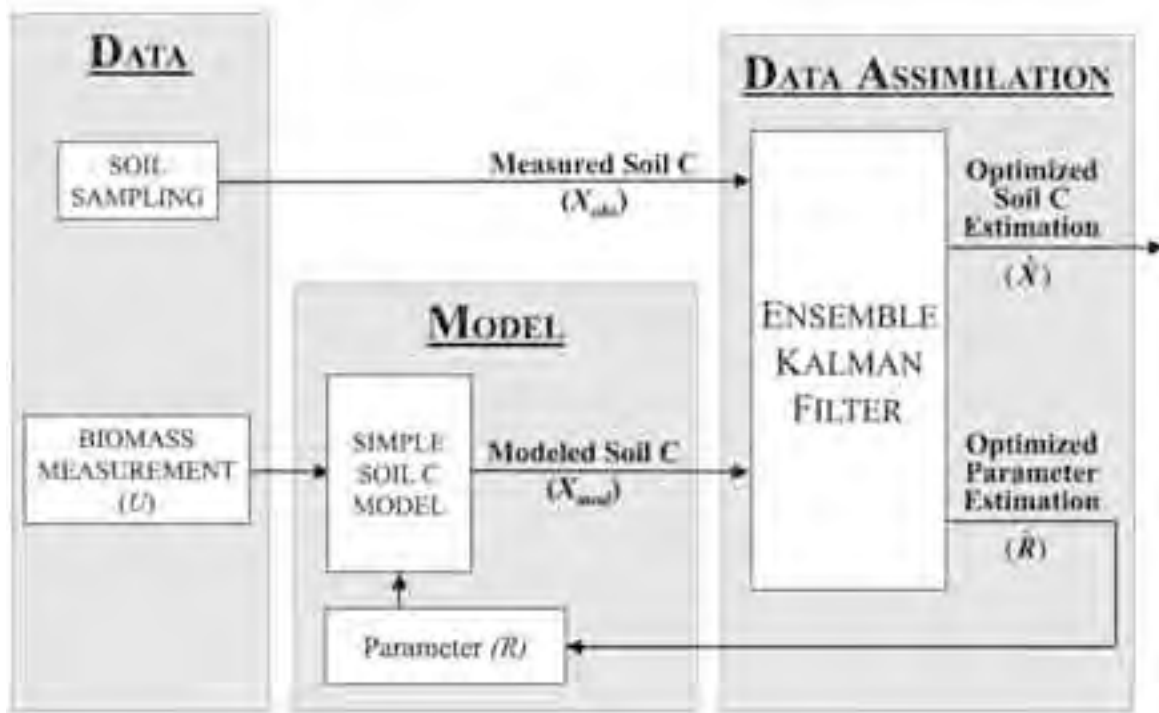
Figure 33. Framework for integrating soil C sampling and models for monitoring soil C. An Ensemble Kalman Filter (EnKF) is used to combine information from different sources to produce estimates of mean aggregate soil C over a number of fields and to provide an estimate of the uncertainty (variance) in this estimate

Fig 34 illustrates EnKF application for an area in Wa, Ghana, with 12 fields, comparing numbers of fields sampled each year and ways of selecting which fields to sample each year. The model predicts soil C changes over time using first order decomposition of existing soil C and addition of C from plant residues. The lowest intensity sampling method (sampling only one-fourth of the fields per year) resulted in the highest level of uncertainty in aggregate soil C estimate. Rotating sample fields each year improved the performance of the EnKF. These results demonstrated a quantifiable tradeoff between field sampling intensity and uncertainty in aggregate soil C estimates. This template framework is currently being modified to use more complex biophysical models and to assimilate remote sensing data (page 51).

