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A Search for Strategies for Sustainable Dryland Cropping in Semi-arid Eastern Kenya

Proceedings of a symposium held in Nairobi, Kenya, 10–11 December 1990

Editor: M.E. Probert

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Foreword

The population of Sub-Saharan Africa will have more than doubled between 1985 and 2010. More than half of this tropical region is semi-arid, and most rural people living in such areas must depend on small-scale dryland agriculture. However, in many areas the fertility of the farmed land has fallen as the pressure of human population has increased. Farm productivity has fallen and farmers have found themselves sliding into poverty.

In 1983 the Kenyan National Council for Science and Technology and ACIAR jointly hosted a symposium in Nairobi aimed at identifying how Australia, with its lengthy experience of agricultural research in its own tropical region, might contribute to solving the agricultural development problems of Eastern Africa. The difficulties of farmers in semi-arid cropping areas in eastern Kenya emerged as a high priority. Consequently, a joint project, sponsored by ACIAR and centred on the Katumani Research Station (now the National Dryland Farming Research Centre) and on farms in the Machakos and Kitui Districts, commenced in 1985. The project involved close collaboration between research staff from the Kenya Agricultural Research Institute (KARI) and the Tropical Crops and Pastures Division of CSIRO, Australia's national research organisation.

The results of nearly six years of research were presented to 64 Kenyan government administrators and researchers, and representatives of national and international development aid donor agencies, at another two-day symposium sponsored by KARI, ACIAR and CSIRO, and held in Nairobi during December 1990. These proceedings present the 15 papers delivered. Shortly, ACIAR will also be publishing a companion digest of the results.

A major difficulty that confronts researchers investigating agricultural problems in semi-arid tropical regions is the variability of the climate. This poses special problems when interpreting experimental results and formulating sound crop husbandry recommendations for farmers. The KARI/ACIAR dryland farming project has used a maize crop model to tackle these issues. Consequently, a tool now exists that can explore the interactions between water supply, nitrogen nutrition and such agronomic practices as adjusting the time of planting and planting density of crops, and simulate crop performance using historical weather data.

As well as describing the development and application of the model, the papers support the theme that a strategy of augmenting traditional soil fertility maintenance practices (such as applying manure) with modest amounts of commercial fertiliser provides the best prospects for food security and sustainable agricultural development in heavily populated semi-arid tropical lands. This view runs contrary to previous popular wisdom that prevailed when the land was less degraded. The level of interest among participants at the symposium was most gratifying. Equally gratifying is the fact that the approaches advocated are already being applied successfully by a few farmers in the Machakos and Kitui Districts.

ACIAR and the scientists involved in the project believe that the approaches and strategies developed could do much to improve the lot of poor farmers living in semi-arid areas of Kenya and other tropical African countries.

The project and the symposium could not have succeeded without the enthusiastic support of the Directors and staff at the Katumani Research Station, and the interest shown by Mr G.Muhoho, Minister of Research and Technology, and other Kenyan Government ministries is gratefully acknowledged. The contributions of the late Mr Peter Kusewa, who was Director of the Katumani Research Station during the formative stages of the project until his untimely death in 1990, and Mr Benson Wafula, who subsequently became acting Director, deserve special mention.

Mr Neil Huth of the CSIRO Division of Tropical Crops and Pastures did much of the hard work needed to bring the papers delivered at the symposium to the high standard of presentation in these proceedings.

G H L Rothschild
Director
ACIAR

Preface

Developing countries in Africa struggling to increase food production face a dilemma in the form of limited essential physical resources, such as land, water, nutrients and energy, and lack of proper technologies. This situation is exacerbated by high population growth rates, which make it even more challenging for governments to achieve the elusive goal of alleviating poverty and suffering.

Kenya is one of these countries that is short of arable land (20% only). Four-fifths of the country consists of arid and semi-arid lands (ASAL), which are characterised by a bimodal rainfall pattern that ranges from very low to 800 mm per annum. This rainfall is extremely variable and unpredictable, which leads to frequent crop failures. Physical features include large areas of flat land and gently rolling hilly areas as well as steep and ragged hills and valleys. Elevations range from 700 m to 1800 m above sea level, and slopes can be as high as 30% or more, making large areas prone to erosion.

The ASAL received prominence during the 1979–83 Fourth National Development Plan in response to the plan theme of poverty alleviation. They, in particular, have come under increasing pressure. The ASAL areas are inhabited by small-scale farmers, farming mostly at the subsistence level. They have the greatest population change, with a natural rate of increase of 3.5–4.0% per annum, and a higher actual growth rate due to migration from the crowded fertile areas of the highlands. Farm sizes range from 1.5 to 17 ha.

The area under crops in the ASAL is usually smaller than the area under grazing. However, due to the rapid increase in population, an increasing proportion of the grazing area is being put under cultivation. Migrant populations have brought with them farming technologies developed for the well endowed high-potential areas that are inappropriate to their new settlements. Inevitably, this has led to recurrent crop failures, hunger and suffering, which can be alleviated only by costly famine-relief operations. Even more serious is the problem of rapid resource degradation in this fragile environment, which is leading to declining productivity and possible eventual permanent barrenness.

The needs of the high-potential areas of Kenya have to a significant extent been met through research and the application of new technologies. The ASAL have, however, not received sufficient research attention, and therefore traditional production systems have benefited little or nothing from research-tested innovations. This gap became acutely apparent during the early and mid-1970s, when many parts of Kenya experienced a series of years with poor rainfall that coincided with population migrations from high-potential to marginal areas.

It was during this period that research scientists in the Ministry of Agriculture and the former East African Agricultural and Forestry Research Organisation (EAAFRO) began to give serious thought to strengthening research in rainfall-deficient areas. The initial thrust was to be in the Machakos and Kitui Districts of Eastern Province — populous parts of the country where crop failures and famine are virtually endemic.

The first positive action taken was the gradual strengthening of Katumani Research Station by the Ministry of Agriculture, culminating in its elevation in status to the National Dryland Farming Research Station (NDFRS) in 1980, with responsibility for planning and coordinating dryland research activities throughout Kenya. Financial constraints made initial program development slow. In 1979, however, technical assistance was secured from UNDP/FAO, and Project Document No. Ken/74/017, entitled 'Dryland Farming Research and Development', was endorsed by the Kenya Government and the donor agencies.

At an earlier date, UNDP/FAO and the Kenya Government had signed a Project Agreement (KEN/74/016), 'The Kenya Sorghum and Millet Development Project', a major objective of which was to develop sorghum and millet for the dry lands of Eastern Province. Though administratively separate, this project complemented KEN/74/017.

While the latter project was still in progress, bilateral negotiations in 1979 between USAID and the Kenya Government resulted in the formation of Project No. 615–0180, 'Dryland Cropping Systems Research Project', based administratively at KARI, Muguga, but with field studies carried out at the NDFRS, Katumani. Special care was taken at the project design level to ensure complementarity and collaboration between KEN/74/017 and Project No. 615–0180. The approach was multidisciplinary, and involved both expatriate and Kenyan scientists.

The two donor projects were due to end in early 1984. A symposium on Dryland Farming Research in Kenya which would bring together the results achieved during their rather short 4–5-year lifetime in a form easily available for reference was therefore convened in November 1983. Meanwhile, following the establishment of the Australian Centre for International Agricultural Research (ACIAR) by the Australian Government in June 1982, efforts were being made to identify major agricultural problems and priorities in eastern Africa where the Australian agricultural research community, with its experience of research in Australia's own tropical and subtropical regions, might effectively be applied in collaborative programs. A highly successful consultation between senior scientists and scientific administrators from Australia, seven eastern African countries, and international research and development organisations took place in Nairobi in July 1983, sponsored by ACIAR and the National Council for Science and Technology of Kenya.

A Memorandum of Understanding for scientific and technical cooperation between the Government of the Republic of Kenya and ACIAR was signed in June 1984, the year when most parts of Kenya were experiencing a drought of a severity not recorded for many decades. Arising from this agreement, the joint Australian–Kenyan Government project entitled, 'Improvement of Dryland Crop and Forage Production in Semi-Arid Regions of Kenya' (ACIAR Project No. 8326), and centred on the NDFRS, Katumani, commenced in 1985. The project involved collaboration between the Kenya Government, ACIAR and the Tropical Crops and Pastures Division of CSIRO, Australia's national research organisation.

The main emphasis in the first phase of the project was in support of some of the activities of the NDFRS, Katumani — namely socioeconomics, forage legume evaluation, climatic risk analysis and management, soil and water management and soil fertility management.

The project concluded on 30 June 1987. The Government of Kenya/Donor Appraisal Mission of the National Agriculture Research Project (NARP), in which Dr R.K. Jones the ACIAR co-project leader participated, took place in October–November 1986. It was timely as well as essential for consideration of the future of Project No. 8326, which was due for review in April 1987. All parties were anxious to ensure that the follow up project's objectives remained consistent with the priorities which emerged in the formulation of the NARP.

The follow up ACIAR project (No. 8735), entitled 'Improvement of Dryland Crop and Forage Production in the African Semi-Arid Tropics', commenced in January 1988 and was due to be concluded in June 1991. It was favourably reviewed in December 1990 with a recommendation that it continue for a further 2–3 years. The project involved close collaboration between research staff of the Kenya Agricultural Research Institute (KARI) and the CSIRO Division of Tropical Crops and Pastures. Immediately before the review, the two-day KARI/ACIAR/CSIRO symposium covered in these proceedings was convened at the International Centre of Insect Physiology and Ecology (ICIPE), Duduville.

Modern published scientific works are rarely the result of a single intellect. Often they involve a mixture of individuals with different attitudes and aptitudes. The proceedings of this symposium owe their success to dozens of dedicated scientists and policymakers. ACIAR deserves special mention for defraying the cost of sponsoring the symposium and the publication of these proceedings. Much of the coordinating responsibility was shouldered by Dr J.R. Simpson, ACIAR Joint Project Leader, and Dr B.W. Ngundo, KARI Assistant Director.

Special mention is also due to the late Mr P.K. Kusewa, who was the Director of the National Dryland Farming Research Centre, Katumani, during the formative stages of the project until his untimely death in 1990. The Australian High Commissioner, His Excellency D.C. Goss, and the Deputy Director of ACIAR, Dr J.G. Ryan both delivered special tribute speeches at the farewell dinner function in honour of the late Mr Kusewa for his contribution to the project. The Minister for Research, Science and Technology, the Hon. George Muhoho, who delivered the closing speech at this function also made a special tribute to the late Mr Kusewa.

The technical sessions were ably and voluntarily chaired by Dr B.W. Ngundo, Assistant Director, KARI; Dr F. J. Wang'ati, Secretary, National Council for Science and Technology; Dr B.M. Ikombo, Acting Director, NDFRC, Katumani; Dr A.M. Kilewe, Director, NARC, Muguga; Dr R.L. McCown, CSIRO Division of Tropical Crops and Pastures; Dr F.N. Muchena, Director, NARL, Kabete; and Dr J.G. Ryan, Deputy Director, ACIAR. Their contributions were much appreciated. The cost of this symposium was minimised through the generous offer of the excellent facilities of ICIPE by the Director, Professor Thomas R. Odhiambo.

C G Ndiritu
Director
KARI

Setting the Scene

Agriculture of Semi-arid Eastern Kenya: Problems and Possibilities

R.L. McCown* and R.K. Jones†

UKAMBANI is the traditional name for the homelands of the Akamba people and is today the Districts of Machakos and Kitui (Fig. 1). Unsustainable agriculture in this region has been a recurring national problem during most of this century, with drought, over-population, and unfortunate policies all contributing. 'The history of smallholder agriculture in Machakos has been one of population continually bumping up against a land-cum-technology constraint' (Lynam 1978, p.34).

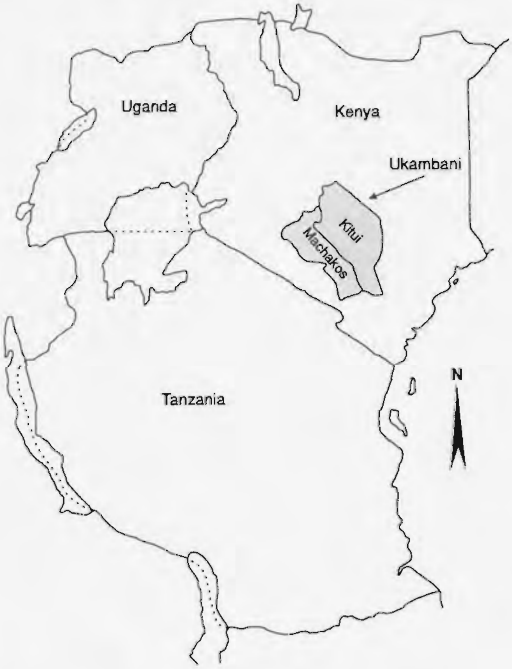

Fig. 1. Map of Kenya and some of its immediate neighbours, showing the location of Machakos and Kitui districts.

During the 19th century, the Akamba were settled on hill masses (Zone 3, Fig. 2), and largely confined to these restricted but relatively productive areas by the Maasai of the surrounding plains. They grew a red maize, beans, sorghum, millets, and cowpeas and herded cattle locally. Rainfall failed periodically, and serious famines are recorded (O'Leary 1984).

Farming practices used in hill farming were strongly conditioned by land shortage. There was increasing pressure to shorten fallows; limited grazing resources meant that manure was always in short supply, as were

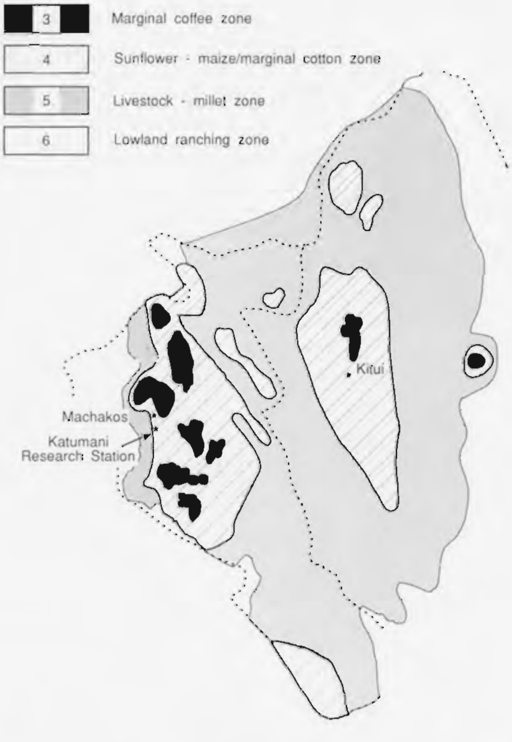

Fig. 2. Agro-ecological zones in Machakos and Kitui districts, Kenya (after Jaetzold and Schmidt 1983).

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oxen for ploughing. There were serious problems of soil fertility decline, over-grazing, soil erosion, and poverty.

As conflict with the Maasai subsided in the early 20th century, it became common for Akamba families to have seasonal cattle camps on the plains (O'Leary 1984) (Zone 4, Fig. 2). It is likely that the introduction of the ox plough in 1910 (Moore 1979) contributed to a gradual migration of farmer settlers to the plains by enabling more extensive crop production.

The Quest for Improved Technology

The traditional response to population pressure on land has been out-migration, to other hill areas when possible but, as hill areas filled up, to the best-endowed plains areas. This involved a shift of enterprise balance and factor substitution but virtually no changes in technology. However, significant changes in technology brought about by colonial government intervention did occur around 1950. These changes had two foci, i.e. the plains and the hills.

In 1947 an official scheme began to resettle families from over-populated hill areas to plains using an imposed new farming system better designed to be adapted to more marginal conditions. Makueni was the first area. The approach was agro-ecological, with settler farms designed on the basis of the best current knowledge and a research station (Katumani) established to improve this knowledge base.

Lynam (1978, p.53) reports the characteristics of the Makueni farm plan.

- Twenty acres freehold, single family, restrictions on fragmentation
- Cropping integrated with livestock within individual farms (no communal grazing areas)
- Five to eight cows
- Ox power for cultivation
- At least 5 acres cleared and terraced (forced permanent cropping)
- Soil fertility to be maintained by manure, crop rotation, and grass leys
- Maize, millets, drought-resistant grain legumes, fruit trees
- Two acres cleared and planted to pasture grass.

The second intervention was in the hill areas and was an attempt to restore and sustain this more intensive production system. The first strategy was to gain control over soil erosion using terraces. The second was to increase incomes with new cash crops, high-yielding cultivars, and better agronomy (Lynam 1978, p.56).

Both these interventions alleviated the so-called 'Machakos problem' and, following independence, attention focused on the high-potential areas where problems and opportunities were seen to be greater. Good rainfall in the 1960s contributed to the impression that Ukambani was no longer a problem area (Lynam 1978, p.61).

However, by the 1970s, Ukambani had re-emerged as a problem area, but with the focus shifted from Zone 3 (hill areas) to Zones 4 and 5 of the plains (Fig. 2). The dynamics of the old problem of population outstripping production as the forage resources degraded and soil stocks were depleted had not changed (Fig. 3). While the pressure was relieved for a while, the same problem recurred, only this time in a climatic region where seasons with low potential yields occur more frequently.

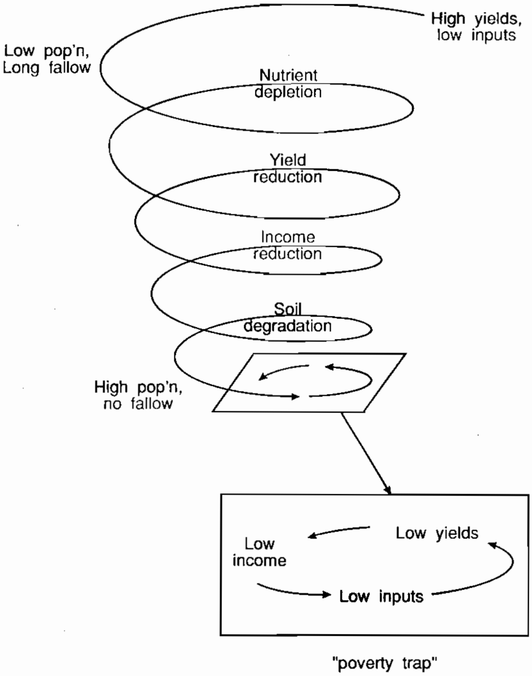

Fig. 3. Diagram showing how increasing populations and continuous cropping without inputs degrade farming systems in the semi-arid tropics to low levels of productivity (the 'poverty trap').

The technological strategy since the 1950s has been based on (a) sufficient land for integration of crops and livestock and fallowing of cropland, and (b) breeding of drought-resistant crops. By 1958 the first early-maturing cultivars of maize had been developed at Katumani and, although production is risky, maize production is viable in Zone 4 (Fig. 2). However, after only 40 years, population growth has again reduced farm size and fallow length to the point where soil impoverishment and accompanying erosion threaten viability of agriculture. The Makueni design for soil fertility maintenance (manure, rotations with legumes, and grass leys) can now be seen as inherently inadequate. While yields are low in the seasons of poor rainfall, over much of the region they are also low in the good seasons because of nitrogen and/or phosphorus deficiencies. With continued increase in exploitation pressures, the possibilities for use of chemical fertilisers, costly as these are, must be explored.

Fertiliser input can be considered most feasible when there is off-farm income, or savings from past off-farm endeavours. Off-farm employment became common during World War II, and 'by the fifties many households in Kitui regarded migrant work on a temporary or permanent basis as an essential source of income and as a means open to young men of poor families to establish their own households' (O'Leary 1984, p.44). This was true of the region in general, the degree differing mainly in relation to the surplus of agricultural labour and proximity to urban areas.

The availability of capital is a necessary but not sufficient condition for investment in increasing productivity. For the wage earner, there are many competing investment opportunities, both agricultural, e.g. terracing, and non-agricultural, e.g. education of children. The optimum proportion of off-farm earnings invested in intensification of production depends also on the future importance of agriculture in the family economy. O'Leary's (1984) warning about over-investment in agriculture in this region probably applies to the more resource-limited households. However, there are notable local examples of successful capital investment by farmers using savings, which inevitably involve a soil enrichment strategy of which commercial fertiliser is a component. It is clear that productive, profitable, and apparently sustainable crop production in this region is possible by augmenting traditional use of rotations and manure with commercial fertiliser. Such fertiliser-augmented soil enrichment hereafter will be referred to as a FASE strategy.

The Mineral Fertiliser Option: Precedents, Principles, and Possible Problems

The problem in Ukambani of declining yields due to soil fertility decline with continuous cropping is much the same as in smallholder systems with similar soils and climates in both sub-Saharan Africa and much of India. Knowledge of the outcomes of attempts to deal with the problem in these places should be helpful in devising a response in Kenya.

The following generalisations can be made.

- Manure supplies are inevitably inadequate to prevent yield decline to a 'low-level equilibrium' (Fig. 3) (Ruthenberg 1980; Nambiar and Abrol 1989).
- While nitrogen is generally the most deficient nutrient, responses to mineral N fertiliser are often low unless phosphorus is also applied (Nambiar and Abrol 1989; Bationo et al. 1985).
- Repeated application of mineral N and P fertiliser leads to yield decline and soil problems, specifically decline in organic matter (allowing increased acidity and exchangeable aluminium) and deficiencies of other nutrients (most commonly potassium, sulfur and zinc) (Pichot et al. 1981; Nambiar and Abrol 1989);
- The simplest means of avoiding these problems is to combine mineral N and P fertiliser and manure application (Pichot et al. 1981; Nambiar and Abrol 1989).
- Where the quantity of manure provides an insufficient supply of carbon for maintaining adequate soil organic matter, crop residues can substitute, but there is an increased risk of nutrient imbalance (Pichot et al. 1981).
- Fertiliser use is profitable without a subsidy for a sizeable proportion of farmers even in the dry semi-arid tropics (McIntyre 1986; Baanante 1986).
- Although it is well known that fertiliser use in Asia is high only in irrigated areas, old assumptions about the reasons why more is not used in dryland agriculture are being challenged. Indian states with extensive irrigation also have the highest proportion of rainfed areas fertilised (Anon. 1989). This may indicate the importance of limitations of supply of fertilisers and knowledge to smallholder use in dryland regions (Desai 1982, cited by McIntyre 1986; Mudahar 1986).
- The yield response expected by farmers seems to be more important than cost in the decision to buy or not to buy fertiliser (Desai 1982, cited by McIntyre 1986). In evaluating fertilisers, both farmers and professional agronomists face a situation where many things can go wrong, and too often do. Farmers often have inadequate knowledge to prevent mis-purchase, poor storage, or misapplication. The scientists understand the technology, but often are inexpert in growing the test crops in the given unfamiliar circumstances and/or suffer logistical problems. It may be that such factors have caused farmers and planners to underestimate the potential benefits of chemical fertiliser.

The overwhelming weight of evidence is that, while organic sources of nutrients are essential for good soil management, supplies are inadequate. Augmentation by commercial fertiliser is both generally profitable and essential for sustainable production at moderate to high levels.

Management Requirements for Efficient Yield Improvements from Fertiliser

Reports on response to fertiliser in smallholder systems tend to be highly variable, and this often masks the general importance of the soil fertility deficiencies. A more helpful interpretation is that, even when the applied nutrient is deficient, response may be poor due to a deficiency in any of several other factors, many of which can be controlled by the knowledgeable manager. Although the high cost is generally considered to be the main deterrent to fertiliser use, at least as important may be the management demands for getting other things right. The most important considerations are indicated in the following principles for efficient fertiliser use.

- Manage all deficient nutrients together. After sustained exploitative cropping without any fertiliser inputs, nitrogen will normally be most deficient, with phosphorus close behind. When this is the case, a response to supply of nitrogen alone will decline as phosphorus becomes increasingly limiting, and greatest economic returns at some point will be to phosphorus.
- Ensure that the maximum amount of applied nutrient gets to the crop. Fertiliser must be put at the right place at the right time and weed competition prevented.
- Grow a nutrient-responsive crop and cultivar. Maize is more responsive than millet and sorghum. Improved cultivars and hybrids are generally more responsive than local types, but fertilisation of local types is often profitable (McIntyre 1986).
- Minimise all other environmental constraints. Beyond planting at the optimum time, restraining runoff using structures, and mulching, water supply in dryland systems is largely out of farmer control. In this environment, risk of water deficits is considered the most important deterrent to fertiliser use. This is often expressed as the risk factor, but the more important effect of this climate may be simply the limit to expected (average) yields (McIntyre 1986). There is no doubt that the average returns to fertiliser are greater the more favourable the water environment, hence the high usage of fertiliser where there is irrigation. This does not negate the possibility that when soil fertility has declined to levels where yields are very low even in the best rainy seasons, a soil enrichment strategy that includes some chemical fertiliser is the best of the alternative options although response will be poor in the seasons with low rainfall. The small amount of information that exists indicates that in the latter situation much of the fertiliser nutrient applied is available to the crop in the subsequent season (Keating et al. 1991).

Management Requirements for Long-term Use of Fertiliser

In addition to management for efficient use of an expensive fertiliser material, other considerations are required to ensure that even efficient use is not detrimental to the soil. On poorly buffered sesquioxidic soils with depleted organic matter, such as those that prevail in Ukambani, sustained use of commercial fertiliser as a main source of nutrients could cause soil acidification and related problems (Dommen 1988; Nambiar and Abrol 1989). Compared to the agriculturally productive soils of the world, soils of this region are low in organic matter even at their best. After a long period of intensive cropping and erosion, organic matter has fallen to very low levels, and restoration of productivity will require substantial inputs of carbon as well as nutrients. Organic matter depletion affects soil behaviour physically, as well as chemically, causing loss of water-stable structure and reduced water conductivity. This effect is most apparent as slaking of cultivated seedbeds, reduced infiltration rates, and increased proportion of rain lost as runoff.

Restoration of fertility requires increasing soil carbon as well as N and P. There is good scientific evidence that manure is the best amendment; it provides carbon, prevents acidification, and it generally provides the balance of all nutrients (Pichot et al. 1981; Nambiar and Abrol 1989). Unfortunately, boma manure is seldom available in sufficient quantities on farm, is bulky to transport, and there is no formal market for it.

While fresh crop residues are another possible source of carbon for soil organic matter, the retention of crop residues for soil improvement competes with other household needs, e.g. animal feed, fencing, and fuel. However, once a soil enrichment program is initiated with additions of the appropriate fertiliser, more residues are produced and, even with previous rates of removal, there is an increasing quantity that could be retained for the soil (McCown 1987). This opportunity to reverse the process of Figure 3 is enhanced by the improved water conservation that results from the beneficial physical effects of organic materials. Nevertheless, it is as yet unclear whether manure and/or crop residues in the amounts that are available can be sufficient to prevent carbon supply from strongly limiting organic matter recovery without periods of pasture.

A Research Project in Search of Strategies for Sustainable Agriculture for the Middle Potential Zone

Against this backdrop of problems and possibilities, a research program was designed and has evolved. The original on-farm studies (Fig. 4: socioeconomic components; Ockwell et al., in press) reflected an appreciation

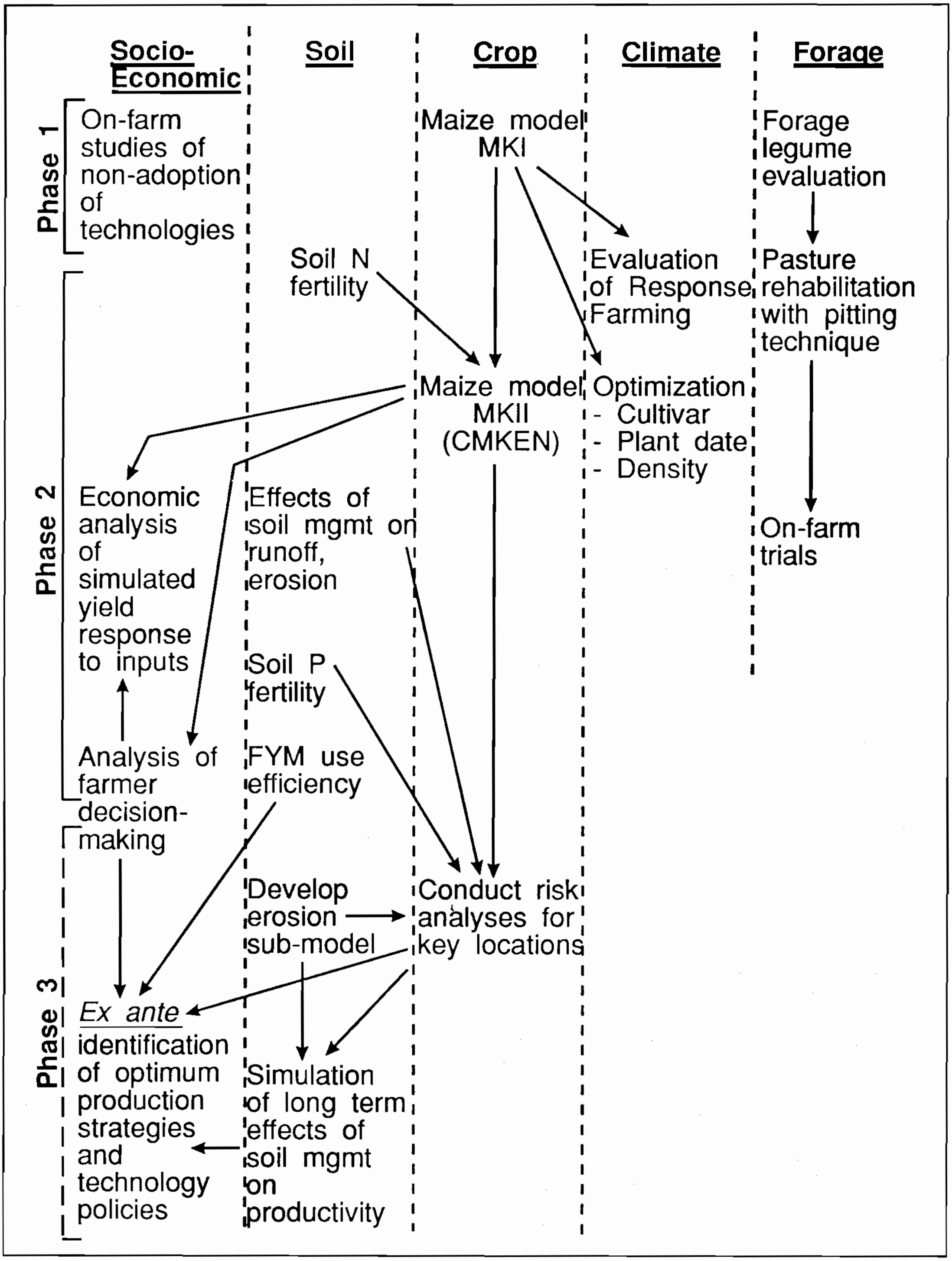

Fig. 4. Schema of research activities, disciplines and phases in the KARI/ACIAR collaborative research project on farming systems in the Machakos and Kitui districts of eastern Kenya.

of the value of diagnosis of problems in the farming system as a basis for design of technical research. However, as is often the case in assistance projects, the assured project duration did not permit completion of the diagnostic work before other research had to commence. The indications that agriculture under existing pressures and practices was unsustainable seemed sufficient to warrant an evaluation of a large number of pasture legumes in search of a well-adapted plant that might enhance the forage and soil nitrogen supplying capacity of fallow (Fig. 4: forage components; Menin et al. 1987). The obvious importance of climatic risk to allocation of scarce production resources suggested that there would be benefit from the early development of a tool for using historical rainfall records to quantify this risk and evaluate alternative farming strategies. A program of testing the CERES–Maize simulation model and adapting it for Kenyan conditions was initiated in Phase I (Fig. 4: crop components; Keating et al., Development of a modelling capability for maize in Kenya, these proceedings). This led to the critical evaluation of Response Farming, a promising scheme for reducing climatic risk to maize production (Stewart and Faught 1984) (Fig. 4: climate components; Wafula et al., these proceedings).

In time, the on-farm studies revealed that:

- even in good seasons, yields are low due to low soil fertility;
- because of the high intensity of land use, there seems little place for pasture legume-enhanced fallows as a main source of N;
- most farmers are aware of fertiliser but do not use it;
- a high risk of rainfall failure is very important in resource allocation decisions; and
- water erosion is a serious threat to productivity on both crop and pasture land.

These findings had several implications for the research program. The forage legume research emphasis shifted from fertility restoration of croplands to rehabilitation of grazing land (Fig. 4: forage component; Simiyu et al. these proceedings). The importance of improved soil surface management and inputs on both fertility maintenance and water and soil conservation formed the basis of a major field study instrumented to measure runoff and soil loss (Fig. 4: soil component; Okwach et al. these proceedings). The outcome should, in addition to providing a direct comparison of strategies, provide an erosion model that, when coupled with the crop model, enables comparison of strategies of soil management in terms which include long-term effects of erosion on productivity (Fig. 4: soil component).

The crop model, once adapted, has indeed provided a means of readily identifying risk-efficient management strategies (planting date, plant population density, cultivar phenological characteristics) (Fig. 4: climate component; Keating et al., Exploring strategies for increased productivity, these proceedings), and with a calibrated N submodel, provides credible surrogate production data for *ex ante* economic analysis of alternative input levels and strategies (Fig. 4: socioeconomic component; McCown et al. 1991; Wafula et al., these proceedings). Such analyses require, in addition to production data, information on farmers' attitudes towards risk and their perceptions of risk levels (Fig. 4: socioeconomic component; Muhammad and Parton, these proceedings).

The main thrust of research on soil fertility has been the efficient use of commercial fertiliser, recognising that boma manure is in very short supply and can only become more scarce as pressure on land continues to increase. Attention initially directed to nitrogen, the most conspicuous and uniformly deficient nutrient, later turned to quantifying phosphorus responses and the efficacy of various forms of phosphatic materials of differing costs (Fig. 4: soil component; Probert and Okalebo, these proceedings). A second thrust was to examine the way in which the boma and its manure content is managed, to see if there are untapped opportunities for more efficient nutrient capture and cycling back through the croplands (Fig. 4: soil component; Probert et al. these proceedings).

The remainder of this volume reports the progress in the various areas of research that have comprised this project in search of a sustainable farming strategy for Ukambani.

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The Problem of Climatic Variability

The Impact of Climatic Variability on Cropping Research in Semi-arid Kenya between 1955 and 1985

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RESEARCH on crop production in the semi-arid lands of Kenya has a history going back at least 35 years, and has an important place in the global scene of agricultural research for the semi-arid tropics. This paper provides an overview of the research conducted in Kenya during the period 1955 to 1985. The work conducted during this period provided a solid foundation for the Australian contribution which is being discussed in this symposium.

This overview does not attempt to acknowledge every research contribution over the 30 years in question, but presents examples that highlight progress made, and common themes throughout the period. It focuses on research for crop production and particularly on the research programs that have operated at or out of Katumani Research Station, now known as the National Dryland Farming Research Centre. It also highlights the problems that have constrained research over the period.

Major Research Topics Evident in the Literature

Ten major themes recur throughout the literature on cropping research in Kenya during the period 1955 to 1985 (Table 1). The first eight deal with crop and soil management issues — plant population, planting date, fertilisation, rotations, intercropping, fallowing, genotypic adaptation and soil surface management. The last two deal with the analysis of the climate constraint and crop yield–climate modelling.

Plant population studies have sought to optimise use by crops of limited supplies of water and nitrogen. Optimisation of radiation use is less important in this region because of the more limiting nitrogen and water constraints.

Planting date studies have sought to resolve the conflict between early planting, when establishment is more risky due to a high probability of water deficit and weed competition is a greater threat, and late planting, with its enhanced risks of losing water and nitrogen resources available early in the season and greater chances of encountering water deficits during grain-filling.

Fertiliser studies have concentrated on nitrogen and phosphorus, and sought to supplement the levels of these nutrients in the available soil pools.

Studies with rotations and fallows can be thought of as ways of optimising the between-season transfers of water and nitrogen. Other effects of rotations, such as pest or pathogen control, have received some attention, but emphasis has remained on the water and nitrogen balances.

Intercropping is a traditional practice of mixing crop types to achieve more efficient utilisation of the resources needed for crop production. Competition for water and nitrogen can usually be shown to determine the outcome of the intercropping experiments conducted in semi-arid Kenya, although more efficient light interception can sometimes confer advantages when water and nitrogen are non-limiting.

Genotype improvement and crop adaptation are fields where Katumani is best known, particularly in relation to the breeding of early flowering maize germplasm. Such material provides an example of how management (cultivar selection) can lead to better utilisation of limited water resources. Early flowering, while associated with lower leaf areas and reduced yield potential, enhances the chances that soil water will be available when maize is at its most sensitive stages, i.e. silking and anthesis. While not generally recognised, the lower shoot biomass of Katumani early flowering varieties probably also improves adaptation to limited soil nitrogen reserves.

Soil surface management to reduce losses due to runoff and increase infiltration into the soil is an effective means of improving water supply to crops. Research at Katumani has focused on control or amelioration of the degradation associated with soil loss, and an outcome

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Table 1. Selected publications on research in Kenya's semi-arid cropping lands: 1955–1985.

Research topics	Authors / Reference	Years	Crops
Plant population	Nadar (1984a)	1978–1982	Maize
Planting date	Dowker (1964)	1959–1962	Maize
	Semb and Garberg (1969)	1967	"
	Nadar and Faught (1984)	1980	"
Fertilizers (manure)	Pereira et al. (1961)	1956–1957	Maize, beans
	Nadar and Faught (1984)	1979–1982	Maize
	Ikombo (1984)	1981–1982	"
	Okalebo (1987)	1975–1981	"
Rotations	Bennison and Evans (1968)	1960–1963	Maize, beans, millet
	Nadar and Faught (1984)	1981–1983	Maize, beans, pigeon pea, cow pea, tepary, cotton, cassava
Intercropping	Fisher (1977a,b)	1972–1974	Maize/beans
	Nadar (1984b)	1978–1981	Maize/pigeon pea cow pea, beans
	Chui and Nadar (1984)		
	Ashley (1984)	1982–1983	" "
Fallowing	Bennison and Evans (1968)	1960–1963	Maize, beans, millet
	Whiteman (1981)	1980–1981	Sorghum, millet, maize
Genotype/crop	Dowker (1963a)	1957–1961	Sorghum, millet, maize
	Dowker (1971)	1957–1961	Maize
	Njoroge (1985)	1977–1983	"
Surface management	Njihia (1979)	–	Maize
	Barber et al. (1981)	–	–
	Ulsaker and Kilewe (1984)	1981–1983	Maize, beans
	Critchley (1989)	1984–1986	Maize, sorghum
Climate analysis	Nieuwolt (1978)	–	–
	Musembi and Griffiths (1986)	–	–
Agroclimatic analysis and/or modelling	Glover (1957)	1943–1953	Maize
	Dowker (1963b)	1957–1960	"
	Dagg (1965)	1963	"
	Wangati (1972)		Maize – beans
	Mugah and Stewart (1982)	1978–1979	Maize
	Lenga and Stewart (1982)	1980–1981	Maize–beans
	Jaetzold and Schmidt (1983)	–	–
	Stewart and Faught (1984)	1979–1983	Maize–beans
	Stewart and Kashasha (1984)	"	–
	Downing et al. (1987)	1984–1987	Maize

of this is enhanced crop production potential. In the longer term, erosion will accelerate the run-down in soil humic-nitrogen pools, with serious consequences for crop yield.

Climate analysis has focused on amounts and variability of rainfall but has always been limited in that its outputs have been in terms of climatic statistics. While these are of interest to the climatologist, they provide little assistance to the agronomist who is primarily interested in assessing the effect of climatic variables on the growth and yield of crops.

The agroclimatic analysis and modelling work has attempted to overcome the limitation of climate analysis, by relating crop growth and yield to climate variables. The interactions between weather, nitrogen or other nutrients on crop growth and yield have not been adequately studied, and this greatly limited the applicability of these past modelling studies.

While not always acknowledged, the majority of the research described above has sought to influence either (i) the processes and pools making up the water and nitrogen balance, or (ii) crop use of the nitrogen and water resources. While other nutrients are potentially important, nitrogen tends to be the most common and most limiting and will be our focus in this paper.

Problems Confronting Research in Semi-arid Kenya

A careful review of the papers detailed in Table 1 emphasises the major problem which climatic variability has posed for researchers seeking to interpret their experimental results. An examination of the interseasonal rainfall variation (Fig. 1) and climatic statistics (Table 2) reinforces this perception. Median rainfall totals for representative sites in the region range from 175 to 297 mm per season in this bimodal rainfall environment, and coefficients of variation of seasonal rainfall are in the range 45–58 per cent (Table 2). In comparison, coefficients of variation for a unimodal rainfall environment in semi-arid regions of northern Australia range from 17 to 25 per cent (Mollah 1986).

In addition, the papers in Table 1 clearly show the complexity of the system under study, and the great difficulties associated with interpreting studies of one or a small number of discrete factors, in a way that is meaningful in the real world. In the remainder of this paper, we provide some examples of these problems and examine strategies that have been used by the researchers of the period to deal with complexity and variability.

Table 2. Characteristics of the two rainfall seasons in semi-arid eastern Kenya.

Site	Season[a]	Median rainfall (mm)	Range (lowest–highest) (mm)	Coefficient of variation (%)
Katumani[b]	Short rains	270	155–925	51
	Long rains	297	133–660	45
Makindu[c]	Short rains	261	38–830	58
	Long rains	175	18–510	52

[a] October–January for short rains, March–June for long rains
[b] Katumani Experiment Station, Machakos, 1956–1982
[c] Makindu Meteorological Station, 1951–1980

The Problem of Complexity and Variability

Water and nitrogen supply tend to be the major determinants of productivity in these systems, so experimental

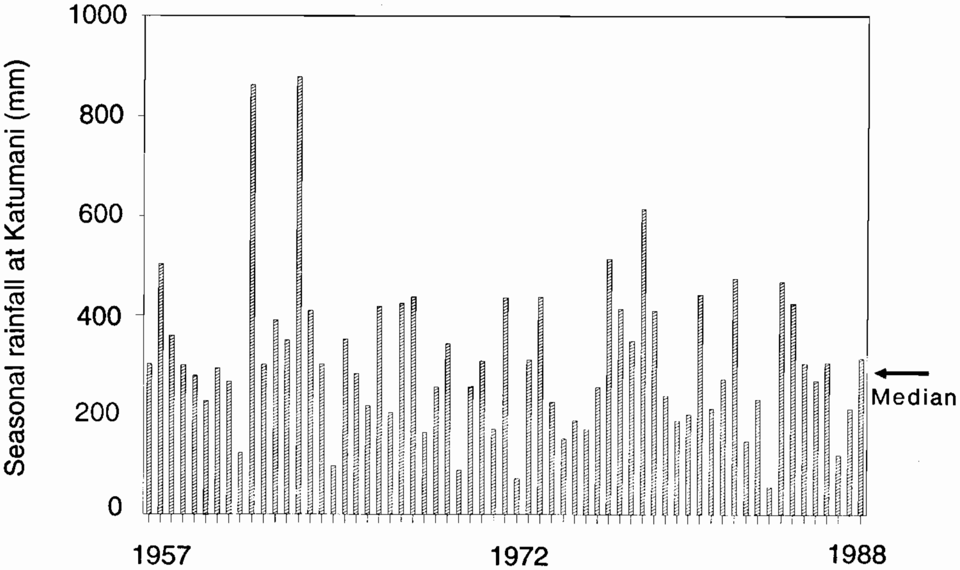

Fig. 1. The variation in seasonal rainfall at Katumani Research Station over the 1957 to 1988 period. Seasonal rainfall is defined as the period from onset to physiological maturity of KCB maize: approximately 110–130 days.

programs that focus on one factor, without considering the impact of the other, are prone to be, at best, equivocal and, at worst, dangerously misleading. Some examples of this follow.

Plant population. Three seasons of plant population studies were reported by Nadar (1984). Both the 1978 short rains (SR) and 1982 (SR) were wetter than average seasons and strong positive responses to increasing plant population were recorded in maize, with optima in the range 7–8 plants/m^2 (Fig. 2). Rainfall in the 1982 long rains (LR) was only slightly below average, but negative responses to increasing plant population were recorded in that season, with optima in the range 1–2 plants/m^2 (Fig. 2). Such variability in results from one season to the next presents a major problem for interpretation. The absence of any assessment of the interactive effects of nitrogen supply and plant population limits the value of this work for farmers' circumstances, where nitrogen is generally limiting. Subsequent investigations (Watiki and Keating, unpublished data) have shown that optimum plant population in maize in this region is strongly influenced by nitrogen supply as well as water supply.