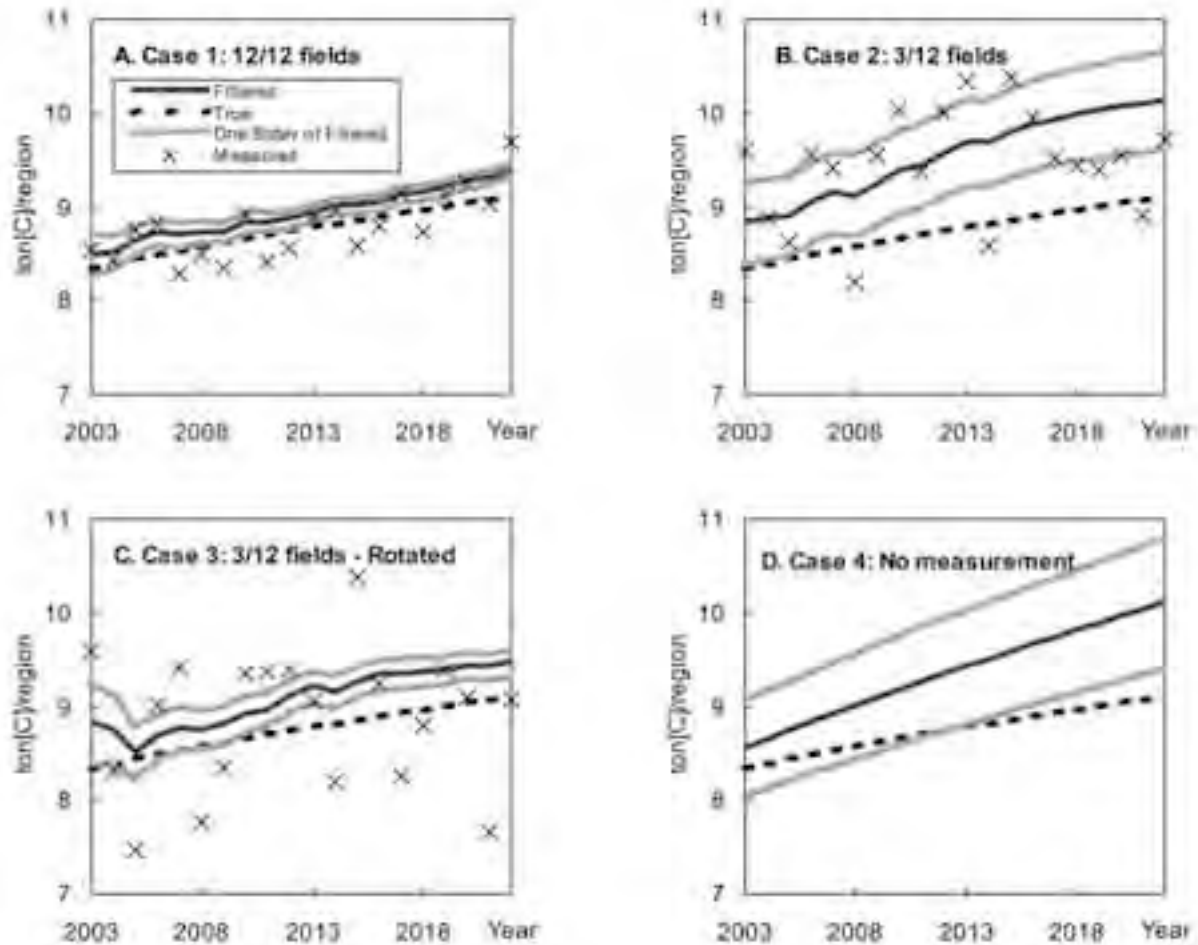*Figure 34. Aggregated soil C sequestration in each of four cases over the study area in Wa, Ghana (0.54 ha). Aggregate measurements were based only on fields that were measured. A) all 12 fields were measured, B) the same 3 fields were measured yearly, C) 3 fields were measured each year but rotated, and D) no measurements were made.*

Intra-seasonal data assimilation for tactical decision making: early crop yield assessments

Fig 35 provides another schematic illustration of a data assimilation (DA) procedure, this time to improve final model yield estimates using in-season rainfall forecasts and satellite biomass observations. At T=0, a crop model (mechanistic or empirical) is initialized with an ensemble of equally likely conditions (using a Monte Carlo technique). The model is then propagated forward in time with each realization of the ensemble. When estimates of system states (eg biomass), model parameters (crop type, sowing date, etc) or boundary conditions (cumulative rainfall) become available an Ensemble Kalman Filter (EnKF) updates these and the measures of uncertainty thereof. Sequential DA such as the EnKF is computationally more efficient than variational DA recently tested for crop yield estimation (Guérif and Duke 2000, Bach and Mauser 2003). It can accommodate a wider range of uncertainty as Monte Carlo ensemble generation allows for any statistical form of time/space correlation in error structure (Crow and Wood 2003), and can propagate the full probabilistic climate information into yield estimates along with measurement and model uncertainties (Jones et al 2005). It is better suited for near-real time applications oriented towards the prediction of future system states that is key to early warning systems.
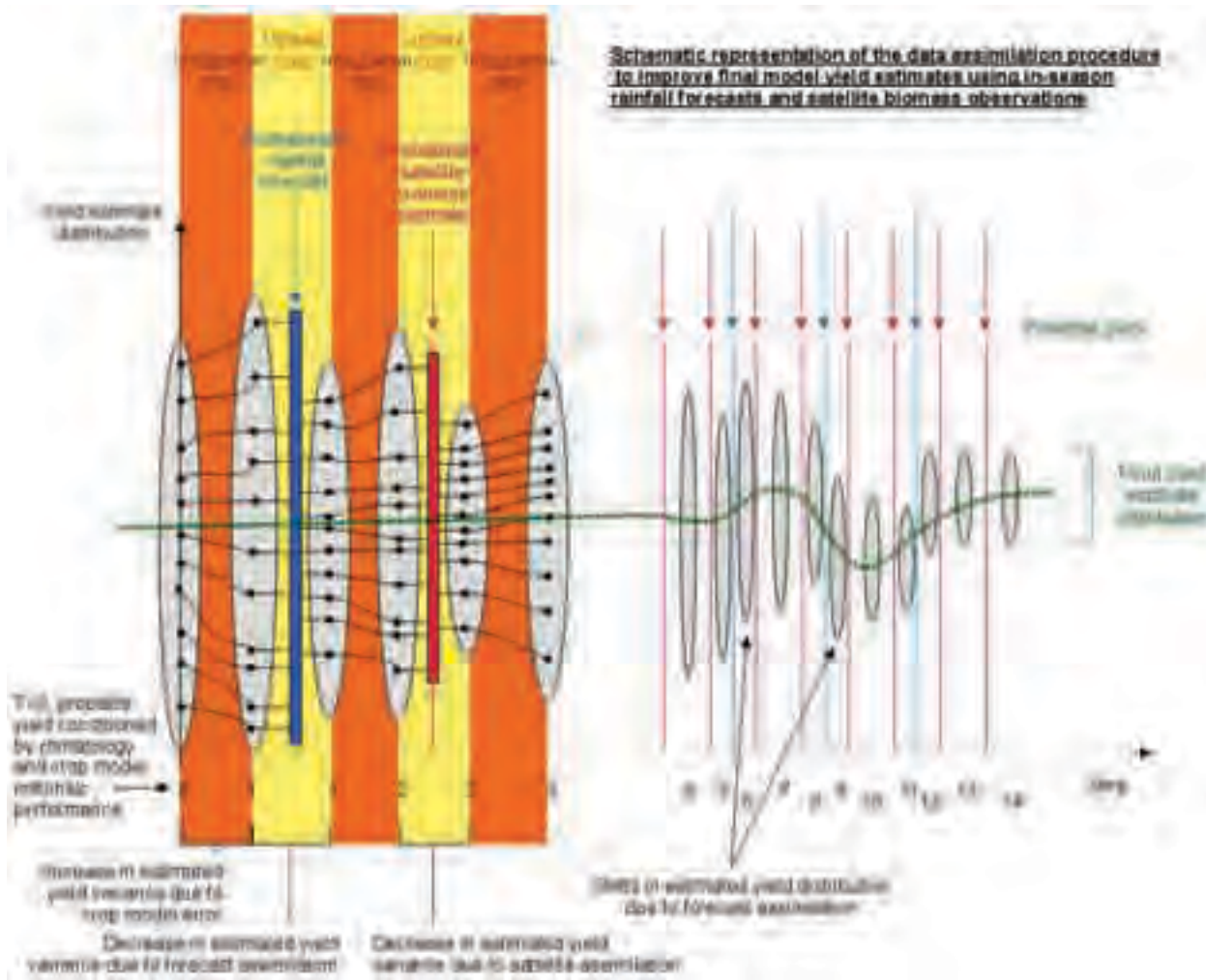
Figure 35. Schematic representation of a data assimilation procedure to improve final model yield estimates using in-season rainfall forecasts and satellite biomass observations.