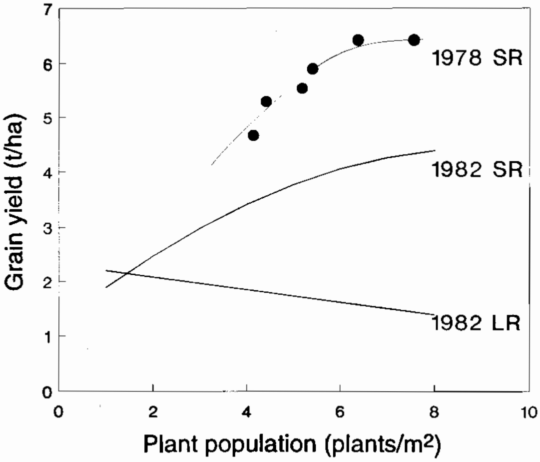

Fig. 2. Responses to plant population in maize for two wetter-than-average seasons (1978SR — 550 mm and 1982SR — 460 mm) and a drier-than-average season (1982LR — 245 mm) at Katumani (after Nadar 1984a).

Genotype. A comparison of the early-flowering Taboran maize with the traditional later-flowering Local Machakos White material was reported by Dowker (1971). Over the eight seasons studied from 1957 to 1961 at Katumani, earliness was an advantage in only two seasons, made no difference in another three seasons and was a disadvantage in three seasons (Fig. 3). Based on these results alone, the scientists of the day could have been forgiven for not pursuing the breeding program for earliness. Fortunately, they did continue and this program led to the highly successful Katumani Composite germplasm. The importance of rainfall distribution within a season in relation to crop development can be appreciated by comparing the results for the 1959 and 1960 long rains (Fig. 3). Seasonal rainfall totals were similar in both seasons, but the early-flowering Taboran maize was inferior in 1959 and greatly superior to the late-flowering Local Machakos White in 1960. A closer examination of rainfall patterns in relation to the date of silking of each cultivar (Fig. 4) reveals that, despite the similarity in the total rainfall received during each growing season, the timing and distribution in 1960 was less favourable for the longer maturity type.

Nitrogen. The extreme year-to-year variability in response to fertiliser nitrogen is well illustrated in the work of Nadar 1984a (Fig. 5). All Nadar's results came from the same site, while the work of Okalebo (1987) shows that there is also great site-to-site variation (Fig. 6). Such results make the task of formulating simple recommendations for farmers almost impossible. Determining the appropriate rates of fertiliser application requires some means of quantifying crop responses in terms of climate and soil parameters (especially the nitrogen supply available to the crop).

Intercropping. Similar problems have beset the intercropping research conducted in the region over the years. In general, maize–grain legume mixtures gave higher combined yields in wet seasons and lower combined yields than sole-crops in drier seasons (Ashley 1984; Nadar 1984b). The situation is more complex with intercrops than with sole-crops because of the host of variables that can influence yield in such situations. The populations of each of the component crops and their spatial arrangement, together with the nitrogen status of the soil and rate of nitrogen fertilisation, can all be expected to interact strongly with the pattern of rainfall in determining yield in cereal–legume intercrops. In many situations, the experiments have not been conducted in such a way that it is possible to distinguish between a true response to intercropping and response to the higher population in the intercrop. Little of the intercropping research has considered the impact of limited nitrogen supply, which is likely to dominate the performance of the mixture of a cereal and N-fixing legume. The 'riskiness' associated with intercrops in experimental situations under adequate N supply, probably does not apply under the N-limiting conditions which generally characterise farmers' fields.

Rotations. The problem of rainfall variability in research for semi-arid tropical environments is also well illustrated by the fallowing studies of Whiteman (1981). In one series

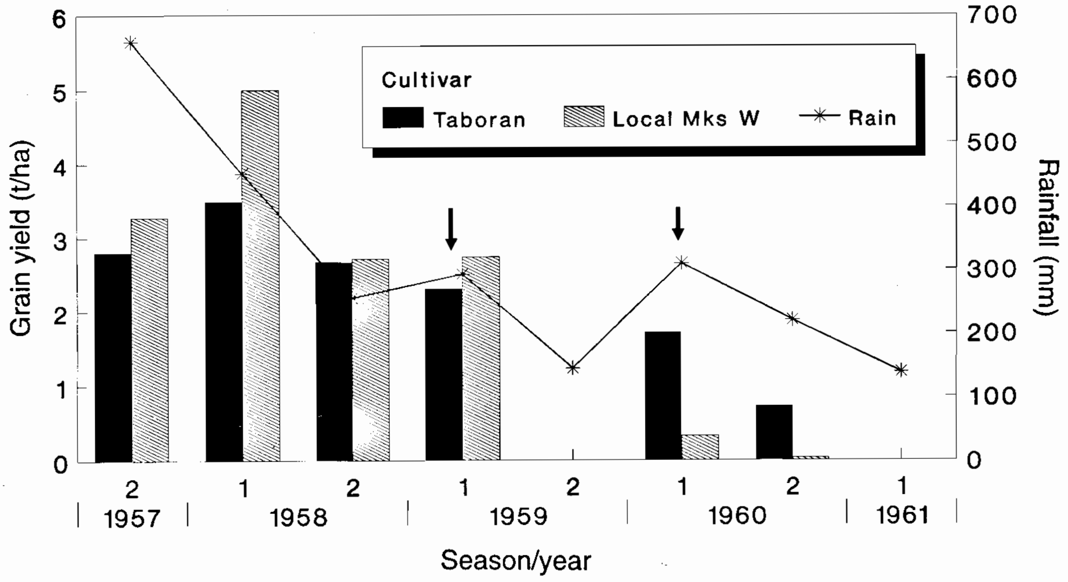

Fig. 3. Grain yield of Taboran (early flowering) and Local Machakos White (late flowering) maize over the 1957 to 1961 period at Katumani. Seasonal rainfall is also shown (after Dowker 1971). See text for explanation of arrows.

of experiments, the sorghum yield produced after a bare fallow exceeded that produced from two continuous crops without a fallow (Table 3). In the next series, lower yields were produced after fallowing relative to continuous cropping (Table 3). The explanation for these different outcomes can be found in the rainfall data. In series 1, large benefits of fallowing occurred when a dry season followed a wet season (i.e. enhanced water supply due to fallowing), while the negative effects of fallowing in series 2 occurred when a dry fallow-season was followed by a wet cropping-season. The problems that rainfall variability creates in the interpretation of experimental results increase manyfold when carryover effects within sequences of seasons are considered.

Table 3. Yields of continuous crops and crops after bare fallows reported by Whiteman (1981) for sorghum following sorghum (Series 1) and sorghum following maize (Series 2).

Series	Season	Crop	Grain yield (kg/ha) Cropped	Fallowed
1	1980 LR	sorghum	694	–
1	1980 SR	sorghum	320	1720
2	1980 SR	maize	46	–
2	1981 LR	sorghum	4122	3694

Strategies Used to Deal with Complexity and Variability

Many researchers have failed to deal adequately with the problems associated with rainfall variability. Trials have been, and continue to be, reported without provision of the vital information needed to interpret the results in the broader context. While quantitative tools may not have been available, some information on the soil characteristics and the amount and pattern of rainfall is essential, even for qualitative interpretation. Likewise, trials in which, because of low rainfall, the crops yielded little or nothing should not have been left unreported or thought of as failures. In some respects, they provide data of special interest.

Where efforts have been made to deal with the complexity and variability inherent in semi-arid farming systems, three approaches can be distinguished.

(1) Some authors have reported the basic climatic and soil data relevant to their trial (with varying degrees of adequacy) and attempted to qualitatively interpret their results in the light of these data. Examples include the work of Dowker (1964), Bennison and Evans (1968), Semb and Garberg (1969), Fisher (1977a,b), Ashley (1984), Nadar (1984a) (although soil data are limited) and Njoroge (1985).

(2) Other authors have attempted to build quantitative

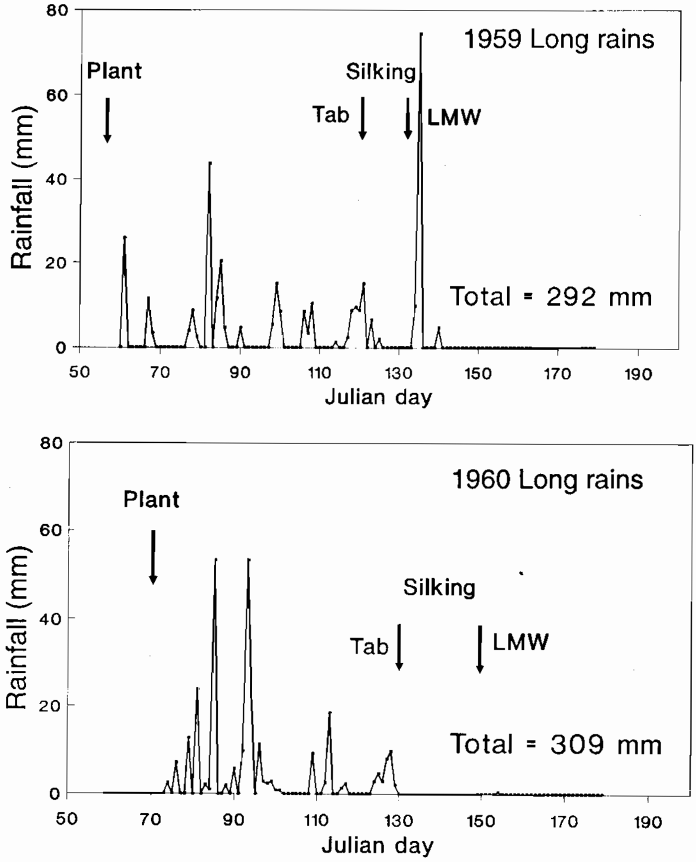

Fig. 4. Daily rainfall distribution at Katumani over the 1959 and 1960 long rains seasons in relation to estimates of planting, silking and harvest dates for Taboran (TAB) and Local Machakos White (LMW) (adapted from Dowker 1971).

models of the systems or responses they were studying and use such models to interpret their results. Such model building is not a recent phenomena, but can be traced back at least as far as Glover (1957) who related maize yield data collected over the 1943–1953 period to rainfall in the Kenya highlands (Fig. 7). Refinements to this basic approach appeared over the years with rainfall being replaced by evapo-transpiration (Lenga and Stewart 1982; Mugah and Stewart 1982) or some other estimate of 'effective rainfall' (e.g. Stewart and Faught 1984) (Fig. 8).

Dagg (1965) developed a more elaborate water balance model from what he referred to as 'first principles' and used it to analyse the supply and demand for water by a maize crop grown at Muguga in 1963. The supply term was determined by rainfall, soil depth and soil water-holding characteristics and rooting depth. The demand term was a function of potential evaporation and the pattern of crop water use as a fraction of this potential evaporation. The model was stochastic in the sense that it used the 70% monthly rainfall probability as an input and dynamic in the sense that it operated a crop and soil water balance on a monthly or 10-day time step. It was proposed as a 'rational approach to the selection of crops for areas of marginal rainfall'. Such developments in Kenya in the early sixties were in the forefront of progress world-wide in this field. It is of interest to note that similar work was under way at Katherine, in semi-arid northern Australia only a few years earlier (Slatyer 1960).

(3) In a limited number of cases, quantitative models were used in conjunction with the historical weather information to extrapolate from the period when the work was done to the longer period covered by the historical weather record. Dowker (1963a, 1971)

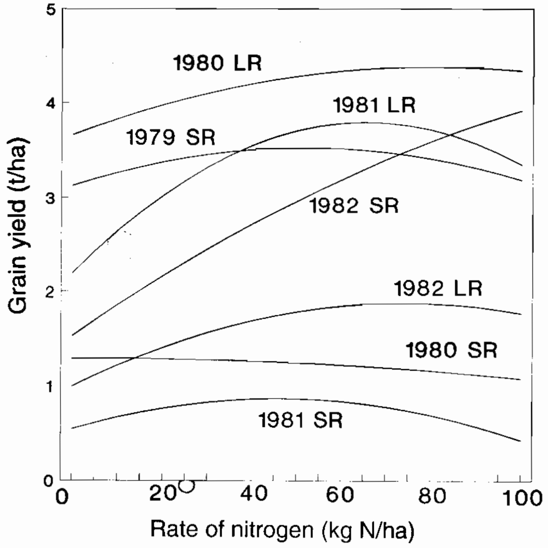

Fig. 5. Response of maize grain yield to nitrogen fertiliser at Katumani over the 1979 to 1982 period (after Nadar 1984).

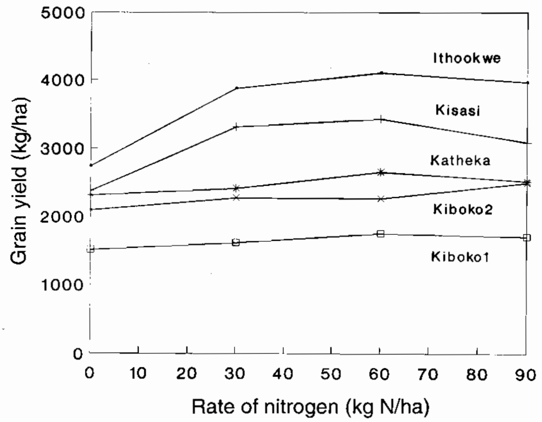

Fig. 6. Response of maize grain yield to nitrogen fertiliser at a range of sites in the short rains of 1981 (after Okalebo 1987).

provided an early example of this approach in Kenya, when he reported work done at Katumani from 1957 to 1961. This report combined historical weather data (rainfall probabilities for Potha Estate near Katumani) with simple regression models of maize yield on rainfall (Fig. 9), for two cultivars differing in maturity characteristics and for two plant populations. Dowker was able to estimate and compare the risks associated with growing the traditional cultivar [Local Machakos White] and an early maturing cultivar [Taboran —

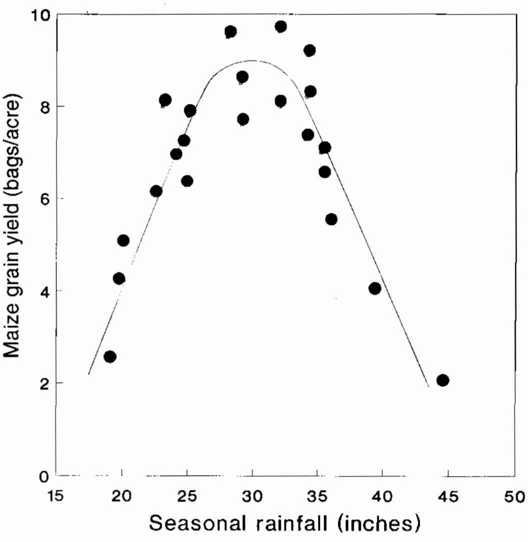

Fig. 7. The relationship between maize yield in Western Kenya and rainfall over the 1943 to 1953 period (after Glover 1957).

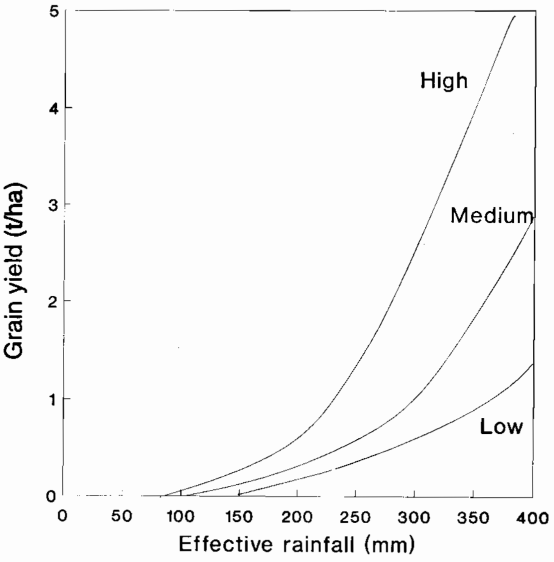

Fig. 8. The relationships between the yield of maize grain (KCB) and estimates of effective rainfall (mm) for different levels of fertility and management (after Stewart and Faught 1984).

which later went on to become the source of earliness in Katumani Composite B (KCB)]. In later years, Whiteman (1981) used a similar approach to estimate how often fallowing would be beneficial for maize

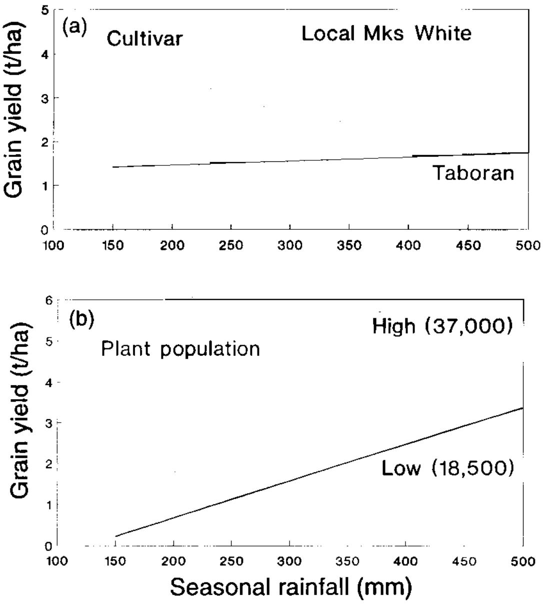

Fig. 9. Regression models of maize grain yield on seasonal rainfall for (a) two cultivars and (b) two plant populations developed by Dowker (1971).

and sorghum production and Stewart and Faught (1984) used 54 seasons of Katumani weather data to estimate average returns from maize and bean production with different forms and levels of inputs.

The linking of crop yield–rainfall models with historical weather data was a major advance over the traditional approach of assessing new technologies on the basis of weather in the years in which they were tested. Examination of the variability of the rainfall record at Katumani (Fig. 1), which is typical of the variability elsewhere in the region, indicates how inadequate this traditional approach was.

While the work of J.I. Stewart and his colleagues did not advance basic modelling capabilities (his models were essentially based on seasonal rainfall as were those of Glover in 1955), his work was unique in one respect. For the first time in Kenya, research focused on the problem of rainfall variability and attempted to deal with it tactically by adapting within-season management to perceived season potential. While others had been concerned with rainfall variability or reliability, as it was often referred to in the literature, their approach had always been to attempt to stabilise production. In contrast, Stewart sought to maximise the potential of individual seasons.

Discussion

While considerable progress had been made with the simple empirical models of yield and rainfall, a major problem existed with models based on seasonal time steps and this was recognised by many authors. Such models cannot deal with the important impact that within-season rainfall distribution has on crop growth and yield. Likewise, such models can deal only empirically with a change in management, cultivar, population, soil type etc. by fitting another regression curve.

Over the 1955 to 1985 period, the most advanced water balance model used in Kenya was that of Dagg (1965). While many new relationships were subsequently developed for specific circumstances, progress in developing the basic modelling tools (i.e. the underlying water and nitrogen balances) did not advance much past that pioneering work. However, elsewhere in the world, advances were made, particularly over the period 1975–1985. The models developed by Netherlands and U.S. groups (e.g. Texas for the CERES models, Kansas for SORGF, Florida for the grain legume models, SOYGRO, PNUTGRO, etc.), overcame many of the objections to seasonal or monthly models by using daily time steps. The models were also much more comprehensive than those previously available and, through contributions from the Wageningen and IFDC-Alabama groups, nitrogen was considered for the first time.

The ACIAR project commenced in Kenya in 1984–85. While modelling was not given a high priority in the initial proposals, once the magnitude of the problem that rainfall variability posed for both farmers and research was recognised, a modelling capability became a focus of the research.

Conclusions

Research for Kenya's semi-arid cropping lands can be largely interpreted in terms of management effects on the water and nitrogen balance.

A common problem that links most of the research papers and reports written over the 1955–1985 period was the difficulty of interpreting research results which varied greatly in response to the amount and distribution of rainfall. Difficulties in interpreting site to site variability in results was also a problem, because of both soils and weather influences.

Many authors attempted to deal with the problems of complexity and variability by building models. This was an appropriate response which dates back as far as Glover's work in 1957, the data for which were collected from 1943 to 1953. Hence, modelling is not a new activity in Kenyan agricultural research. A few researchers, starting with Dowker in 1971, have tried to link their models to historical weather information and this is seen as a very powerful technique.

Models developed and applied in Kenya to date have been limited by:

- their basis on empirical regressions which are site and season specific; and
- the fact that they consider only one or a few factors.

As a result, they are not well suited to comparative studies of system constraints or analysis of prospects for technical innovations.

Continued progress will depend on the availability of robust quantitative models which take into account the complexity and variability of these systems.

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Development of a Modelling Capability for Maize in Semi-arid Eastern Kenya

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THE place for models in the conduct of agricultural research under variable climates is discussed by Keating et al. elsewhere in these proceedings. Models that relate crop growth to climate, soil, genotype and management factors can assist in the evaluation of strategies for enhancing crop productivity under variable climates. To be a useful tool, a model needs to provide acceptably accurate estimates of crop growth and yield in relation to the major factors which determine productivity. In this paper, we report on research carried out in semi-arid eastern Kenya over the period 1985–89, aimed at developing a capability to model maize growth and yield in relation to the major soil, management and climatic constraints.

Choice of Model

Maize is the preferred cereal in the region (Rukandema 1984) and it dominates the farming system. Hence, we chose to examine the prospects for modelling maize growth and yield. While intercropping of maize with grain legumes is common, lack of suitable intercropping models precluded examination of such systems. Crop production is almost entirely rainfed and the rainfall regime is highly variable and often limiting (Downing et al. 1987). When not constrained by water deficits, the most common constraint appears to be nitrogen supply. It was thus essential that the chosen model be capable of dealing with both water and nitrogen constraints and their interaction with management in the most effective way. The analysis of previous research in the region (Keating et al., these proceedings) highlights the importance of the within-season distribution of rainfall in relation to the timing of crop development. Hence, it was also clear that a dynamic model was required and a daily time step was the most appropriate, given that the majority of climate data is available on this basis. CERES–Maize was the only model that met these selection criteria.

Model Description

CERES–Maize was originally developed by the Agricultural Research Service of the United States Department of Agriculture at Temple, Texas. The model and its components have been documented elsewhere (Godwin et al. 1984; Jones et al. 1984; Ritchie 1984; Jones and Kiniry 1986). Briefly, CERES–Maize is a model that simulates maize growth and yield in relation to climate, soil, genotype and management inputs. The routines used to estimate phenology and growth under non-limiting moisture and soil fertility regimes form the central core of the model. The model estimates soil water and nitrogen status and this information is used to modify growth under sub-optimal conditions. Major inputs and outputs to the model are summarised in Table 1.

Model Testing — Development of the Database

Whilst research on maize had been conducted in the eastern Kenya region for more than 30 years, the data available were not generally suitable for testing CERES–Maize. Incomplete reporting of management or location data, combined with difficulties in obtaining weather data and the general absence of any detailed soil characterisation, were frequent problems. We therefore embarked on an experimental program in 1985 to build up the necessary datasets.