Our request for data acquisition has been granted by the American-Japanese ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) team. They will provide targeted 30-meter multispectral data collected by an ASTER sensor onboard the TERRA satellite at the full nominal frequency of the repeat cycle (every 16 days) and for three growing seasons 2005-2007. Targeted at two intensive study sites of the Soil Management CRSP in Ghana and Mali (Fig 36), it will allow the finescale, spatially continuous monitoring of biomass production throughout the season for use in the spatial data assimilation framework. Similar novel data procurement efforts are underway to identify the best suited experimental in-season (zero lead time) hybrid monthly rainfall forecasts, with acceptable prediction skill levels, for continental West Africa. Potential candidates include new products routinely published by ECMWF since Oct 2004 (Grassl 2005).

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Figure 36. Map of SM-CRSP West Africa benchmark areas (in red) where ICRISAT is active, with the selected intensive study sites of Oumarbougou and Wa (in black).

Agricultural Extension Approaches in Southern Africa

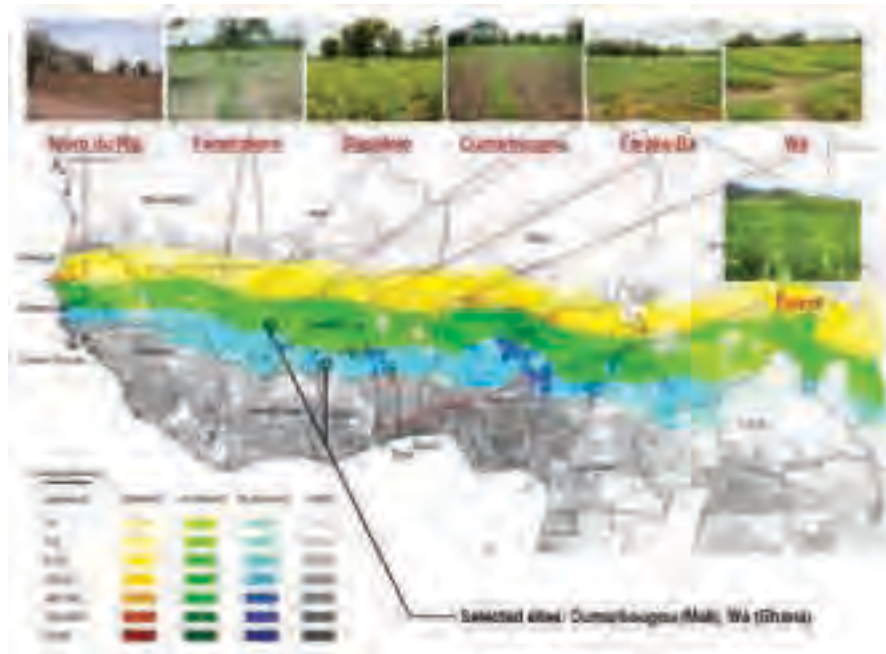Improved varieties of maize, sorghum and pearl millet have been released and adopted in many countries in sub-Saharan Africa. But despite the high adoption, yields in smallholder agriculture remain low. Farmers have been unable to capture the yield gains that new varieties offer, because of poor adoption of improved crop management practices – especially soil water and nutrient management. Researchers have hypothesized that farmers adopt soil water and nutrient management technologies much more slowly than they adopt new varieties, because with a new variety, the 'information' is embodied in seed – farmers can capture benefits simply by planting it. This is in sharp contrast with soil fertility technologies, where farmers need additional knowledge and experience: what product to use, when and how to apply it. In low-rainfall areas most recommended soil fertility technologies are risky and uncertain. This increases risks of implementation failure and limits adoption.

Over the last 10 years ICRISAT has been working closely with the research and extension services in southern Africa to develop participatory approaches to improve technology development and adoption by smallholder farmers. Two such approaches are described below: the Mother-Baby design for on-farm trials, and the use Farmer Field Schools to delivering extension messages on improved soil and water management technologies and alternative livelihood options, in drought-prone areas.