Experiment 1 was conducted in the 'short rains' of 1985–86 at Katumani Research Station (lat. 1°35' S, long. 37°14' E, altitude 1601 m) on a Chromic Luvisol (Gicheru and Ita 1987). The composite maize cultivar, Katumani Composite B (KCB), was sown at the times shown in Table 2. Plant population, N fertiliser and irrigation treatments imposed are also shown. Replicates are modelled separately in this experiment since they differed slightly in the established plant population, the depth of soil (a stone layer that varied in depth from 110 to 190 cm restricted rooting depth) and, in the case of irrigated treatments, the timing and quantity of applied water. The degree of water limitation experienced by the

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Table 1. The CERES–Maize model

(a) Major inputs

Factor	Inputs
Climate	Maximum temp. (daily) Minimum temp. (daily) Rainfall (daily) Solar radiation (daily) Mean annual air temperature Difference between the highest and lowest mean monthly air temperature
Irrigation	Amount (mm) applied on any day
Soil	Saturated soil water content Drained upper limit soil water content Lower limit of plant extractable water Layer thickness and bulk density Runoff curve number Root distribution weighing factors for each layer Whole profile drainage rate coefficient Stage 1 soil evaporation coefficient Soil albedo Organic carbon concentration (%) Soil water at start of simulation Mineral NO_3–N and NH_4-N concentrations at start of simulation
Genotype	Heat units from emergence to end of juvenile phase Photoperiod sensitivity coefficient Heat units from silking to physiological maturity Potential kernel number Potential kernel growth rate
Management	Sowing date Plant population Sowing depth
Location	Latitude
Residues	Surface residue weight and C:N ratio Depth of incorporation of surface residues Root dry weight of previous crop Root C:N ratio
Fertilisers	Fertilisation dates Fertiliser type, amount and depth

(b) Some outputs

Factor	Output
Phenology	Emergence date Tassel initiation date Silking date Physiological maturity date
Growth	Leaf number* Grain number per unit area Ear number per unit area Leaf area index* Leaf, stem, grain, root dry weight per plant* Biomass production* Grain yield per unit area* Root length extension*
Water	Soil water content* Soil evaporation* Plant transpiration* Potential evapotranspiration* Actual evapotranspiration* Runoff* Drainage out of profile* Water stress indices
Nitrogen	Grain nitrogen (%) Total plant nitrogen content Nitrogen stress indices Soil NO_3–N and NH_4-N concentrations* Immobilisation

* These outputs are available on a daily basis.

crops grown in this experiment ranged from none in the irrigated plots to strong water stress during grain filling for the late planted dryland crops. The corresponding grain yields ranged from 1600 to 8000 kg/ha.

Experiment 2 was conducted at Katumani during the short dry season (December to March) in 1985–86. This experiment consisted of two plant density levels grown at a range of water regimes achieved with a line-source irrigation installation. Crops in this experiment generally experienced strong water stress around the silking period and grain yields ranged from 0 to 3300 kg/ha depending on the severity of this stress.

Experiment 3 was conducted at Kiboko Research Station, Kenya (lat. 2°13' S, long. 37°43'E , alt. 915 m) on a Ferric Luvisol (Siderius and Muchena 1977) during the short rains of 1986–87. Kiboko (997 m) is lower in altitude than Katumani (1601 m) and therefore warmer (mean annual air temperature of 23.5°C compared with 19.5°C at Katumani). This experiment was similar in design to experiment 1 except that a second cultivar, Dryland Composite (DLC), was included (Table 2). Grain yield ranged from 1370 to 6160 kg/ha.

Experiment 4 was conducted at Katumani during the short rains of 1986–87. The experiment explored the interaction between plant population (varied over the range 0.88 to 8.88 plants per m^2 in a systematic design) and water regime (early-planted, irrigated compared to late-planted, non-irrigated). Two cultivars were studied (Table 2) and grain yields ranged from approximately 1500 to 8000 kg/ha in the wet treatment and 1200 to 3000 kg/ha in the dry treatment.

Experiment 5 was initially designed to investigate the plant density by nitrogen interaction, with variation in water regime being achieved by early and late planting (Table 2). It was conducted on a Chromic Luvisol at Katumani during the 1987 short rains. Poor early season rainfall meant that all plants from both planting dates were dead or close to death by the end of December 1987. Rain in January 1988 did not lead to significant recovery. Grain yield was zero for all treatments and biomass yield ranged from 10 to 150 kg/ha.

Experiment 6 was a repeat of experiment 5 (plant population and nitrogen supply interaction) in the long rains of 1988, at two sites, Katumani and Kiboko. Treatments consisted of factorial combinations of 2 nitrogen fertiliser rates (0 and 120 kg N per ha) and 5 plant populations over the 1.1 to 7.4 plants per m^2 range. The trial was rainfed at Katumani and fully irrigated at Kiboko. Yields increased from 2000 to 5400 kg grain per ha and 1000 to 6000 kg grain per ha at Katumani and Kiboko, respectively. In both cases, strong N × plant population interactions were observed.

Experiment 7 commenced in the short rains of 1988–89 (expt. 7a) at both Katumani and Kiboko. Response to rate of N fertiliser (over the range 0 to 160 kg N per ha) was examined. In the long rains of 1989 (expt 7b) the residual value of fertiliser applied in expt 7a was compared with fresh applications.

Table 2. The range of cultural treatments for maize crops grown to evaluate the CERES–Maize model.

Expt no.	Site	Sowing date(s)	Cultivars	Nitrogen treatments (kg N/ha)	Plant population (plants/m^2)	Seasonal rain (mm)	Irrigation (mm)
1	Katumani	29-10-85	KCB	0 and 80	2.0–6.5	255	6–176
	(Field C)	21-11-85	KCB	–	2.0–6.5	227	0
2	Katumani (Field C)	18-12-85	KCB	–	2.1–6.8	127	11–222
3	Kiboko	12-11-86	KCB, DLC	–	2.1–6.7	219	50–200
	Kiboko	26-11-86	KCB, DLC	–	2.1–6.7	167	50
4	Katumani	3-11-86	KCB, DLC	–	0.88–8.88	337	104
		20-11-86				303	0
5	Katumani	9-11-87	KCB	–	1.1– 6.3	79	0
	Katumani (both Field E)	27-11-87	KCB	–	1.1– 6.3	12	0
6	Katumani	25-3-88	KCB	0 and 120	1.1–7.4	310	0
	Kiboko	8-4-88	KCB	0 and 120	1.1–7.4	124	375
7a	Katumani	27-10-88	KCB	0, 20, 40, 80, 160	4.4	427	0
	Kiboko	11-11-88		0, 20, 40, 80, 160		332	0
7b*	Katumani	1-4-89	KCB	0, 20,40, 80, 160	4.4	227	0
	Kiboko	31-3-89		0, 20, 40, 80, 160		319	52
8	Wamunyu (Kyengo farm)	1-11-88	KCB	0, 20, 40, 80, 160	2.9 to 3.7	491	0

* Fertiliser treatments include a comparison of fresh and residual sources.

Experiment 8 examined the response to fertiliser N (5 rates from 0 to 160 kg N per ha) under farmer management. The experiment was conducted in the short rains of 1988 on the farm of Mama Kyengo, near Wamunyu (lat. 1°25' S, long 37°34'E, altitude 1190 m). The soil was a Haplic Alisol (Aore and Gatahi 1990). The terrace was planted by the farmer and subsequently managed by him. Fertiliser treatments were applied as 30 m long strips, banded beside the young maize plants, randomised across a terrace and replicate three times. Rainfall was recorded on the farm and soil mineral nitrogen monitored.

A total of 159 datasets was available from these eight experiments. One hundred and seventeen came from the cooler Katumani location, 37 from the warmer Kiboko site and 5 from the Kyengo farm site which is at an intermediate altitude. Forty-two relate to maize grown at low plant densities (2.2 plants per m^2 or lower), 46 were grown at high plant densities (above 6.6 plants per m^2) and the remainder at intermediate plant populations. The majority (129) of the data are from the cultivar KCB, while 30 feature the cultivar DLC. Forty-eight of the crops were grown under favourable water regimes using supplementary irrigation, whilst the remaining crops experienced a degree of water stress ranging from mild to severe. Zero yield was recorded in eight of the data sets when the crops died due to extreme water stress prior to silking. Fertiliser was supplied such that nitrogen was not a constraint in 114 of the datasets and no or low rates of fertiliser-N were used to achieve nitrogen deficits in the remainder of the database.

All grain yields reported in this paper are expressed at 15.5% moisture content. Times to silking and physiological maturity (blacklayer formation) were measured from emergence.

Model Adaptation

We commenced this work with a visual-interactive version of CERES–Maize v.1 (Hargreaves and McCown 1988). This version is compatible with both the original standard and nitrogen versions (Jones and Kiniry 1986), but which features operational enhancements which facilitate interactive use of the model.

While performance of the original model was reasonable, a number of revisions were made to deal with problems encountered during its application in Kenya. In addition, problems identified and enhancements made in the maize modelling program in northern Australia (Carberry et al., these proceedings) were applied in Kenya. The scope of the model in use in Kenya was also broadened to allow more realistic simulation of both fixed and tactical management options.

Modifications

The severity of the water deficits encountered in the region under study were so great that crops actually died (e.g. expt 5). The original model would not simulate crop death, but allowed severely stressed crops to remain in 'suspended animation'. If rain was received later in the vegetative growth period, the simulated crops recommenced growth, and low, but significant, yields could be achieved. In reality, such crops were dead and the farmer would have considered re-sowing on the late rain. Routines were introduced which killed crops in response to an accumulated index of water deficit during the early- to mid-vegetative growth period.

Silking was found to be delayed by severe water or nitrogen stress, and changes were made to the model to simulate such delays. A number of other changes were made which we felt improved model integrity or had conceptual advantages. For example, the method used to simulate leaf area was modified to better account for the relationships between total leaf number and leaf area (Keating and Wafula 1991), and the capacity to simulate multiple cobs per plant was added. The temperature optimum used in the thermal time calculation (34°C) was found to be too high, leading to an overprediction of development rates when the model was tested under warmer temperatures (Lenga and Keating 1992). This was corrected by invoking a plateau in the development rate versus temperature curve between 28 and 34°C.

Problems were encountered when simulation was extended from one rainy season, over a long dry season, and into a second rainy season (e.g. when simulating the residual fertiliser effects in expt 7). Mineral-N during the early weeks of the second rainy season was underestimated. While the precise reasons for this remain uncertain, changes were made to the nitrogen mineralisation routines to better reflect the flush of mineral nitrogen that appears in soils of the region after prolonged dry periods.

Enhancements

Planting date was an input in the original model, fixed for any particular crop being simulated. This was unrealistic in this region where farmers plant in response to what they perceive as the onset of the rainy season. Routines were introduced which allow the user to define criteria for season onset in terms of the length, pattern and quantity of rain needed to initiate a planting opportunity. Related routines allow for replant options should a crop emerge but fail to survive during an onset window.

Management information such as plant population and fertiliser rate were also fixed inputs for a particular crop being simulated in the original model. Enhancements were made which allowed these inputs to be conditional on the timing of onset of the season. For instance, if the rains started and sowing took place before a nominated date, high plant populations and fertiliser N could be set. If the rains started late, the simulation could be set up to use low plant populations and not apply fertiliser. Opportunities were also made for within-season management (fertiliser side-dressings, thinning) to be conditional on the timing and quantity of early-season rain. This capability to deal with conditional management strategies meant that strategies such as response farming (Stewart and Faught 1984; see also Wafula et al., these proceedings) could be simulated.

The adapted model is referred to as CM–KEN.

Model Performance

All Data

The model validation dataset contained information from 159 crop/treatment combinations, with yields ranging from 0 to 8000 kg/ha in response to variation in sowing date, water, nitrogen, plant population and climatic conditions (Table 2). The line of best fit between predicted and observed grain yield (Fig. 1) was close to the 1:1 line (slope (s.e.) = 0.94 (0.03) and intercept (s.e.) = 249 (103)) and coefficient of determination (r^2) was 0.88, with a root mean squared deviation (RMSD) of 689 kg/ha.

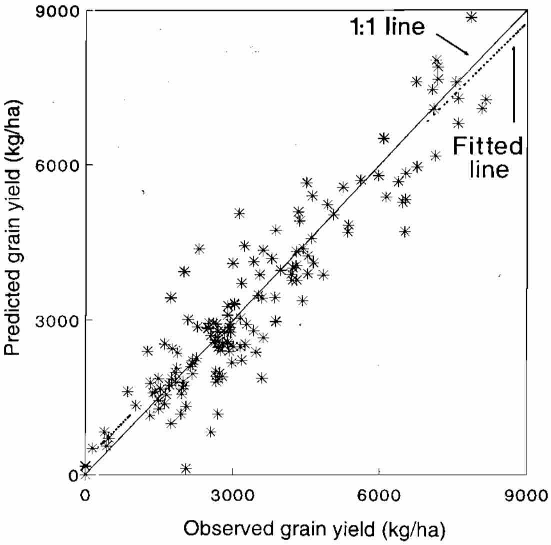

Fig. 1. Comparison of observed maize grain yield with that predicted by CM–KEN. Solid line is 1:1; the fitted (broken) line has slope (s.e.) = 0.94 (0.03); intercept (s.e.) = 249 (103), r^2 = 0.88, n = 159.

Plant Population Responses

Experiment 4 provided a large dataset to test the model's capacity to simulate the response of maize yield to plant population, under both favourable and limiting water regimes. The experimental data show that when water was freely available (441 mm over the season), yields increased from approximately 1500 to 7000 kg/ha as plant population was raised from 0.88 to 8.88 plants per m^2. When water was limiting (303 mm over the season), yields peaked at approximately 2800 kg/ha and stayed steady (DLC) or declined (KCB) as plant populations were raised above 3.7 plants per m^2. This strong water × plant population interaction was accurately simulated (RMSD = 549 kg/ha) by CM–KEN for both the KCB and DLC cultivars (Fig. 2).

Experiment 6 investigated the interaction between plant population and nitrogen supply. As was the case for water, the interaction was strong. Grain yields increased in response to increased plant population in the presence of adequate nitrogen. Yields reached a plateau or declined as plant population was increased in the presence of a nitrogen constraint (Fig. 3). While the absolute precision of the predicted grain yields was not always good, the model was clearly capable of predicting the general nature of the plant population by nitrogen supply interaction (RMSD = 582 kg/ha).

N Rate Trials

The model slightly overestimated yields in the SR of 1988 at Katumani (Fig. 4). Yields were lower in the 1989-LR crops because of water stress and were well simulated. At Kiboko, the model underestimated the response to N in 1988-SR. Responses to freshly applied N fertiliser up to 80 kg N per ha were recorded at both sites in 1989-LR and these were accurately simulated (Fig. 4).

Fertiliser applied in 1988-SR at rates above 40 and 80 kg N per ha at Katumani and Kiboko, respectively, provided a residual benefit to 1989-LR crops. The model simulated residual effects although the predictions were not as accurate as was the case for fresh fertiliser applications in the same season.

RMSD for yield prediction within the 30 datasets collected in the N rate experiments (7a and 7b) was 665 kg/ha while observed yields ranged from 1500 to 7000 kg/ha (r^2 = 0.85, Slope(s.e.) = 1.2 (0.1), Intercept = 739 (362)).

N Response under Farmer Management

A strong response to nitrogen fertiliser was recorded in the trial that was located on Kyengo's farm (expt 8). CM–KEN overestimated the overall yield level in this trial, but accurately simulated the general magnitude of

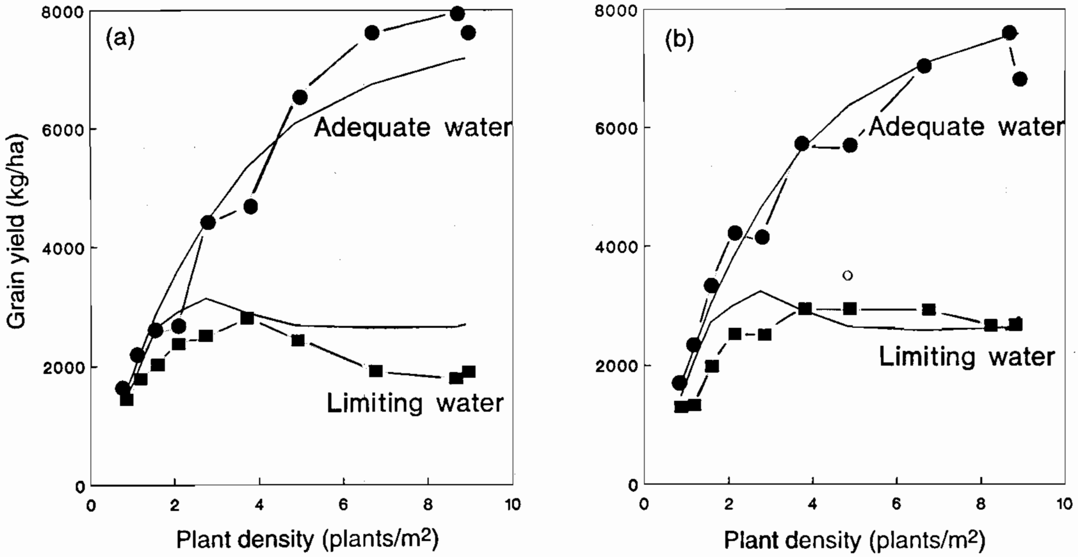

Fig. 2. Observed (symbols, broken lines) yields for maize under two water regimes (wet = circles, dry = squares) at a range of plant populations (Experiment 4). Yield predicted by CM–KEN is also shown (solid lines). Details of water regimes are given in Table 2.

(a) The cultivar Katumani Composite B (KCB).

(b) The cultivar Dryland Composite (DLC).

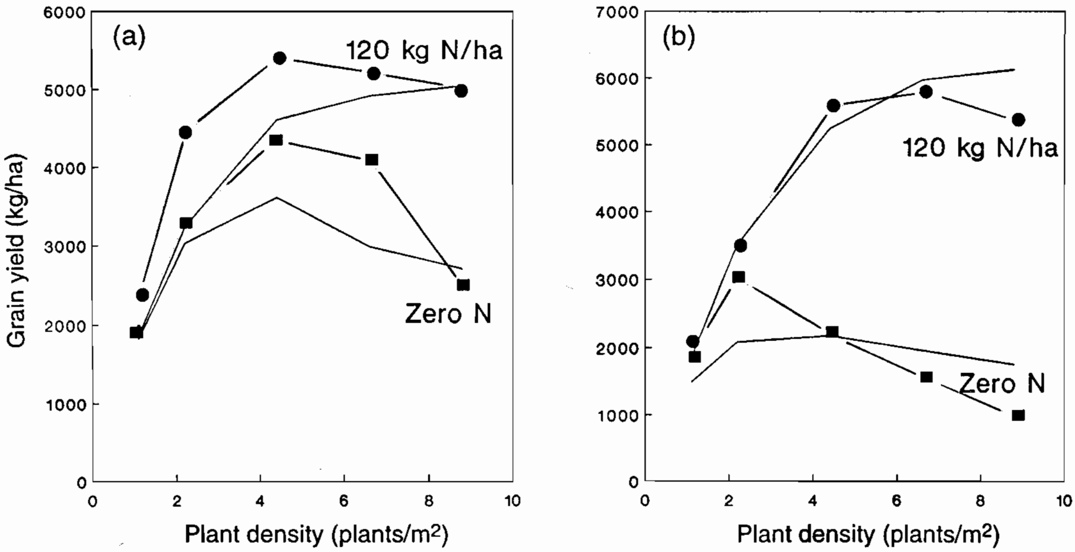

Fig. 3. Observed (symbols, broken lines) yields for maize under two nitrogen regimes (high N = circles, low N = squares) at a range of plant populations (Experiment 6). Yield predicted by CM–KEN is also shown (solid lines). Other details are given in Table 2.

(a) At Katumani – rainfed.

(b) At Kiboko under irrigation.

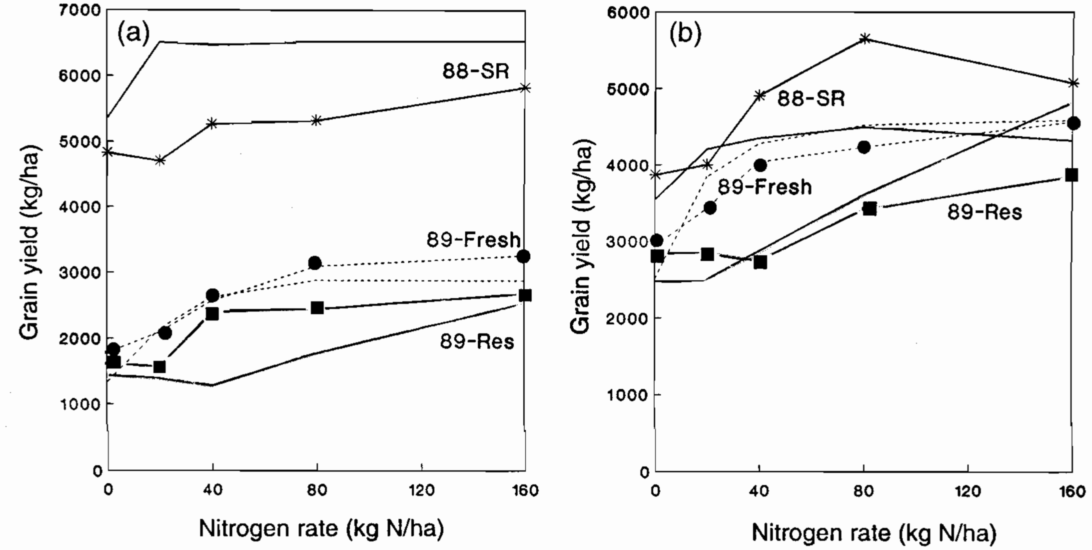

Fig. 4. Observed (symbols) yields for maize in relation to rate of nitrogen fertiliser (Experiment 7). Upper heavy solid line and * (fresh application in 1988-SR – expt 7a). Middle dashed line and round symbols (fresh application in 1989-LR). Lower solid line and square symbols (residual value of fertiliser in 1989-LR – expt 7b). Yield predicted by CM–KEN is also shown (corresponding lines without symbols).

(a) At Katumani – rainfed.

(b) At Kiboko.

the N response (Fig. 5). This trial was planted and managed by the farmer and the yield overestimation is thought to be the result of some constraint or management limitation not simulated within the model. The uniformity of the plant stand was much poorer on the farm than in other experimental situations. Gaps and multiple plants from the same planting position existed in this crop and may represent a yield limitation not considered within CM–KEN. While weeds were not a major problem in this crop, they were more frequent than in experimental crops and may have also constrained yields.

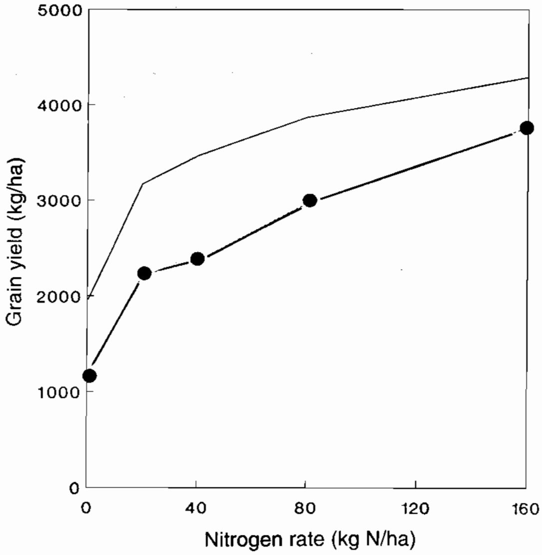

Fig. 5. Observed yields (symbols, lower line) for maize in response to nitrogen fertilisation on Kyengo's farm under farmer management (Experiment 8). Yield predicted by CM–KEN is also shown (upper line).

Discussion

This work has shown that CERES–Maize is capable of simulating maize growth and yield in relation to water, nitrogen and management controls in this environment. The modifications and enhancements made within CM–KEN build on the basic validity of CERES–Maize and make it a more useful tool for application in semi-arid Kenya. It is acknowledged that the changes made were based on limited data and may not have wider validity, but our objective in this work was to develop the best possible simulation within a defined region.

The general level of precision with which responses were simulated was better under water constraint than under nitrogen constraint. We believe this reflects, at least in part, the sensitivity of the model to initial soil N status and errors inherent in estimation of mineral-nitrogen in the soil profile under variable field conditions. Shortcomings in predicting nitrogen mineralisation will also contribute to errors in simulation.

The present model deals inadequately with longer-term changes in soil organic matter content, and does not simulate how soil properties change as a result of tillage and soil erosion. Neither does it attempt to deal with limitations imposed by weeds, pests, diseases or nutritional limitations other than nitrogen.

These limitations mean that the model is not suitable for the regional estimation of farm production, as many of these constraints will be operational, and suitable input data are unavailable on a regional scale. We believe it is best suited to the evaluation of alternative strategies to improve productivity or reduce risk. Under such circumstances, the assumption can be made that these other constraints (weeds, pests, diseases, etc.) must be overcome, prior to invoking the technical innovation under evaluation. The model is used in such a context in the final paper in these proceedings.

Acknowledgments

The contribution of J.N.G. Hargreaves to the programming of many of the operational enhancements contained within CM–KEN is acknowledged.

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Model Development in Northern Australia and Relevance to Kenya

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J.N.G. Hargreaves† and S. Nguluu§

IN 1978, a project was initiated by CSIRO to assess the feasibility of a new dryland cropping system in the semi-arid tropics (SAT) of northern Australia. The system centred on the use of no-tillage technology and the inclusion of legume leys into the cropping system (McCown et al. 1985; McCown 1989). This research in the Australian SAT led to the development of the KARI/ACIAR/CSIRO Dryland Project in the Kenyan SAT, the origins of which, its objectives and an overview of research undertaken are provided by McCown and Jones elsewhere in these proceedings.

Of consequence to the Australian research was the early recognition in the Kenyan project, firstly, of the overriding influence of climatic risk to dryland crop production and, consequently, that only through simulation techniques could this variability be readily quantified and options for reduction explored. This corresponded with a recognition in the Australian project of the need for models to assess the climatic and soil constraints to dryland cropping in northern Australia and to develop and evaluate cropping practices that reduce risks and costs. Research in both countries focused on developing this modelling capacity to simulate yield of maize crops in response to the important environmental constraints.

One benefit of developing models that can simulate soil and crop response to environment is their portability across regions. Innovations in model development in either northern Australia or Kenya that are relevant to the other location can be readily transferred. One of the goals of the Kenyan KARI/ACIAR/CSIRO Dryland Project was to conduct research in Australia to support and complement the research in Kenya and this goal has been well fulfilled. The objectives of this paper are to briefly describe research in model development as part of the Australian project and to specify the relevant links to research in the Kenyan project.

Environmental Constraints of Northern Australia and Relation to Kenya

The climate of the SAT of northern Australia is distinguished by a single annual cycle of wet and dry seasons, with potential for dryland cropping only within the monsoonal months of November to April. The rainfall distribution of Katherine (14°28'S, 132°18'E, 108 m) is unimodal with most rain falling between December and March (Fig. 1a). The cropping season in this region is dominated by high radiation load, extreme temperatures and consequent high evaporative demand which greatly reduces effective rainfall for dryland crop production (Williams et al. 1985). The high evaporative rates frequently result in periods of soil water deficit developing soon after rain during the crop's life. High air temperatures during crop development can reduce yields. Poor crop establishment, from rapid drying of the soil surface and either high soil temperatures or seedbed slaking, frequently results in crop failure in the low altitude SAT (Carberry and Abrecht 1991). The dominant cropping soils of northern Australia are the red earths, which nevertheless are generally of low fertility, low water- holding capacity and of poor structural stability (McCown et al. 1984; Williams et al. 1985). Under conventional tillage systems soil loss rates can be very high and this represents the major challenge to sustainable crop production.

Although the climate and soils of the northern Australian SAT have been shown to be very similar to regions of West Africa (McCown et al. 1984; Williams et al. 1985), environmental constraints of this region are similar to many of those in East Africa. As in Australia, soil constraints of low fertility, high runoff and erosion are characteristic of the Kenyan SAT (McCown et al. 1984). Cropping in the high altitude Kenyan SAT does not have to contend with injurious effects of high temperatures. Classification of regions of both Australia and Kenya as semi-arid is indicative of similar constraints due to their variable water environments. The bimodal distribution

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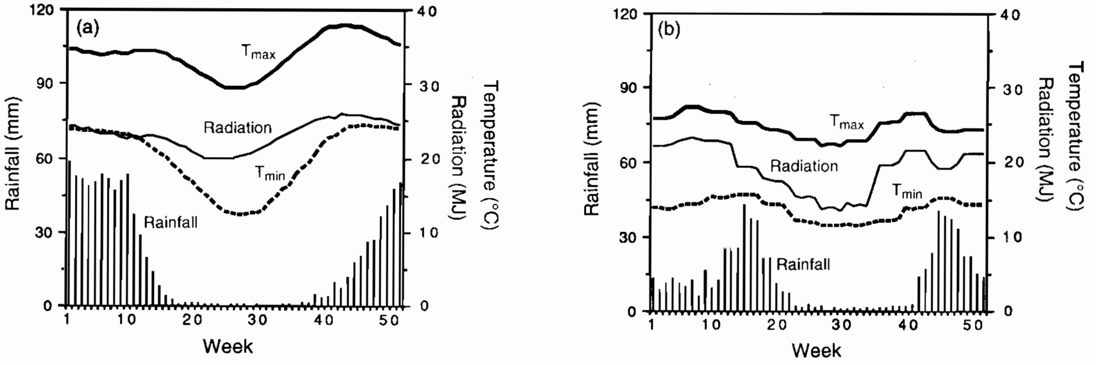

Fig. 1. Mean weekly rainfall, solar radiation, and maximum and minimum temperatures at (a) Katherine, Northern Territory, Australia (lat. 14°S; elev. 120 m; annual rainfall 871 mm); and (b) Machakos, Kenya (lat. 1°N; elev. 1600 m; annual rainfall 890 mm).

of rainfall at Machakos, Kenya (1°35'S, 37°14'E, 1601 m) (Fig. 1b) produces two cropping seasons each of approximately 110 to 120 days duration (Keating et al., Impact of climatic variability, these proceedings). Due to constraints on crop establishment at Katherine which delay sowing until mid-December (Carberry and Abrecht 1991), the cropping season is also very short, ranging from 90 to 110 days. Maize genotypes of similar short duration are therefore required in both regions.

A significant difference between the Australian and Kenyan SAT is the degree of cropping currently undertaken in each region. In Australia, there is minimal cropping in the SAT and research has concentrated on evaluating the potential for cropping given prevailing environmental constraints. In the Kenyan SAT, large populations rely on crop production for basic food requirements and hence lifting the current low yield potential of the region has been a basic goal of research.

Model Development

At the start of the project, existing maize models had been developed from research conducted under high input conditions in temperate agricultural systems. The environmental constraints of the SAT are often outside the domain in which these crop models have been developed. For this reason, this project has invested heavily in the modification and then validation of simulation tools which can be applied to the important constraints to cropping in both northern Australia and Kenya.

Model development in both Kenya and Australia commenced with the selection of the CERES–Maize simulation model, developed in North America to simulate the growth, development and yield of maize crops in response to climate, soil and management information (Jones and Kiniry 1986). Our approach in applying CERES–Maize to northern Australia has been to validate each component of the model, the three main processes being the simulation of maize physiology, the soil water balance, and the soil nitrogen dynamics. In this regard, the Australian project can be readily divided into research activities analogous with these model components.

Research in Australia also included enhancements to the original model, dealing with other crops and other processes. The effects on seedling establishment by altering the seedbed environment, the consideration of rotations or intercrops, the supply of phosphorus to crops, the inclusion of soil degradation by erosion and organic matter rundown, and the ability to interpret simulations by economic decision analysis were important additional requirements sought through research undertaken as part of the Australian project. This work has gone well beyond the simulation model of a maize crop and as such has been encapsulated into the cropping systems model AUSIM (McCown and Williams 1989). Consequently, recent focus of model development in Australia has been the AUSIM model and its application in operational research objectives (McCown 1989).

Crop Models

The initial testing and calibration of CERES–Maize to the Australian (Carberry et al. 1989) and Kenyan (Keating et al., Development of a modelling capability, these proceedings) SAT regions were undertaken through parallel yet independent research in both countries. Close collaboration between the two groups facilitated error detection and correction, and enabled development of innovations within the model to improve predictive capacity at both sites. The two groups collaborated on the development of an innovative procedure to better simulate leaf area development of crops based on the appearance, expansion and senescence of individual leaves of plants (Fig. 2) (Muchow and Carberry 1989,1990; Carberry

1991; Keating and Wafula 1992). Subsequently, however, emphasis in model development diverged, with work in Australia concentrating on crops other than maize and on the issue of poor crop establishment, whereas Kenyan work has concentrated on validating the nitrogen version of CERES–Maize.

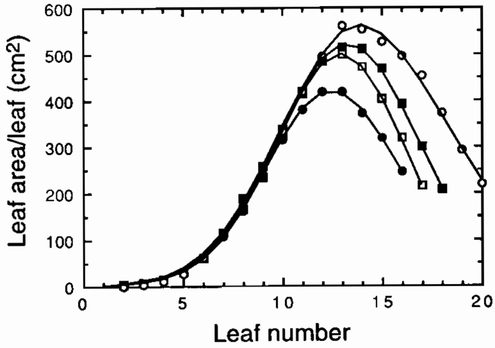

Fig. 2. Fully expanded area of individual leaves for sorghum plants with final leaf numbers of 16, 17, 18 and 20 leaves. The fitted relationship is of the form

$$Y = Y_0.\exp[a.(X - X_0)^2 + b.(X - X_0)^3]$$

where X_0, Y_0, a and b can be expressed as linear functions of final leaf number per plant (Muchow and Carberry 1990).

To date, simulation models of maize (Carberry et al. 1989; Carberry and Abrecht 1991), sorghum (Birch et al. 1990; Carberry and Abrecht 1991) and kenaf (Carberry and Muchow, unpublished data) have been developed and validated for use in northern Australia (Fig. 3). These models include enhancements to simulate the effect of soil water deficit on phenology, leaf development, and seedling mortality (Abrecht and Carberry 1992; Carberry and Abrecht 1991). The models predict maximum soil surface temperatures, and high soil temperature effects on crop establishment are simulated (Carberry and Abrecht 1991). Current research involves validation of the maize and sorghum models in subtropical Australia. The development of similar models for peanut, soybean and mungbean crops is also planned in recently initiated research.

The maize simulation model can be run for at least seven contrasting maize genotypes. The genotypes were parameterised from data collected at sites in northern Australia ranging in latitude from 13.8°S (Douglas Daly, N.T.) to 27.6°S (Gatton, Qld). Data on the Kenyan genotype, KCB, were collected at four of the sites (Table 1). Crop duration of KCB ranged from 85 to 115 days between sowing and maturity. Mean leaf numbers per plant of KCB ranged from 15.7 to 19.1, which indicated a significant photoperiodic response. The current Kenyan version of the maize model, CM-KEN, does not incorporate a photoperiodic response and so the Australian data will be used to this end. Also apparent was an effect of high air temperatures on grain numbers which is also unaccounted for by CM-KEN.

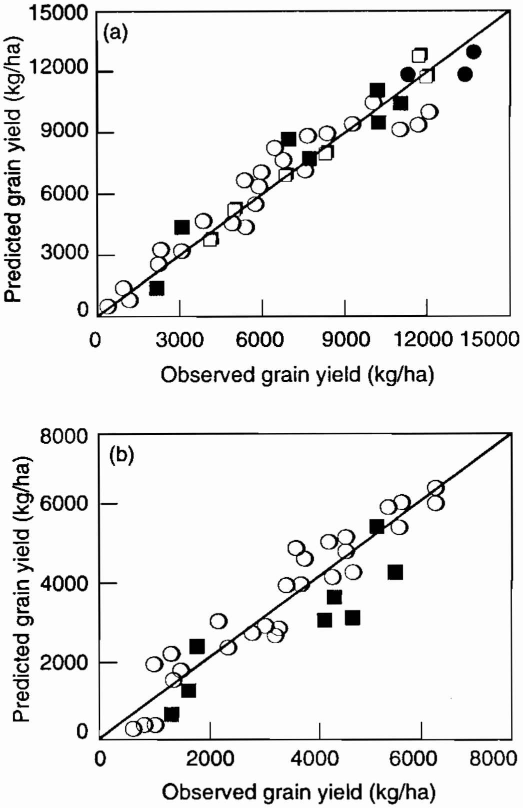

Fig. 3. Grain yields predicted by maize and sorghum simulation models versus observed oven-dry grain yields for a number of experiments: (a) maize; (b) sorghum. Key: ○ = Katherine; ▲ = N.T.; ☐ = W.A.; ● = S.E. Qld; ■ = N. Qld; —— = 1:1 line.

Soil Water Balance

The infiltration, drainage and runoff functions of the CERES–Maize WATBAL water balance have been evaluated against data collected in both Australia and Kenya (B.H. Wall, unpublished data). Several problem areas were identified in the simulation of soil water balance. For two soil profiles characterised by Jones and Kiniry (1986), CERES–Maize greatly underestimated drainage under saturated conditions as calculated using known values of saturated conductivity. When compared to data for bromide leaching for soils at Katherine (J.P. Dimes, unpublished data), the model adequately simulated

Table 1. Information on maize grown at four locations in northern Australia, giving latitude (°S), date of sowing, daylength (h) at 20 days after sowing, mean leaf number per plant and mean days from sowing to 50% silking for both the Kenyan KCB and Australian Dekalb XL82 genotypes.

Location	Latitude (°S)	Sowing date	Daylength (h)	Leaf number KCB	Leaf number XL82	Silking KCB	Silking XL82
Katherine	–14.5	23.12.88	13.7	17.9	18.9	46	48
Kununurra	–15.7	9.06.89	12.0	15.7	18.8	61	73
Walkamin	–17.1	19.12.88	13.9	16.1	17.0	56	60
Gatton	–27.6	8.11.88	14.5	19.1	20.7	60	62

drainage on a clay loam soil, but underestimated drainage on the sandy loam soil. In Kenya, simulations by CERES–Maize overestimated the amount of runoff measured for selected rainfall events at Katumani Research Station (Ulsaker and Kilewe 1984). Finally, CERES–Maize proved inadequate in simulating soil water balance of a thin surface layer (D.G. Abrecht, unpublished data), an important requirement for predicting surface soil temperatures and surface residue decomposition.

CERES–Maize employs separate empirical equations for each process in the soil water balance and, as such, a number of inadequacies have been identified. The USDA curve number system (USDA Soil Conservation Service 1972) is used to simulate runoff, and although it can be calibrated for overall estimation of seasonal runoff, it is less appropriate for runoff prediction of particular storms. CERES–Maize does not account for problems such as surface sealing and the influence of rainfall intensity of soil properties. Alternatively, the SWIM (Soil Water Infiltration and Movement) model, which numerically solves Richard's equation (Ross 1990), provides an improved, more physically based method for simulating the soil water balance.

The SWIM model has been implemented in AUSIM for use with both Australian and Kenyan crop models. SWIM has made redundant the routines by which CERES–Maize calculated soil evaporation, surface water runoff, drainage and nitrate leaching. In contrast to CERES–Maize, SWIM also permits the simulation of soil water in thin layers at the soil surface. The implementation of SWIM has been done such that minimal additional input information is required by AUSIM. This extra data can be readily derived from data collected in the same experiments as detailed for users of CERES–Maize. Consequently, users are no worse off by using SWIM but with the prospect of achieving better results by allowing for simulation of relevant management scenarios. For this reason, SWIM is currently being evaluated in comparison with CERES–Maize. Event-based data on rainfall, runoff and soil loss are being collected as part of the Kenyan project in order to test SWIM and to develop routines to simulate the processes of soil erosion (Okwach et al. 1991)

Another departure from CERES–Maize is the method of determining transpiration and root water uptake. In transferring CERES–Maize to a different environment or converting it to a different crop, the requirements for detailed root data have proved prohibitive. Alternatively, transpiration in Australian versions of the maize, sorghum and kenaf models is now calculated as a function of biomass accumulation, a transpiration efficiency coefficient, daily vapour pressure deficit and a 0–1 soil water deficit factor. The root-defined fraction of available soil water on a given day is determined from the ratio of available soil water in a simulated rooting zone to a maximum soil water deficit value, which increases as a function of time after sowing.

Soil Nitrogen and Phosphorus

To date, research on nitrogen supply to crops in Kenya has concentrated on validation of crop yield predictions of CERES–Maize under conditions of low soil fertility supplemented by different application regimes of nitrogen fertiliser (Keating et al. 1991c; Wafula et al., these proceedings). Research in Australia has complemented the Kenya work by concentrating on validation of the routines which simulate the soil-N dynamics, primarily the processes of N mineralisation, immobilisation and leaching. Such research is easier undertaken in Australia where access to ^{15}N labelled nitrogen and chemical analyses are routine. The initial testing of the nitrogen modules of CERES–Maize in Australia was undertaken under the no-till ley farming system proposed by McCown et al. (1985).

At Katherine, mineral-N supply under a bare fallow (Wetselaar 1962) or mineralisation following a grass pasture were generally well predicted by CERES–Maize, but prediction of mineral N after a legume pasture was underestimated (J.P. Dimes, unpublished data) (Table 2). Several other problems with the prediction of soil N by CERES–Maize were also identified. Mineral-N released deep in the soil profile was overestimated, there was insufficient sensitivity of mineralisation to variation in the soil water regime, and periods of low mineral-N supply due to high immobilisation were not well sim-

Table 2. Predicted and measured levels (kg/ha) of soil nitrate under three different residue systems.

System	Soil nitrate	
	Predicted	Measured
Bare fallow	111	124
	169	179
	222	236
Grass	61	62
Legume	102	149

Table 3. Determinants of mineral N supply following grass and legume pasture leys on two red earth soils at Katherine.

	Clay loam		Sandy loam	
	Grass	Legume	Grass	Legume
C:N ratio	59	22	80	32
Total N (0–20 cm)	2014	2014	681	690
Labile N pool	132	110	41	38
Root dry weight	10530	5690	4611	3914

ulated. Levels of nitrate leaching were generally underestimated, a problem that can be traced to the soil water balance of CERES–Maize. Inaccuracies in simulating water flux through the profile to deep drainage or in soil evaporation impact especially on the N balance. Finally, CERES–Maize simulates mineralisation of fresh organic matter incorporated into the soil but has no function for decomposition of residues situated on the soil surface — an obvious deficiency for simulating the no-till farming system at Katherine.

To address the problems identified in the N subroutines, several modifications have been made to CERES–Maize. The substitution of the SWIM water balance model in place of the CERES WATBAL subroutine has potential to improve simulation of nitrate leaching and decomposition of organic matter which is essentially water-driven in the biologically active and important surface layer. CERES–Maize simulates mineralisation from two main N pools, a humic pool and a pool of fresh organic matter. A third pool of potentially mineralisable N has been quantified for the system at Katherine (Table 3), and this labile pool is being added to the CERES mineralisation subroutines. Its importance was identified from Katherine data where, in the grass system, the supply of mineral N from the labile pool was immobilised by the demand for N associated with the decomposition of a large, N-poor root system. In contrast, for the legume system, demand for N associated with decomposition of a smaller and higher N content root system resulted in a substantially larger net mineral N supply (Table 2).

Using experimental results from ^{15}N labelled surface residues (J.P. Dimes, unpublished data), the mineralisation routines of CERES–Maize have been modified to account for decomposition of residues on the soil surface. Given residue amount and its C:N ratio, potential mineralisation calculated from the rate coefficients in CERES–Maize is modified by a water index and a contact factor to accurately simulate measured dry matter decomposition of surface residues (Fig. 4a). Whereas rates for organic N mineralisation mirror those for carbon decomposition in CERES–Maize, 37% of legume N and 18% of grass N was leached from surface residues in soluble form. When this leaching of soluble N was taken into account, the function for decomposition of surface residues successfully predicted N mineralisation from surface residues (Fig. 4b).