Mother-Baby Approach

We field tested the Mother-Baby participatory on-farm approach for testing low-cost soil water and fertility management technologies. Rather than a single 'ideal' technology, the Mother-baby approach was used to test and promote a basket of options, to account for diversity in farming objectives, resource endowments, farming risks, and tolerances for risk. The trial design was used to evaluate researcher-derived best-bet technologies in Malawi for four seasons, 1997/98 to 2000/01. The trials were implemented in collaboration with the Department of Agriculture and Technical Services, Department of Extension, Bunda Agricultural College, Concern Universal, and CIMMYT. The trials were extended to Zimbabwe during 1999/2000 and 2000/01 in collaboration with the Department of Agricultural Research and Extension Services (AREX), CIMMYT, TSBF, and the Intermediate Technology Development Group.

The Mother-Baby trial design served multiple functions: generating data on performance of alternative technologies, encouraging researcher-farmer dialog to refine the options being tested, and encouraging farmer experimentation even in the absence of researchers. The approach was also used to help characterize farmers' risk management strategies, target technology to specific groups (eg women farmers), and provide lessons on how to broaden technology adoption.

The Mother Baby approach is particularly useful for crop management and plant breeding technologies that are characterized by high information costs, variable performance over space and time, location specificity, risks, strong complementarities, and that are knowledge-intensive to exchange and adopt. The approach is so successful that the CIMMYT's Southern African Drought and Low Soil Fertility Project (SADLF) has adapted it for cultivar evaluations. The design enables farmers and researchers to test maize cultivars under researcher managed (Mother) and farmer managed (Baby) conditions. It also useful for technologies that are easily copied and can be spread through

spontaneous farmer-to-farmer exchange but are currently limited by cultural constraints such as witchcraft and grant systems of exchange. More information on the Mother-Baby approach can be found in:

- Rusike J, Snapp S and Twomlow SJ. 2005. Mother-baby trial approach for developing soil, water and fertility management technologies. Pages 102-109 *in* Participatory research and development for sustainable agriculture and natural resource management, vol 3 (Becker, JT, Braun A, Campilan D, De Cnavez H, Fajber E, Kapiriri M, Rivaco-Caminade J and Vernooy R, eds). International Potato Center-Users' Perspectives with agricultural research and development, Laguna, Philippines and International Development Research Centre, Ottawa, Canada.

Farmer Field Schools

Farmer Field Schools (FFS) are characterized by learning-by-doing, learning-by-using, experimentation and peer learning, and have been shown to be more effective and efficient than traditional extension approaches, in stimulating adoption of knowledge-intensive technologies such as soil fertility and water management.

ICRISAT and AREX in Zimbabwe jointly pilot-tested the efficiency and cost-effectiveness of FFS in the country's dry areas. Pilot FFS have operated in four drought-prone districts for four cropping seasons, 2000/01 to 2003/04. This pilot program differed from other FFS projects elsewhere in sub-Saharan Africa in one important respect: it linked advice on soil water and nutrient technologies with development of input and product markets, in order to overcome both information and market constraints.

The study evaluated the performance of FFS relative to two other approaches, the traditional Master Farmer approach and Participatory Agricultural Extension (PEA). The analysis focuses on the interaction between attributes of soil fertility and water management technologies, characteristics of extension services, characteristics of farmers and farms, and the resulting economic performance. The impact of each extension approach was tested by a number of indicators, including changes in farmer knowledge and practice, changes in extension knowledge and practice, farmer empowerment, and cost-effectiveness.

Results show that FFS training had a positive impact. FFS graduates had better knowledge of rainwater harvesting and soil fertility management, compared to non-FFS farmers. They also had higher adoption rates of improved soil fertility management practices and higher average yields: 5% higher for sorghum, 32% higher for maize. FFS graduates interviewed in this study indeed expressed their strong preference for FFS over the traditional Master Farmer training and group approaches, citing various reasons. Essentially, farmers feel FFS builds confidence through knowledge sharing, learning-by-doing, and observing and discussing (as a group) the performance of an FFS plot during the course of a full season. They decide almost everything themselves, including the curriculum; extension officers leading the FFS facilitate rather than teach.