Phosphorus deficiency limits the productivity of legumes grown at Katherine in terms of total dry matter

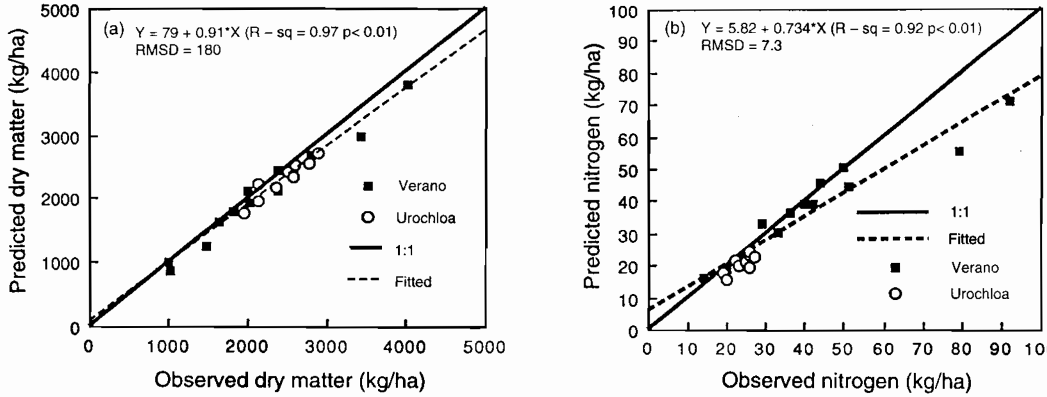

Fig. 4. Predicted versus observed recovery (kg/ha) of (a) dry matter, and (b) nitrogen from residues applied to the soil surface.

produced and biologically fixed N (S. Nguluu, unpublished data). This research project aims at quantifying the legume response to applied P, its influence on N-fixation and the resulting N supply from legume residues to following crops. Results will be employed in the development of a P submodel to be added to the crop models for application in both Australia and Kenya (cf. Probert and Okalebo, these proceedings).

The AUSIM Cropping Systems Model

To deal with crop production systems, including different cropping strategies, soil management alternatives and problems such as soil erosion, we needed a cropping systems model for use in operational research in both Australia and Kenya. The AUSIM cropping systems model (McCown and Williams 1989) has been developed to utilise our existing crop, soil water and nutrient models, thus retaining their level of process treatment. AUSIM is well structured and modular, with modules for different crops, environmental variables and management rules readily replaceable and communicating via a 'tallyboard' of state variables (Fig. 5). While, in most cases, the operational objective in using models is simulation of crop yield, the significance of AUSIM is its emphasis on the dynamics of the soil environment. In simulations, crops can come and go, but the soil accrues their effects.

Developments in programming the AUSIM cropping systems model (J.N.G. Hargreaves, unpublished data) include a running prototype of the modules to simulate intercropping, which allows growth of concurrent crops to be simulated. A generic crop module has also been developed which supplies a common format for the development of crop models. This commonality between crop modules will greatly increase efficiency in the development and maintenance of models for new crops. Finally, a comprehensive management module has been detailed for implementation in AUSIM. This management module has been based on the Response Farming module developed for Kenya (Wafula et al. 1991) and will allow for complex simulation of systems phenomena such as rotations and sowing and fertiliser decisions dependent on incident climatic conditions.

Model Applications

Rainfed crop production in the SAT of both northern Australia and Kenya is risky. Figure 6 shows predicted maize yields at Katherine for the period 1889–1988. In these situations, yield simulation provides a means of

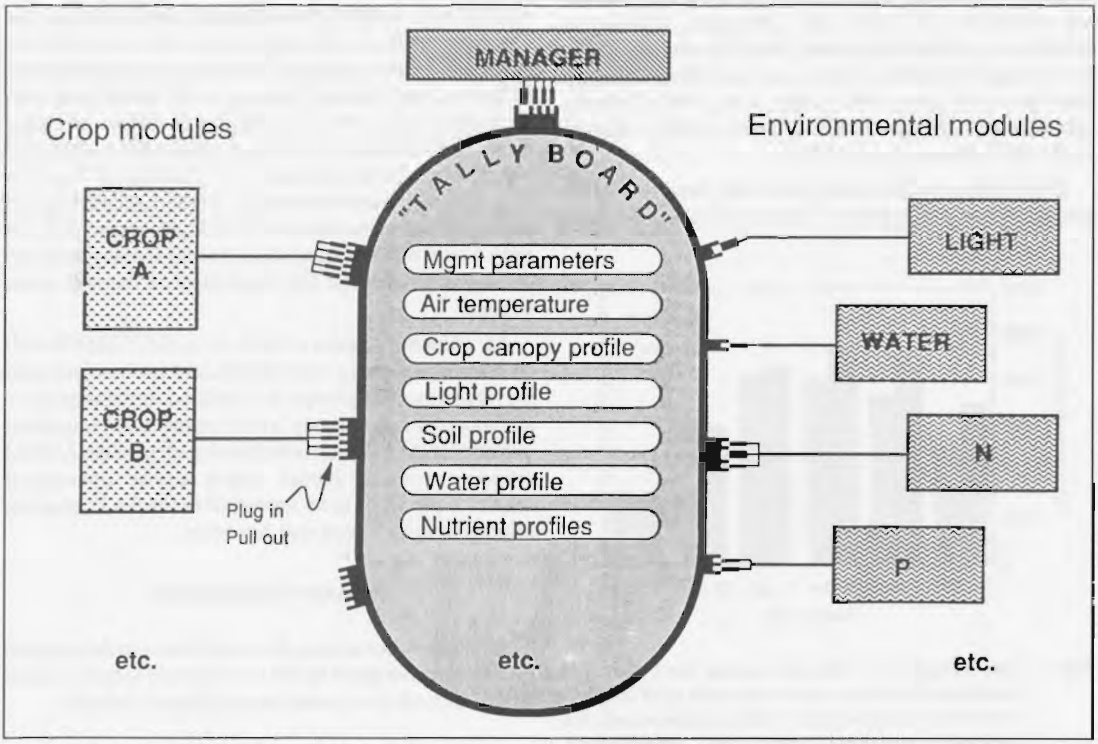

Fig. 5. Program structure of the AUSIM cropping systems model.

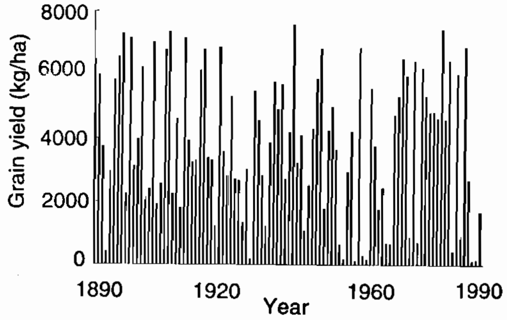

Fig. 6. Simulated maize grain yields from 1889 to 1988 at Katherine (Carberry and Muchow 1991).

quantifying production risk by utilising the whole climatic record, whereas field experimentation is hampered by a relatively small number of sample years. The potential of maize at Katherine differed markedly between short runs of years: simulated mean yields for the periods 1958–1965 and 1973–1980 were 1636 and 5638 kg/ha, respectively, compared with 3770 kg/ha for the complete 100-year period (Fig. 6).

Using the crop models, the prospects for cropping in northern Australia have already been assessed in a number of studies. For maize and sorghum, these studies include the simulation of yields and assessment of risks to cropping at different locations, for different genotypes, for a range of planting times, and for different tillage strategies (McCown 1990; Cogle et al. 1990; Carberry and Abrecht 1991; Muchow and Carberry 1991; Carberry et al. 1991; Muchow et al. 1991).

The significance of model improvements made by the project can be highlighted in the results of the example application study shown in Figure 7. In the Australian SAT, both the opportunities and yield advantage from early sowings that were simulated when seedling mortality was ignored were negated once seedling mortality from soil water deficit and high soil surface temperatures was simulated. Therefore, only models which realistically deal with key constraints in SAT enable the design and evaluation of crop and management strategies for this zone.

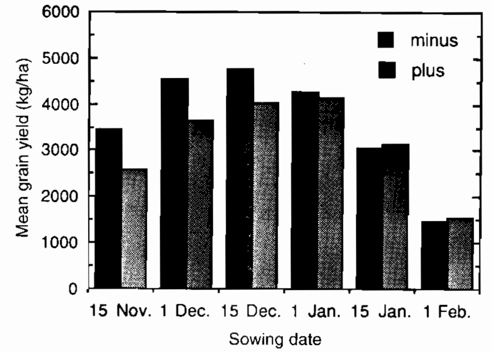

Fig. 7. The influence of different sowing dates over 100 seasons at Katherine on the mean grain yield of maize simulated with either plus or minus enhancements for simulating problems during crop establishment (Carberry and Abrecht 1991).

Relevance of Research to Kenya

Research undertaken in Australia has unquestionably benefited research in Kenya, and the converse is equally true. The recognition in the Kenyan project of the need for an operational research approach introduced the opportunity to undertake component research in Australia to support model development in both places. The resulting transfer of information between the two locations has been achieved through models which can account for temporal and spatial variation in the soil and climatic influences on crop production.

After the early, concurrent work on testing CERES–Maize in both countries, the ensuing divergence in activities nonetheless complemented both groups. The Kenyan project validated predictions of maize yield response to fertiliser N and this work has given added confidence in the nitrogen subroutines for use in Australia. The template for a management module in AUSIM was developed for the purpose of analysing Response Farming in Kenya, and research leading to the development of phosphorus and erosion modules is being primarily undertaken in Kenya. The Australian research has provided, in turn, improved routines to simulate soil N, model enhancements which account for seedling retardation and mortality, access to data for the Kenyan genotype KCB grown over diverse locations, a model for sorghum and an improved method for simulation of the soil water balance.

An attractive aspect of this ACIAR/CSIRO/KARI-sponsored project has been the efficient allocation of tasks between research groups that utilised the comparative advantages of each group's environment. An important outcome of this research is the development of the AUSIM cropping systems model which allows operational research questions to be answered in the SAT cropping regions of both Kenya and Australia.

Acknowledgments

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The Problem of Declining Soil Fertility

Effects of Legumes in a Cropping Rotation on an Infertile Soil in Machakos District, Kenya

J.R. Simpson,* D.R. Karanja,† B.M. Ikombo† and B.A. Keating§

In agro-ecological zone LM4/5 there is a problem of low crop yields due to poor soil fertility after a long period of maize cropping. The soils are very sandy with very low organic matter (Aore and Gatahi 990). Normal farming practice in the region involves little return of crop residues or use of manure. The particular terrace chosen for this experiment yielded only 80 kg grain/ha in the season prior to the experiment despite good rainfall. Similar problems confront many resource-poor farmers in semi-arid regions.

Farm resources do not allow the purchase of fertilizers, and the possibility of pronounced leaching of nutrients in wetter seasons means that fertilizers would, in any case, have to be used with care.

The major goal of this research was to identify whether a rotation of grain legumes or a fast-growing forage legume (lablab) could have a role in improving soil fertility and maize production, in a system where current productivity is extremely low. Grain legumes received emphasis because these farms are short of food grains in many seasons and there is considerable resistance to devoting crop land to non-food crops. Pigeon pea had been observed to grow well on the farm in previous seasons and is widely grown in the district. However, little information exists on its possible contribution to subsequent cereal crops.

Experimental Procedures

General

The experiment was conducted on the Kyengo farm, near Wamunyu (lat 1°25' S, long 37°34' E, altitude 1190 m) where the soil is a Haplic Alisol (Aore and Gatahi 1990). It was carried out during four growing seasons covering the period from October 1988 to June 1990 [Short rains (SR) 88, Long rains (LR) 89, SR89 and LR90]. In the first two seasons, appropriate plots of the experiment were planted with treatments consisting of (1) pure stands of maize, (2) intercropped pigeon peas with cowpeas and (3) intercropped pigeon peas and lablab. The whole terrace was planted with maize or sorghum in the third season and with maize in the fourth, as test crops. A basal application of soluble inorganic nutrients (excluding nitrogen) was applied to the entire terrace at first planting in the following amounts (kg/ha): P 48, S 20, Ca 85, Mg 25, Cu 2, Zn 2, B 0.5.

The experiment had five replicates of the three treatments (Table 1) set out as randomised complete blocks along the terrace.

Each plot was 10 m long and 8 m wide. However, maize growth was consistently much better on the first replicate than on the other replicates. This was associated with a much higher soil N status, probably due to its proximity to a cattle boma. The data from this replicate have been discarded in evaluating the treatment effects.

Cultural Details

Maize (cv Katumani composite B) was planted in both of the first two seasons in the maize treatments plots, and as a test crop on all plots in the third and fourth seasons. Plant spacing was 0.75 × 0.4 m (i.e. 33 300 plants/ ha) in the first two seasons, and 0.9 × 0.3 m (37 000 plants/ ha) in the third and fourth seasons. Sorghum was also grown as a test crop in the third season on sections of plots that had received treatments 1 and 2.

Pigeon pea (a local long-season variety) was planted in both the legume treatments in the first season and allowed to grow through to the second season. The spacing was 1.2 × 0.3 m but it was not rigorously thinned and resulted in about 40 000 plants/ha.

Cowpea (cv M66) was planted as an intercrop in both of the first two seasons in treatment 2. It was planted in single rows midway between the pigeon-pea rows (i.e. 0.6 m from the pigeon peas). Intra-row spacing was 0.15 m giving a plant population of 55 600 plants/ha.

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Table 1. Details of treatments and test crops.

Treatment no.	Species grown (SR88, LR89)	Test crops	
		SR89	LR90
1	Maize	Maize, sorghum	Maize
2	Pigeon peas and cow peas	Maize, sorghum	Maize
3	Pigeon peas and lablab (retained)	Maize	Maize
	Pigeon peas and lablab (removed)	Maize	Maize

Lablab purpureus (cv Rongai) was planted only once — in the first season of treatment 3 — and allowed to grow on after cutting back at the end of the first season. Plant arrangement was the same as for the cow peas.

All species were over-planted and then thinned to ensure the desired stands. Grain legumes were sprayed to control insects as required.

Management of the Legumes

Cow peas. At harvest, pods were removed but stems and fallen leaves were left on the plots to decompose. In the second season (LR89) cowpeas were replanted between the now well-established canopy of pigeon peas.

Pigeon peas. Pods were harvested progressively during the long dry season and the total grain yield was calculated. Leaves were allowed to fall on the plots but woody stalks were removed after harvest of pods had been completed, and weighed.

Lablab. In the first season (SR88) lablab grew profusely and was not defoliated until late March 1989. At this stage it was cut back to 0.2 m height, yielding 2100 kg DM per ha. The prunings were retained in situ on one half of each plot, but removed from the other half plot for recording of yields and then discarded.

In late July 1989, the remaining lablab residues were removed on the appropriate half of each plot (as in March) while the residues were incorporated on the other half plot.

Assessment of Soil Fertility by Cereal Cropping

In October 1989 the whole site was cultivated using hand tools. Crops of maize (KCB) and sorghum (cv Serena) were planted at onset of the short rains 1989. All plots except those after lablab were split and planted half to maize and half to sorghum. The plots previously split for removal or return of lablab residues could not be split any further and so were planted to maize only.

Any possibility of complicating deficiencies of phosphorus or sulfur was avoided in the test crops by augmenting the basal nutrients already applied in 1988 with additional single superphosphate (100 kg/ha) placed along the rows soon after planting. The maize established well. Sorghum was more troublesome and slow to establish, but was planted as an assurance of obtaining some grain yield if the season was a poor one.

Soil sampling

The soil was sampled at the start of the experiment in November 1988, samples being collected from all plots for the depth intervals 0–15, 15–30, 30–60 and 60–90 cm. In October 1989, following cultivation, and again in March 1990, the following samples were collected:

(a) A composite from each plot of 10 cores to 20 cm depth taken with a 5 cm diameter auger.

(b) Profile samples from all half-plots for the same depth intervals as previously.

Sub-samples were taken for moisture and the remainder of each sample was frozen for later analysis.

Analytical Methods

Plant materials were dried at 70°C before weighing. Total nitrogen in plants and soils was determined by conventional Kjeldahl methods on the ground materials from dried samples. Total soil carbon was obtained by Walkley and Black digestion with a factor of 1.30 being applied to allow for incomplete recovery.

Mineral nitrogen was determined on soil extracts obtained after shaking a 25 g sample for 1 hour in 100 mL of 1M KCl containing 5 mg/L of phenyl mercuric acetate. After filtration, 50 mL of extract was steam distilled (after adding 5 mL of 12% water suspension of powdered calcined MgO) into 5 mL of 2% boric acid and indicator to collect the extractable ammonium-N. Powdered Devarda's alloy (0.2 g) was then added to the extract and distillation was repeated to obtain the nitrate-N. Ammonium and nitrate were determined separately by titrating the distillates with standard sulphuric acid. Nitrite-N was assumed to be negligible.

Results

Crops in the First and Second Seasons (SR88 and LR89)

Legume growth was excellent in the first season (SR88). Pigeon peas grew well after cowpeas (treatment 2) in the second season (LR89), but the cowpeas interplanted in this season failed due to competition. Lablab grew well in the first season but a number of plants died in the second season after defoliation. Approximately 2000 kg/ha of lablab dry matter was achieved on healthy plots in both seasons, but the death of large patches of plants on some plots in LR89 reduced the average yield in the second season to about 1000 kg/ha. Cow peas yielded 1200 kg/ha of grain in the first season. Pigeon peas yielded 690 kg/ha after cowpeas but only 310 kg/ ha in the presence of lablab (Table 2).

Maize yields on the continuous maize plots were very poor. In SR88 the average grain yield was 67 kg/ha and in LR89, due to the short abrupt season and extreme N deficiency, all plots failed to produce grain. The severity of N deficiency was highlighted by a neighbouring maize crop fertilised with complete nutrients (including nitrogen) which produced over 2000 kg/ha in LR89.

Soil Mineral Nitrogen

Soil profiles could be sampled consistently to only 90 cm because of stone lines at about 1 m depth. Analyses showed that at the start of the experiment there was 47 kg/ha of nitrate-N in the profile to 90 cm depth (mean across four replicates) with no difference between the treatment plots (Table 3).

Following the growth of legumes for two seasons, differences in mineral-N were marked in the composite surface (0–20 cm) samples. The difference between the continuous maize plots (16.5 kg N per ha) and the legume plots (30.4 kg/ha) was highly significant ($P < 0.001$).

Profiles taken from each plot showed that these differences existed throughout the 0–90 cm layer. Nitrate-N was quite evenly distributed throughout the 0–90 cm zone (Fig. 1). Ammonium-N also tended to increase after the legume treatments, but the amounts present were small (4 –10 kg N per ha) and accounted for only about 10 per cent of the total mineral-N. Differences between the two legume treatments were not significant, but the legume plots contained significantly ($P<0.05$) more mineral-N (88.3 kg N per ha) than the plots previously under maize (50.6 kg N per ha).

In March 1990, the soil mineral N content was low, with a mean of only 20 kg N per ha in the 0–90 cm depth and no obvious treatment effects. Total soil nitrogen analyses revealed no long term effects or differences between treatments. Averaged throughout the profile, total N was 0.029% and showed no trends with depth.

Table 2. Crop and nitrogen yields (kg/ha) in the first two seasons (SR88 and LR89).

		Treatment				
		(1)	(2)		(3)	
		Maize	Cow pea/Pigeon pea		Lablab/Pigeon pea	
			CP	PP	LL	PP
SR88	grain	67	1217	–	–	–
	total biomass	237	3275	–	2020	–
LR89	grain	–	–	694	–	309
	total biomass	(100)[a]	–	4785	994	2276
Estimated total N uptake (over 2 seasons)		5	92		85	
Estimated N removal		5	75		75	

[a] Estimated (not measured)

Table 3. Mineral N (kg/ha) in soil.

Date/sampling type		Treatments			Significance of the difference between treatment (1) and the mean of the legume treatments
		(1)	(2)	(3)	
16.11.88	profiles (90 cm)	46	54	39	ns
7.11.89	composites (20 cm)	17	34	27	($P < 0.001$)
7.11.89	profiles (90 cm)	51	79	97	($P < 0.05$)
21.3.90	profiles (90 cm)	(24)[a]	28	21	ns

[a] Very variable replicates

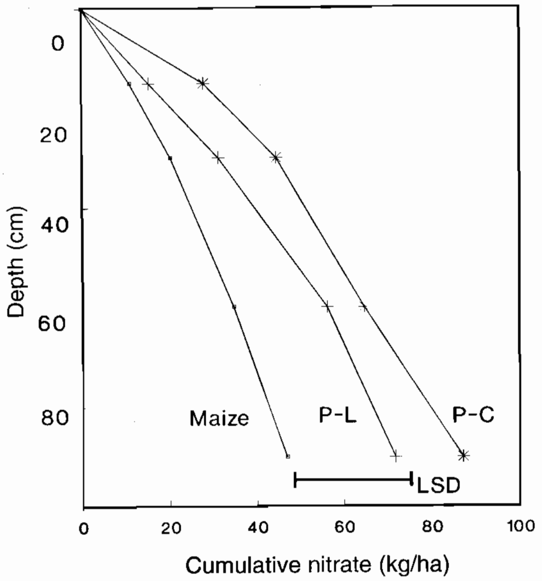

Fig. 1. Cumulative amounts of nitrate-N in soil profiles to 90 cm depth after two seasons of three different cropping treatments, viz. continuous maize, pigeon pea/cow pea (P–C) and pigeon pea/lablab (P–L).

Cereal Crops in SR89 and LR90

Despite the legume treatments, the indicator crops of maize and sorghum, planted in November 1989 at the onset of the short rains, looked severely N-deficient from an early stage.

However, the overall N-deficiency did not prevent differences in maize biomass from appearing after 2 months growth. Biomass after maize was 190 kg/ha compared with 470 kg/ha after legumes. Sorghum was still poorly established at this stage.

Differences increased over the remainder of the season, both in maize and sorghum. At final harvest, the differences were significant ($P < 0.05$) in maize total biomass and in grain (Table 4). Grain yield after maize was only 82 kg/ha compared with 485 kg/ha after legumes. The difference in sorghum yields was similar but the effect was more convincing statistically ($P < 0.001$ for biomass, $P < 0.01$ for grain). Grain yield of sorghum increased from 102 kg/ha following maize to 402 kg/ha after cow pea/pigeon pea. There were no significant differences between the two legume treatments, or between the subplots that compared the removal or incorporation of the lablab residues.

In the subsequent long rains (LR90), maize was replanted throughout and was severely N-deficient. The crop was variable and yielded no significant treatment differences, but a trend in grain yields remained, from 54 kg/ha after maize to 175 kg/ha after legumes.

Discussion

The inclusion of legumes in the cropping rotation clearly gave a large increase in biomass and grain production over three seasons compared with continuous maize cropping on this low nitrogen site. The cow pea crop is estimated to have contained 45 kg N per ha in grain and hulls, and the subsequent pigeon pea crop contained another 30 kg N per ha. This nitrogen was removed from the plots and thus did not contribute to the subsequent increased growth of the cereal crops. The residual effect was due to a sparing of soil nitrogen by biological fixation and return of haulms and roots.

Similarly, the lablab/pigeon pea combination is also estimated to have produced an average of about 75 kg N per ha in lablab biomass (60 kg N per ha) and pigeon pea grain plus hulls. Surprisingly, the removal of lablab from one half of the plot did not produce a detectably different residual effect on cereal yields from that after returning all cut material. This could be partly explained by volatile losses and transport of dried plant residues across the site by termites or wind, or by the late removal of herbage after some leaf fall had occurred.

The residual effect of the legumes on subsequent cereal yields did not differ between legume species and amounted to an extra grain production of 300–400 kg/ha. Despite the slow establishment of the sorghum crop, the total biomass achieved after legumes by maize and by sorghum was very similar — about 1000 kg/ha.

Substantial amounts of mineral nitrogen, mainly nitrate, remained in the soil profiles after legumes, adding about 40 kg N per ha to that in the plots previously under maize. However, only about 30% of this extra nitrogen was recovered in the above-ground cereal biomass. The mineral nitrogen at planting was well distributed down the soil profile. It would be susceptible to leaching in this sandy soil and could evade being absorbed by the roots of a deficient, weak and widely spaced crop.

While legume crops are clearly very advantageous in this soil environment, their residual effects on cereal yields may be less per unit of nitrogen present than nitrogen fertiliser carefully placed near the plants at 30 days after planting, when a nitrogen recovery of > 50% could be expected.

One important observation on the site was that soil fertility was noticeably higher close to trees of *Acacia* and deciduous species. Within 30–50 m of a cattle boma surrounded by trees which deposited their leaf fall into the plots, cereal growth and yield were several times greater than those in plots further away from the trees.

Table 4. Cereal yields (kg/ha) in SR89 after rotation-cropping treatments.

	Treatment (1) (maize)		Treatment (2) (Cow pea/pigeon pea)		Treatment (3) (Lablab/pigeon pea)	
					Lablab removed	Lablab retained
Test crop	Maize	Sorghum	Maize	Sorghum	Maize	Maize
Total DM	289	274	983	940	1172	1063
Grain	82	102	464	402	562	449

These higher fertility patches occurred in two areas of the experiment site, and had to be avoided in the analysis of the data. Thus the use of perennial plants, as in agroforestry or alley cropping, may offer considerable advantages in enabling the recycling of soil nutrients back to the soil surface in organic matter. Even pigeon peas, intercropped in their first season and maintained for a whole year, have some advantages in this regard.

The present work in Kenya, though only a single experiment at one site, is consistent with studies elsewhere (Table 5). The positive residual effect of two seasons of legume providing about 40 kg N per ha of soil nitrate is typical of other observations made on an annual basis by various methods. This amount of nitrate was not nearly sufficient to provide the full N requirements of the maize or sorghum crops but it was a useful boost. The legume–cereal rotation was clearly many times more productive than continuous cereal cropping.

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Table 5. Residual effects of legumes on nitrogen available to cereal crops in semi-arid areas.

Authors	Legume (location)	kg N/ha/year	Method
Narain et al. 1980	Pigeon pea (India)	40	Leaf litter N
ICRISAT 1981	Pigeon pea (India)	40	N fert. equiv.
MacColl 1989	Pigeon pea (Malawi)	12–55	N fert. equiv.
Eaglesham et al. 1982[a]	Cowpea (Nigeria)	36	N balance
Singh 1983	Cowpea intercrop (India)	46	N fert. equiv.
Singh 1983	Green gram intercrop (India)	31	N fert. equiv.
Reeves et al. 1984	Lupin (Australia)	41	Soil mineral N
Doyle et al. 1988	Lupin (Australia)	20–37	N uptake (wheat)
MacColl 1989	Lablab (Malawi)	36	N fert. equiv.
MacColl 1989	Groundnut (Malawi)	9	N fert. equiv.
MacColl 1989	Soybean (Malawi)	7	N fert. equiv.
Puckridge and French 1983[b]	Legume pastures	30–150	Total soil N

Notes:

[a] As calculated by Ofori and Stern (1987)

[b] Review of studies in southern Australia

Explanation of methods

N fert. equiv. denotes the amount of fertilizer which had to be added to the test crop growing after a non-legume control crop to produce an equivalent yield to that after the legume.

Other methods depend on analyses of legume leaf litter, balance of soil and crop N, N uptake in the relevant test crops, and accumulated soil N, respectively.

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Phosphorus Status of Cropland Soils in the Semi-arid Areas of Machakos and Kitui Districts, Kenya

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CROP production in the semi-arid areas of Kenya is significantly influenced by the inadequate and poor seasonal rainfall distribution and commonly low levels of nitrogen (N) and phosphorus (P) in soils (Siderius and Muchena 1977; Okalebo 1987). Crop response to fertiliser P application has been reported if the test levels for available P, using the routine Bray No. 2, Olsen or Truog methods of extraction, are below 10 mg/kg of soil (Roche et al. 1980; Okalebo 1987).

In the semi-arid areas of Machakos and Kitui districts in Kenya, nitrogen deficiency is widespread in maize crops that are grown on continuously cultivated land. The occurrence of P deficiency can be expected to interact with response to applied nitrogen, thereby affecting the economics of using nitrogen inputs to increase maize production. A survey of available P status of soils in Machakos and Kitui districts has been made to study the distribution of available P within and among the cultivated terraces on a range of small farms.

Soil Sampling and Analysis

The survey was carried out in October 1988 and June 1989. Surface (0–20 cm) soils with different characteristics, mostly luvisols (alfisols), were sampled from twenty farms in Machakos district (including the new Makueni district) and from one farm from nearby Kitui district, to determine the range of extractable P within and among terraces on a farm. The samples from each terrace were taken in grids spaced at 5 m width × 10 m length. The soils were air-dried and sieved to pass a 2 mm screen prior to analysis. Soil pH was measured in 0.01M $CaCl_2$. Total nitrogen content was determined by the semi-micro Kjeldahl method, whereby the ammonium was distilled off and measured by titration with standard acid. Organic carbon was estimated by the dichromate method of Walkley and Black (1934); no correction was applied for incomplete carbon recovery. Phosphorus was measured by the Bray No. 2 extraction, using 0.03 N NH_4F plus 0.1 N HC1 (Bray and Kurtz 1945), with the P being determined as described by Murphy and Riley (1962).

For this study the choice of the Bray No. 2 method of P extraction in soils was based mainly on speed and reproducibility of results. Elsewhere (Okalebo 1987; Okalebo et al. 1989b) it has been reported that the levels of P from Bray No. 2 extraction are highly and positively correlated with the levels of P extracted using other routine methods of extraction (Olsen, Truog, Egner-Riehm, Mehlich, calcium chloride and calcium acetate).

Phosphorus in Surface Soils

A total of 59 terraces was sampled on the 21 farms. Mean extractable P for these terraces ranged from 3 to 159 mg/kg, with an overall mean of 25 mg/kg. The frequency distributions for extractable P, organic C and pH are shown in Figure 1. Forty-one per cent of the samples had extractable P below 10 mg/kg and these can be confidently expected to respond to applications of fertiliser P.

Correlations between the soil properties were not strong, though there was a tendency for soils with higher extractable P to be associated with higher contents of organic carbon (0.95–1.2% C), total nitrogen (0.09–0.15% N) and pH (5.7–6.5). The relationship with pH arose mainly from higher extractable P (72–159 mg/kg) being measured on fine, dark grey to black soils (those with vertic properties). Such soils are found on bottomlands (Kamba Farm, Wote) and have higher pH than the alfisols.

The lowest levels of extractable P in surface soils were found on sandy to loam grey soils (Kyengo and Kavuu Farms, Wamunyu) and on eroded red soils on sloping ground (Mutua, Munyoki, Waita Farms). These low P

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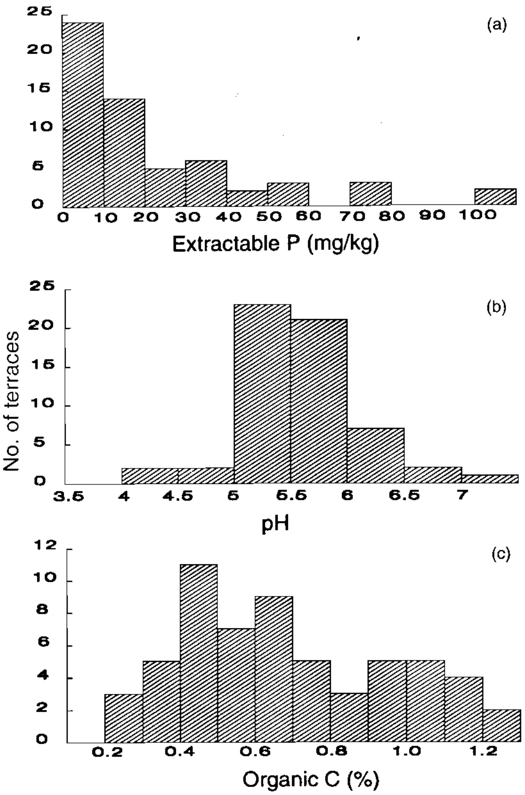

Fig. 1. Frequency distribution of (a) extractable P (Bray No. 2, mg/kg), (b) pH (in 0.01 M $CaCl_2$) and (c) organic C (%) in surface soils (0–20 cm) from farmers' terraces. Total number of terraces = 59.

soils (< 10 mg/kg) were rather widely distributed and contained low levels of organic carbon (0.4–0.7%C) and total nitrogen (0.04–0.09% N).

The results of this on-farm survey can be compared with the extractable P found in soils on Katumani Research Station (Gichera and Ita 1987). The dominant soils (four luvisols and a cambisol) had extractable P in the range 18–188 mg/kg. It can thus be inferred that low levels of extractable P occur much more frequently on-farm.

Between and Within Terrace Variability

A feature of the results of the survey was the very high variability that existed between terraces on a given farm, and between samples collected within a terrace. This is illustrated for some selected farms in Figure 2.

The coefficients of variation for extractable P within the cropped terraces ranged from 7 to 136% (mean 47%); uncultivated areas included in the survey were not much less variable with coefficients from 8 to 76% (mean 29%). These uncropped areas were not uniformly low in phosphorus with mean values ranging between 6 and 43 mg/kg.

Farming practices undoubtedly have had an influence on both between and within terrace variability. Some phosphorus will have been applied as boma manure (and perhaps fertiliser in a few instances), and there will be localised effects from burning (including charcoal burning) and termite mounds.

As an example of the possible effect of boma manure we can consider the Kyengo Farm (Fig. 2). The two terraces have been continuously cropped with maize, cow peas and pigeon peas for over 10 years but the terrace closer to the homestead receives occasional boma manure applications. The amount of extractable P was much higher on the terrace where manure has been used. By contrast, on Mutua Farm (Fig. 2) there is rather uniform distribution of extractable P across the terraces. This farm has no history of using boma manure and the soils show indications of considerable erosion having taken place.

The variation within the terraces was notable. Possible reasons for this have been outlined above. To support these suggestions we can again use the example of a terrace from Kyengo's farm where two samples had very high extractable P, both of which had pH well above the average and one had a very high content of organic carbon (Table 1).

Table 1. Variability of soil properties within a terrace on Kyengo Farm.

Sample number	Extractable P (mg/kg)	pH in 0.01M $CaCl_2$	Organic C (%)
5	155	6.0	2.67
6	168	6.3	0.39
Mean of 7 other samples (s.d.)	28 (16)	5.2 (0.4)	0.16 (0.08)

Distribution of Extractable Phosphorus within Soil Profiles

Profile samples have been analysed for only two sites where field experiments were conducted to measure crop responses to applied phosphorus. These were on the Kyengo and Mutua Farms and showed little variation with depth, except for a slightly higher value in the 20–30 cm layer at Kyengo's (Table 2). However, Okalebo (1987 and unpublished) has data for other sites in the study area that show large amounts of P can be present deep in the profile. It seems inconceivable that these quantities could have accumulated through use of manures. Therefore it would be unwise to interpret the between terrace variation that we have observed solely to effects of management practices. A major effect of parent material would also seem to be involved.

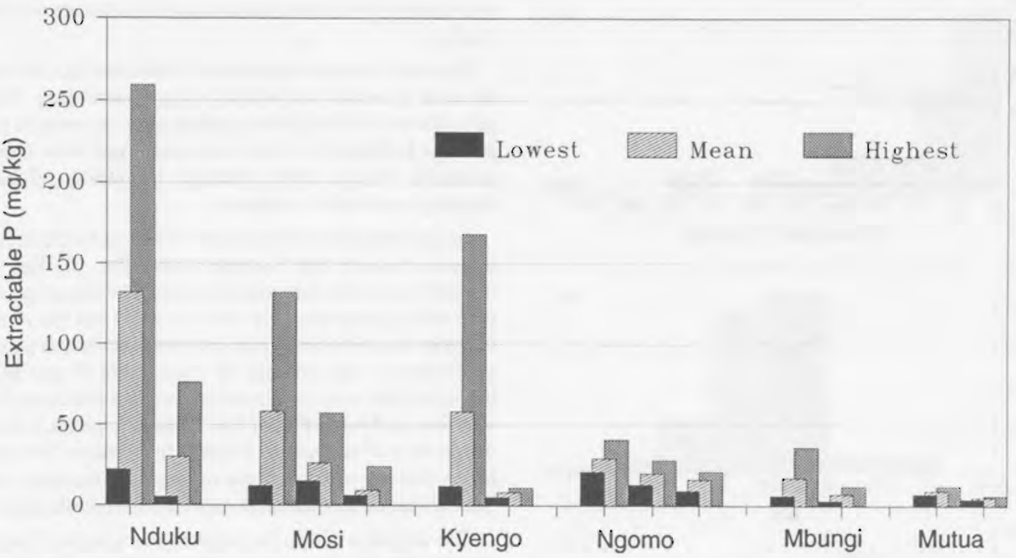

Fig. 2. The range and means of extractable P on terraces from selected farms in the study area.

Phosphate Sorption

The amount of phosphorus that needs to be applied to correct a deficiency of this nutrient depends upon the sorption characteristics of the soil. The sorption isotherms for several surface soils (0–20 cm) from the study area are shown in Figure 3. In contrast to the nitisol from Muguga, these luvisols sorb relatively little phosphorus. This suggests that low rates of application of phosphatic fertilisers would be effective on these soils.

Table 2. Distribution of extractable phosphorus (mg/kg) within soil profiles.

(a) KARI/ACIAR study

Kyengo Farm Depth (cm)	Kyengo Farm P	Mutua Farm Depth (cm)	Mutua Farm P
0–10	7	0–15	8
10–20	7	15–30	4
20–30	16	30–60	4
30–50	6	60–90	5
50–70	6	90–120	5
70–90	6	120–150	4
90–110	5		

(b) Data from Okalebo et al. (Records of Research, ARD/KARI Annual Reports, Muguga Centre 1979–87)

	Katumani Research Station					
Depth (cm)	Field B 1986	Field C 1987	Maruba Farm 1986	Kathonzweni 1979	Ithookwe 1978	Katheka-Kabati 1981
0–20	36	107	17	9	40	340
20–40	24	58	6	2	22	313
40–60	8	98	6	1	19	330

In Figure 3, the soils from Mutua and Kyengo Farms are indicated. These are sites where field studies on the response to phosphorus have been carried out (Probert et al., these proceedings). The phosphorus sorption is very low on the sandy soil at Kyengo Farm. Figure 4 shows how the sorption characteristics change with depth for a site at Ithookwe; this behaviour is very consistent with the pattern observed in similar soils (alfisols) in northern Australia (M.E. Probert, unpublished data). Sorption increases with depth and can be associated with the increasing clay and decreasing organic matter content of the soils. Where surface soil has been removed by erosion, sorption by the exposed sub-soil layers can be expected to be higher than for non-eroded sites. This is likely to be a contributing factor to the higher P sorption in the surface soil at the Mutua site (Fig. 3).

The Chemical Fertility of the Cropland Soils — an Overview

Evidence available from soil analyses indicates that the soils of the study area are generally well supplied with cations (calcium, magnesium and potassium), and soil pH is sufficiently high to infer that there are no serious acidity problems.

In addition to nitrogen, the nutrients of most concern for crop production are phosphorus and possibly sulfur. There have been no reports of major crop failures under circumstances where good yields would have been expected (i.e. adequate rainfall and inputs of nitrogen and phosphorus) and we have no reason to suspect that micronutrient deficiencies are of major importance under current farm practices.

Treatments have been applied to test for the adequacy of sulfur at two sites (Kyengo and Mutua Farms), without significant effects on yield of maize or cowpeas in the presence of non-limiting nitrogen and phosphorus. However, in a current experiment at Masii there are indications that sulfur deficiency is affecting the early growth of maize on control plots that have not received single superphosphate. No information, such as data on extractable S in soils, is available to predict how large the sulfur supply in these soils might be or how long it could meet crop needs if yields were raised through inputs of either fertiliser nitrogen or symbiotic nitrogen.

Conclusions

The results from the survey of farmers' terraces show that phosphorus deficiency is to be expected to occur widely. This has implications for extending the use of fertilisers to increase yields because a phosphorus limitation is likely to reduce the response obtained to inputs of nitrogen.

The large within-terrace variation in extractable P that

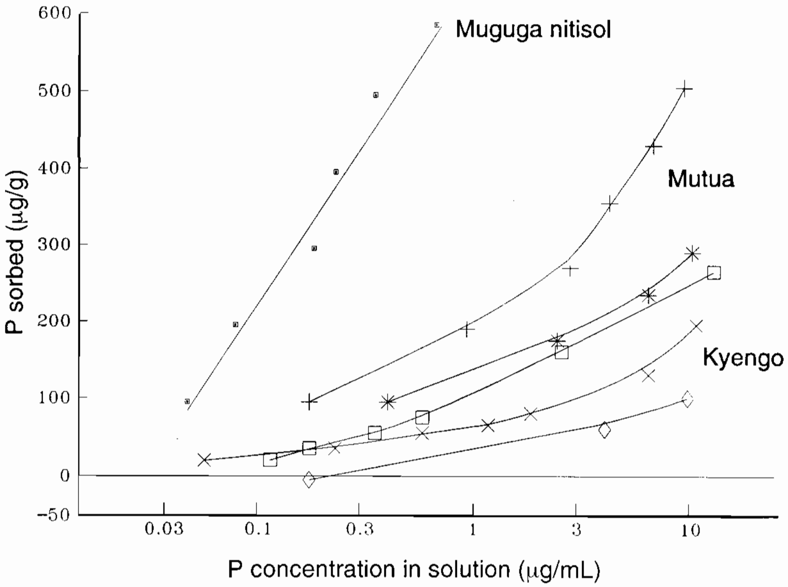

Fig. 3. Phosphate sorption determined by method of Fox and Kamprath (1970) for some luvisols from the study area compared with a nitisol from Muguga. The soils at Kyengo and Mutua Farms where field experimentation has been carried out to study responses to phosphorus are indicated.

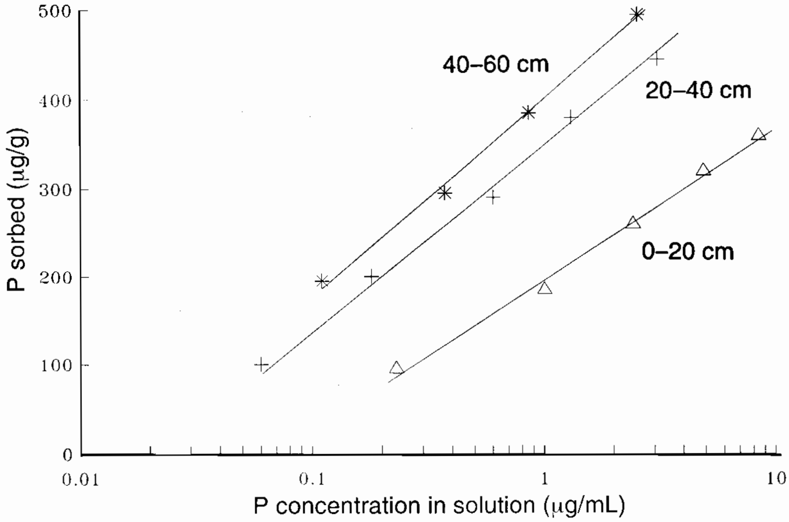

Fig. 4. The effect of depth on phosphorus sorption at the Ithookwe site (J.R. Okalebo, unpublished data).

has been found has consequences for experimentation and especially for selection of suitable experimental sites. It is highly desirable that proposed sites be sampled and analysed for extractable P before crop growth experiments to investigate responses to P are commenced. Alternatively, consideration might be given to using the variability that exists to relate crop growth to measures of the soil P supply.

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Effects of Phosphorus on the Growth and Development of Maize

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It is now apparent that phosphorus deficiency is likely to be a limitation to crop growth on much of the croplands of the semi-arid areas of eastern Kenya (Okalebo et al., these proceedings). A number of on-farm experiments has been carried out to evaluate the magnitude of the response to phosphorus and several other experiments are in progress to assemble datasets that will provide the building blocks needed to adapt crop simulation models to cope with situations where phosphorus is limiting.

The experiments have been located on two subsistence farms. The Kyengo Farm, Wamunyu Location, is situated nearly 50 km northeast of Machakos Town close to the main road to Kitui, whilst the Mutua Farm is near Katumani National Agricultural Dryland Farming Research Centre, about 12 km south of Machakos Town. Some properties of the surface soils of the two locations are given in Table 1 (Aore and Gatahi 1990). The sites were chosen because the soils were found to have uniformly low values of extractable phosphorus.

The region experiences a bimodal rainfall pattern (Stewart and Faught 1984) that permits two cropping seasons. The short rains (SR) commence in October or November whilst the long rains (LR) arrive in March.

Table 1. Some properties of the surface soils at the experimental sites

	Mutua's Farm	Kyengo's Farm
Classification	Haplic Lixisol	Haplic Alisol
Texture	Sandy clay	Sandy loam
pH in water	6.1	6.2
Organic C (%)	0.59	0.43
Total N (%)	0.06	0.05
Bray 2 extractable P (μg/g)	8, 4, 8[a]	8

[a] Values from the sites used for the surface management experiment, the crop development experiment, and the sources of P experiment, respectively.

The Experiments

Kyengo Farm

Two experiments were established during the SR88 to measure the response of maize and cowpeas to increasing rates of application of phosphorus (J.R. Simpson and J.R. Okalebo, unpublished data). The treatments consisted of a control (receiving neither phosphorus nor nitrogen) and four rates of phosphorus (0, 20, 40 and 60 kg/ha) with uniform application of nitrogen applied as calcium ammonium nitrate (CAN). A basal application of sulfur was made to all plots.