FFS are costlier to implement than traditional Master Farmer and community-based Participatory Extension approaches; but they provide more opportunities for experimentation, and collective learning-by-doing and learning-by-using. This improves farmers' understanding of new technologies, their capacity to effectively use the technologies and to make better decisions, and improves adoption rates. To introduce FFS more widely into national programs and make them sustainable, the study makes three recommendations:

- Restructure the Master Farmer approach and integrate it with the FFS approach
- Expand investments for the development of farmer-led FFS
- Target investments by NGOs and agribusiness firms to complement public investments in FFS.

Junior Farmer Field Schools. The Junior Farmer Field Schools builds on the FFS approach, but targets HIV/AIDS orphans and other vulnerable children. The training covered crop/livestock production (including soil water and nutrient management), entrepreneurial skills, and HIV/AIDS awareness. The overall emphasis was to provide livelihood skills; poultry production was a key area, with participants provided training, initial stock and technical advice.

An appraisal carried out by ICRISAT showed that the proportion of youths joining community-based clubs increased from 1.5% in 1996 to 49.6% in 2004. One-fifth of respondents (JFFS participants) indicated knowledge gains on ISWNM: manure application, weeding practices, winter plowing and contour ridging. A similar proportion acknowledged knowledge gains on the effect of feed on productivity. Many participants reported they had a better understanding of basic management practices such as weeding and thinning. More information on JFFS can be found in:

- Alumira J and Sihoma-Moyo T (eds). 2005. Junior Farmer Field Schools in Zimbabwe. Proceedings of a Review and Planning Workshop, 16-17 Nov 2004, Masvingo, Zimbabwe. PO Box 776, Bulawayo Zimbabwe: ICRISAT.

Assessing the Economic and Environmental Impacts of NRM Interventions

Introduction

Well-managed natural resources generate flows of benefits that provide the basis for maintaining and improving livelihoods, improve the quality of life, and contribute to sustainable growth and alleviation of poverty. Impact assessment can be used to measure the outcomes and impact of development interventions, aiming to discern intervention effects from the influence of other external factors. It plays an important role in setting priorities and allocating resources to alternative interventions; and provides feedback to improve the efficiency and effectiveness of research. However, evaluating the actual livelihood and poverty impacts of agricultural and natural resource management (NRM) interventions would require analysis of distributional and equity impacts in addition to computation of simple efficiency indicators like net present values, benefit-cost ratios and internal rates of return. New methods and approaches are needed to extend traditional impact assessments to address these concerns.

Challenges in Evaluating NRM Impacts

Assessing the impacts of NRM interventions is beset by conceptual and methodological challenges that arise from several unique features of such interventions.

NRM impact assessment needs to consider attribution, outreach activities, spatial and temporal scales of interaction and dimension of impact, multidimensional outcomes, and valuation. The cross-commodity and integrated nature of NRM interventions makes it difficult to attribute impact to any particular intervention – in contrast to crop genetic improvement, where it is less difficult to attribute yield improvements to specific research investments. NRM interventions can result in observable research products adopted by farmers; as well as flow of qualitative information on management practices – which may be transmitted through formal and informal outreach activities or by farmer experimentation and exchange of knowledge. Particularly for such knowledge and information-based changes in NRM practice, it is difficult to separate impacts attributable to the intervention. Also, multiple agencies are often involved in the development and promotion of new NRM technologies, making it hard to separate the impacts attributable to specific programs.

Identifying an appropriate counterfactual in NRM interventions is particularly challenging because quantifying the biophysical impacts of interventions on natural resources can be costly, imprecise, and slow. For many natural resources, such as soil, which deteriorate over time, the counterfactual is a declining trend, not a constant level. Uncertainties about the flow of benefits also make it difficult to predict what would have happened in the absence of the intervention.

Scale issues in NRM present methodological challenges in identifying feasible spatial and temporal boundaries for assessing impact. NRM typically involves different spatial scales from farmers' fields to entire catchments, so many levels of interaction may need to be considered in assessing impacts. Multiple scales of interaction create upstream and downstream effects that complicate impact assessment. It is also likely that interventions may have different effects, which in some cases can generate opposite impacts, at different spatial scales.

At the temporal scale methodological challenges arise from slow-changing variables, substantial lags in the distribution of costs and benefits, and construction of meaningful counterfactuals for assessing future impacts. In some cases it may be difficult to perceive the costs or the benefits of interventions. In other cases assessing the full range of impacts (or measuring slow-changing variables in a holistic manner) may involve intensive monitoring of multiple indicators at different spatial scales over long periods of time. Differences in time scale for the flow of costs and benefits further complicate impact assessment.

NRM interventions may also generate multidimensional biophysical outcomes across resource, environmental and ecosystem services. This may include changes in soil quality and movement, water quantity and quality, sustainability of natural resources, and conservation of biodiversity. Appropriate indicators are needed to monitor the impacts on soil and water resources; and on the flow of ecosystem services. The multidimensional outcomes from NRM interventions means that impact assessment often face difficult measurement challenges, including very different measurement units and potentially the integration of very different natural resource outputs into some kind of uniform aggregate yardstick.

NRM interventions may also generate benefits that may not be reflected in current markets – but for which society places a value for multiple reasons. For example, water and water-based ecosystems provide direct values in consumptive (eg fishing, irrigation) and non-consumptive use (eg aesthetic value), indirect use values as ecosystem functions and services, option values for possible future uses, as well as applications and non-use values for intrinsic significance (existence and heritage value). Similarly many people consider biodiversity as having intrinsic value. It is important to place values on non-marketed benefits in assessing impacts of NRM interventions. But empirical valuation of non-market benefits is particularly challenging.

Quest for New Methods

In response to the increasing concerns about degradation of natural resources and sustainability of the agricultural production potentials in many poor regions of the world, national and international organizations have initiated research and development programs for NRM. These cover various areas, including low-cost technologies for integrated soil and water management, ecologically sound cropping systems, conservation and management of agro-biodiversity and forestry resources. Donors, policy makers, planners, development agents, and researchers are anxious to evaluate the potential economic and environmental impacts resulting from such investments through adoption of new resource conserving and/or productivity enhancing technologies.

Towards new methods for NRM impact assessment

Although there have been some attempts to assess NRM research impacts, there is little attempt to bring together researchers from a range of disciplines and institutional backgrounds to critically address the challenges and develop methods for NRM impact assessment. ICRISAT recognized the methodological gaps and took the pioneering steps by bringing together the leading researchers from the biophysical sciences and agricultural and resource economics. In order to review the scientific advances in developing such methods and define directions for the future, ICRISAT organized an international workshop on 'Methods for assessing the impact of NRM research' held at ICRISAT-Patancheru, 6-7 Dec 2002. Discussions at the workshop laid the foundation for the publication of the

new book: *Natural resource management in agriculture: methods for assessing economic and environmental impacts (B Shiferaw, AH Freeman, SM Swinton, eds). 2004. CABI Publishing.*

After the two days of deliberations, the workshop agreed to further review, synthesize and develop these methods for potential publication in a peer-reviewed edited volume. This gathering of leading scholars in biophysical and economic sciences inspired and

The volume brings together 16 peer-reviewed chapters that include conceptual and methodological sections as well as empirical case studies. The contributors are from various disciplines (including economics, agro-ecology and soil and water management), from a range of institutions (CGIAR Centers, universities and research institutes across the spectrum). The book examines the methodological difficulties, synthesizes recent methodological advances, and presents practical methods for assessing the economic and environmental impacts of NRM technological and policy interventions. Several chapters also bring together the current thinking on NRM impact assessment and define the directions for future research to fill the remaining gaps. It covers important areas including special features, economic valuation methods, measurable performance indicators and applicable impact evaluation approaches. The chapters on performance indicators include biophysical indicators for monitoring NRM impacts on diverse natural resource conditions: soil quality, water availability and quality, and other non-market agro-ecosystem services including agro-biodiversity and carbon sequestration. It also reviews methodological advances in simulation modelling for predicting the likely impacts of NRM on resource and ecosystem functions, and the application of remote sensing and GIS tools for monitoring biophysical changes.

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The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a nonprofit, non-political organization that does innovative agricultural research and capacity building for sustainable development with a wide array of partners across the globe. ICRISAT's mission is to help empower 600 million poor people to overcome hunger, poverty and a degraded environment in the dry tropics through better agriculture. ICRISAT belongs to the Alliance of Future Harvest Centers of the Consultative Group on International Agricultural Research (CGIAR).

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