For the maize experiment, the source of phosphorus was triple superphosphate(TSP) and a total of 90 kg/ha of N was applied in three applications. The third application was made at silking by which time the crop was exhibiting a general yellowing of the leaves. For the cow pea experiment, the source of phosphorus was single superphosphate and the nitrogen rate was 60 kg/ha. The phosphate fertilisers were applied as a band at 10 cm depth alongside each row of the crop.

To study the residual effect of the phosphate fertiliser on succeeding crops, maize and cow peas were replanted in the LR89 without further application of P. The nitrogen rate applied in the second season was 60 kg/ha. There was minimal disturbance of the fertiliser bands between the two crops, the second crop being sown along the original rows.

Maize (Katumani Composite B) was thinned to a plant density of 44 444 plants/ha in rows 0.75 m apart and cow pea (var 419) to a stand of 125 000 plants/ha in rows 0.4 m apart. For both experiments there were three replications.

The yield data, measured at maturity, are summarised in Table 2. In no instance was there any significant dif-

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ference between the three positive rates of application of phosphorus, nor any trend for the higher rates of application to give increased yields or P uptakes, so these treatments have been averaged to give the mean response to applied P.

Table 2. The effect of N and P fertiliser on the yields and total P uptake of maize and cow pea at Kyengo Farm.

(a) Maize

	SR 88		LR 89
Treatment	Grain[c] (kg/ha)	P uptake (kg/ha)	Grain[c] kg/ha)
Control	590	2.9	231
N	3860	11.0	349
N + P[a]	4540	13.8	676
LSD (P = 0.05)[b]	416	3.5	573

(b) Cow peas

	SR 88		LR 89
Treatment	Grain[c] (kg/ha)	P uptake (kg/ha)	Grain[c] (kg/ha)
Control	1010	3.9	98
N	1100	5.3	246
N + P[a]	2240	12.0	375
LSD (P = 0.05)[b]	413	2.7	96

[a] Means of P application rates of 20, 40 and 60 kg/ha

[b] Least significant difference for comparing the N (or control) treatment with N + P.

[c] Grain yields on an oven dry basis.

The first crop experienced a wetter than average season (rainfall from planting to harvest was 415 mm). For maize there was a large response to nitrogen, but there was an additional response from application of phosphorus. Cow peas responded to phosphorus only, both grain yield and uptake being significantly increased by its application.

In contrast, the rainfall for the second crop was poorly distributed with only 8 mm being received after the end of April. On this sandy soil, the soil moisture reserves were inadequate to support the crops. Under the conditions experienced, residual effects of the phosphorus applied to the proceeding crop were not well substantiated.

Mutua Farm

Three experiments have been carried out with maize (Katumani composite B) on adjoining terraces.

A. Nutrients and surface soil management (D.R. Karanja, B.A. Keating and J.R. Okalebo, unpublished data). This experiment was carried out in SR88 and investigated the effects of fertiliser and surface soil management. The design was a split plot with three surface management practices (flat surface, tied ridges or mulching with 3 t/ha of maize stover from the previous crop) as main plots and fertiliser treatments as subplots. These were a control (receiving neither P or N) and three rates of phosphorus (0, 20 and 40 kg/ha as TSP) with a uniform N application of 60 kg/ha as CAN applied in two dressings at planting and after thinning. Plant spacing was the same as for the maize experiment at Kyengo Farm.

Rainfall during the season was well distributed and the total received for November–January was 431 mm. However, growth of maize was uneven. Severe visual symptoms of P deficiency (stunted growth and purple leaf coloration) occurred on some plants of the nil P plots that received nitrogen, intermingled with some healthy plants. There were also very obvious effects of position of plots on the terrace with much better growth on the lower side. Consequently, the effect of position of the plots on the terrace was allowed for in the statistical analyses of the data by including it as a covariate (D. Ratcliff, CSIRO, Brisbane, Australia, pers. comm.). Yields of grain and total P uptakes, adjusted for the effects of position on the terrace, are given in Table 3.

There were highly significant effects of both nitrogen and phosphorus increasing yields of grain and P uptake, with responses being obtained up to the highest rate applied. The main effect of the surface management treatments was not significant though there was a marked contrast between the flat treatment and the two conservative treatments (mulching or ridging) at the highest rate of application of phosphorus (Fig. 1). A similar effect can be seen for the treatments that did not receive any fertiliser (Table 3). Though no data are available in support, it seems highly likely that the mulched or ridged treatments retained more water on the plots, permitting better growth on the treatments without fertiliser and a better response to the higher input of P. The movement of water off the plot area would also explain why growth was better on plots on the lower side of the terrace.

B. Effects of P on development of maize. This experiment was commenced in SR89 and continued in the following season. Large plots were used (20 m x 6 rows) to permit successive sampling through the season and 12 plants in each plot were tagged to enable the crop phenology to be followed (leaf counts, leaf areas and stage of growth).

Details of the crop husbandry were as described above and tied-ridging was used to try to retain as much rainfall on the plots as possible. For the second season (LR90)

Table 3. The effects of surface management and fertiliser on maize yield and total P uptakes at Mutua Farm.

(a) Grain yield at 15.5% moisture (kg/ha)

Surface management	Fertiliser treatment				Mean
	Without N or P	With N			
		P0	P20	P40	
Flat	497	1761	2591	2691	1885
Mulched	1346	2544	2506	3920	2579
Tie-ridged	1796	1993	2424	3878	2523
Mean	1213	2099	2507	3496	

LSD (P = 0.05) for effect of surface management = 922
for effect of fertiliser = 450
for surface management × fertiliser = 780

(b) Total P uptake (kg/ha)

Surface management	Fertiliser treatment				Mean
	Without N or P	With N			
		P0	P20	P40	
Flat	1.05	3.11	5.23	5.18	3.64
Mulched	2.16	5.51	4.22	8.28	5.04
Tie-ridged	3.54	3.79	4.69	8.8	5.21
Mean	2.25	4.14	4.72	7.42	

LSD (P = 0.05) for effect of surface management = 2.30 for effect of fertiliser = 0.95
for surface management × fertiliser = 1.65

there was minimal disturbance of the previously banded fertiliser, ridges being reopened and the new crop planted.

In the first season there were five treatments, in two randomised blocks. These comprised three rates of P (0, 10 and 40 kg/ha applied as superphosphate as a band below the seed) at a high rate of nitrogen (90 kg/ha as CAN applied in three splits) together with the two lower rates of P (0 and 10 kg/ha) at a low rate of application of N (30 kg/ha at sowing). The expectation was that the higher rate of application of N would ensure that the crop was not constrained by N.

For the second season (LR90), the different nitrogen treatments were discontinued and all plots received the high, non-limiting rate of application. Treatments were modified so that there were five different histories of P application: nil P; 10 and 40 kg/ha applied to the first crop only so that residual effects could be studied subsequently; 10 kg/ha applied to the second crop on plots that had received no P previously; 40 kg/ha applied to plots that had previously received 10 kg/ha. The fresh applications of P were again banded beneath the seed.

Good climatic conditions for growth of maize were experienced in both seasons: in SR89 rainfall was close to the long-term average, while LR90 was considerably wetter than the long-term average. Yield data and total P uptakes are given in Table 4 for comparison with the other experiments. Relatively small responses were obtained to the different nitrogen treatments in the first season, but large responses were obtained to phosphorus. Other aspects of this experiment will be discussed later.

C. Effectiveness of different sources of phosphorus. An experiment was commenced in the LR90 to compare the response of maize to three different P sources prepared from the rock phosphate from Minjingu, Tanzania. These were the beneficiated rock, single superphosphate manufactured in Nairobi, and a partially acidulated (50%) product (PARP) prepared by IFDC. All sources were banded and the crop was grown at a high rate of application of N (90 kg/ha as CAN applied in three splits). The results from this experiment are illustrated in Figure 2.

Chemical analyses of the fertilisers have yet to be completed. Conclusions on their effectiveness are

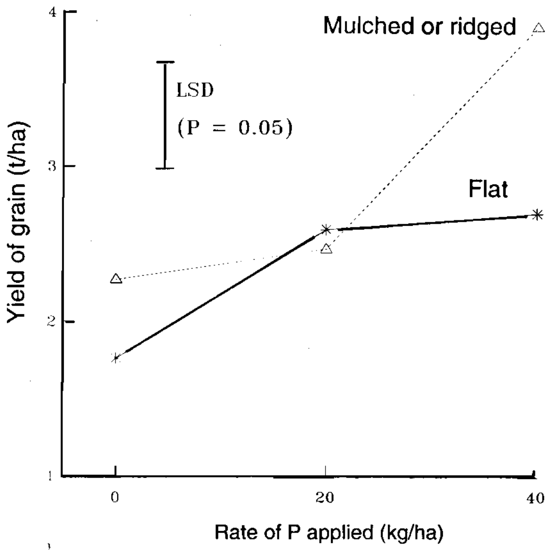

Fig. 1. The effect of surface soil management and rate of application of phosphorus on the yield of maize (t/ha at 15.5% moisture content) at Mutua Farm (short rains 1988). The error bar refers to the comparison between flat surface management and the mean of the two conservative treatments.

therefore based on the assumed total P contents which was the basis on which they were applied. The performance of the PARP was virtually identical to that of superphosphate and a relative effectiveness of 0.92 (s.e. = 0.19) can be calculated based on the grain yields. The rock phosphate source was less effective and the yield data indicate that the asymptotic yield achieved with the other two sources is not being approached. To cope with this, we have fitted a response curve to the rock phosphate data as proposed by Bolland and Gilkes (1990). The implications from this model are that the rock phosphate was unable to supply more than the equivalent of 12.5 kg/ha of P applied as superphosphate no matter how high a rate of application of rock phosphate was used. The experiment is being continued to measure the residual effects of the different sources.

These experiments have shown that large responses can be expected from correction of gross phosphorus deficiencies in both maize and legume crops. It is especially notable that application of nitrogen alone may give disappointing results. For example, in the LR 90 at Mutua Farm, high rates of nitrogen yielded only about 27% of the grain that was obtained when both N and P were applied.

The response to phosphorus observed on these two subsistence farms is in marked contrast to the findings

Table 4. Effects of phosphorus on yield and total P uptakes of maize over two seasons (SR89 and LR90) on Mutua Farm.

(a) Grain Yield at 15.5% moisture (kg/ha)

Rates of P applied (kg/ha)		SR89		LR90
Nov. 89	March 90	Low N	High N	High N
Nil	–	964	1688	1036
10	–	1629	2022	1977
40	–	–	3422	3906
Nil	10	–	–	2101
10	40	–	–	3697
LSD (P = 0.05)		1552		1831

(b) P uptake (kg/ha)

Rates of P applied (kg/ha)		SR89		LR90
Nov. 89	March 90	Low N	High N	High N
Nil	–	1.9	3.3	1.9
10	–	2.7	3.2	3.9
40	–	–	4.9	5.7
Nil	10	–	–	3.3
10	40	–	–	5.8
LSD (P = 0.05)		2.4		2.2

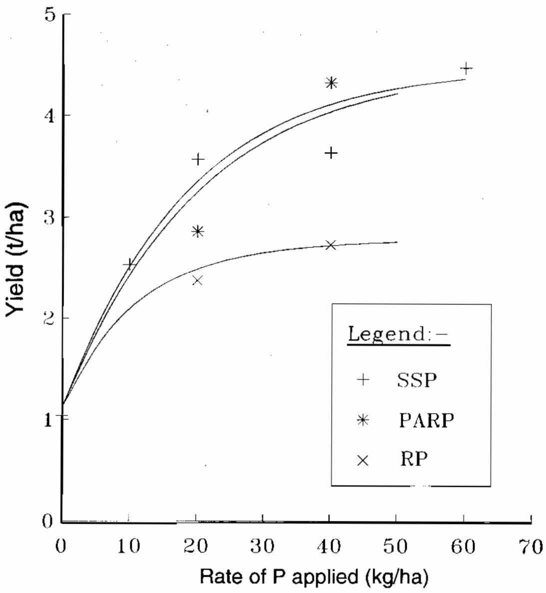

Fig. 2. Effect of different sources of phosphorus on the yield of maize grain (at 15.5% moisture). The lines are derived from the fitted model (Bolland and Gilkes 1990). The data points shown are the means of the applied treatments. The residual standard error for a treatment mean about the fitted model was 271 kg/ha.

of Nadar and Faught (1984) who reported no significant response to phosphorus in their experiment on Katumani Research Station despite cropping the plots for seven seasons. Unfortunately, no soil P data were reported for their experiment.

Towards a Crop Model that Simulates Effects of Phosphorus

The climatic conditions for the experiments that have been carried out were generally favourable (with the exception of the LR89 at Kyengo Farm). This may have exaggerated the magnitude of the responsiveness. It would be desirable to have simulation models that can cope with a phosphorus constraint in order to predict the interactions with climate. To achieve this, it will be necessary to understand how phosphorus deficiency affects the development and phenology of the maize crop. The experiment at Mutua Farm was carried out to provide such data.

Crop Development

Effects of phosphorus deficiency were observed on the rate of leaf appearance. The rate of development of leaf collars is shown in Figure 3. There was good agreement between the two crops grown in SR89 and LR90. Time to 75% silking was also delayed by up to 10 days on plants that had not received phosphorus.

There is some discrepancy between the observations on these experiments and what is 'normal' for the cultivar as incorporated into the current crop simulation model (Keating et al., these proceedings). This may be indicative that the phosphorus limitation had not been entirely overcome, though in the experiment where rates of phosphorus above 40 kg/ha were used there was no significant response in yield to the higher rate (Fig. 2).

P Concentrations in Plants

Nutrient concentrations in plant tissue decline as the plant grows. In Figure 4 the phosphorus and nitrogen concentrations in the whole plant are plotted against growth stage as defined by Hanway (1963). The nitrogen concentrations lie close to the relationship given by Jones (1983) for 'crops with near optimum dry matter yields'. This is the relationship that is used in the CERES–Maize simulation model. However, our phosphorus concentrations lie well below those suggested by Jones (1983). Why should this be?

Firstly there could be an analytical problem, but this seems unlikely because the wet ashing method used compared well with a dry ashing method (Okalebo 1985). Also, we have had some samples analysed independently

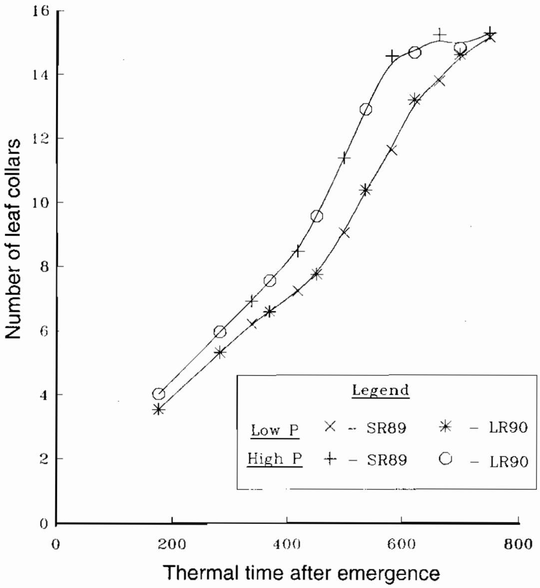

Fig. 3. The rate of appearance of leaf collars expressed in terms of thermal time (base temperature 8°C) after emergence for plants that did not receive phosphorus and those with the high rate of application.

by another laboratory and any bias towards low analytical values is much too small to account for the effect shown in Figure 4. Other explanations possible are that either our plants were less than adequately supplied with P, or that Katumani Composite B dilutes its phosphorus to a greater extent than the cultivars involved in the study of Jones (1983). We found that despite the large effect of applied P on crop yield, there was little effect on the P concentrations in any plant tissues.

In Figure 5, the yields of grain are plotted against P uptake and N uptake. The data from the experiments at Mutua Farm are concentrated around the relation used by Janssen et al. (1990) for maximum dilution of phosphorus. Since their data were derived from other locations in Kenya, it would seem that maize plants in this environment can have overall P concentrations that are as low as we have observed. In order for P to be 'maximally diluted', no other constraint (either water or another nutrient) can be limiting biomass accumulation. It is noticeable that the data from Kyengo Farm that are

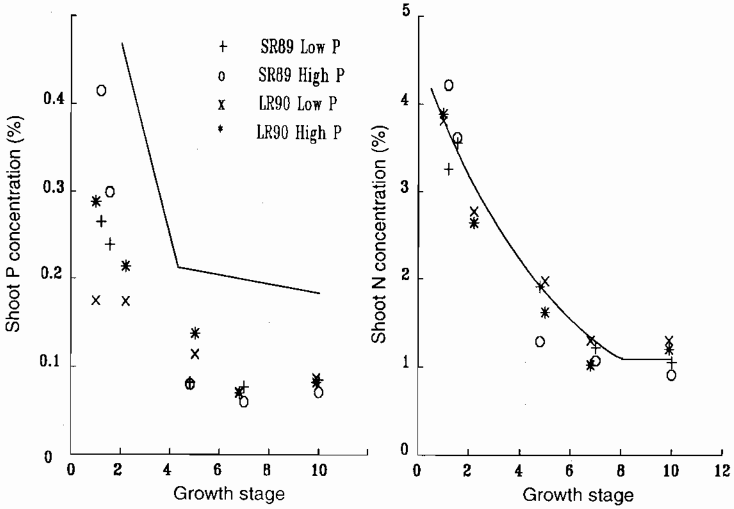

Fig. 4. Phosphorus and nitrogen concentrations in maize shoots at Mutua Farm for treatments that received 90 kg/ha of N. The lines drawn are the relationships given by Jones (1983) for crops with near-optimum dry matter yields.

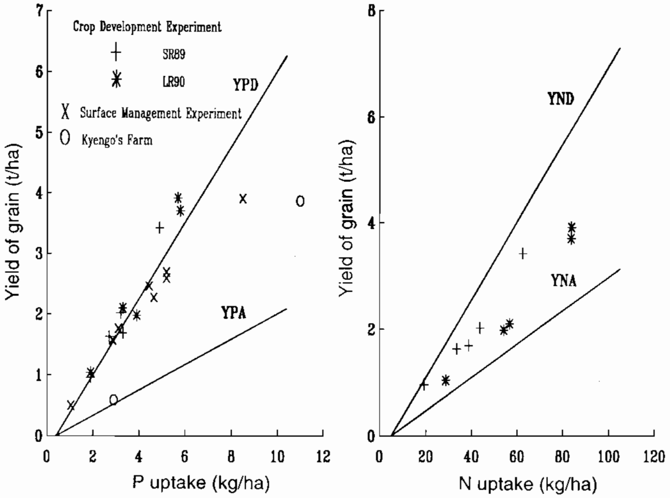

Fig. 5. Relationships between yield of grain (at 15.5% moisture) and total uptakes of phosphorus and nitrogen. The lines drawn are from the equations used by Janssen et al. (1990) for calculation of grain yields from uptakes of nitrogen and phosphorus when the nutrients are maximally accumulated (YNA, YPA) or diluted (YND, YPD).

included on Figure 5 fall below the line of maximal dilution of phosphorus indicating that some other constraint may have been active at this site.

Components of Yield

Figure 6 shows that the main factors contributing to increased yields of maize as the phosphorus constraint was relieved were the greater proportion of plants that set cobs, and the number of grains per cob. The 1000-grain weight did differ significantly between treatments in LR90, but not in SR89; it appears to be of lesser importance than the number of grains per cob.

Aspects Subject to Continuing Experimentation

Residual effects of phosphorus. The data in Table 4 show that very good residual affects to applied P were obtained at Mutua Farm when there was minimal disturbance of the bands of fertiliser. The treatment that received 40 kg/ha of P in the first season gave yields in the following season that were as high as where fresh P had been applied. Further experimentation is under way to investigate the effect of cultivation and mixing of the fertiliser band on the residual effects. Additional data on this aspect will also be obtained from the experiment comparing different sources of phosphorus which is being continued to assess their residual effects.

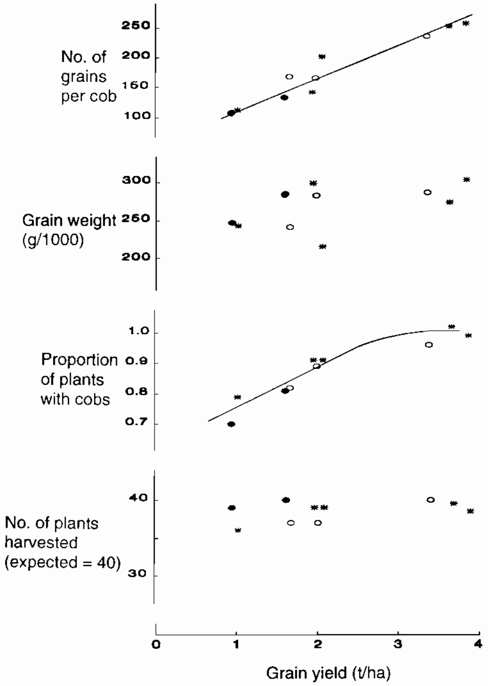

Fig. 6. The influence of phosphorus on the components of maize yield. Data are from Mutua Farm for the SR89(o) and LR90(*). The solid symbols denote the treatments that received the lower input of nitrogen.

Placement of phosphorus. The standard method of applying phosphorus in our experiments has been to apply it as a band beneath the seed. By so doing, it has been expected that its effectiveness would be enhanced compared with broadcast application.

However, those subsistence farmers who do use fertilisers tend to use it very sparingly and even more localised placement may be practiced whereby the fertiliser is placed in individual planting holes. Simulation studies of phosphate uptake by young maize plants (Kovar and Barber 1987) show that there is an optimum volume of soil that should be fertilised in order to maximise the uptake of applied P. The relationship between uptake of P and the degree of placement increases at first, but with further localisation there is a decline in uptake. The optimum fraction to fertiliser was 2 to 5% on the majority of soils. Calculation shows that applying the fertiliser to individual planting holes will result in the volume of soil fertilised being considerably less than what may be optimum. For a wide row crop like maize, even the banded treatment may be too localised for optimum uptake. Experiments are under way that compare broadcast, banded and more localised placement of phosphate.

Phosphorus × nitrogen interactions. With the exception of the data obtained in SR89, when two rates of nitrogen application were compared at sub-optimal levels of phosphorus (Table 3), our studies have been directed towards the effects of P at non-limiting rates of application of nitrogen. Yet it is to be anticipated that the responses to N and P will interact, and the nature of the interaction will be determined by the availability of water.

This aspect is now receiving attention and the large plots at Mutua Farm have been split with the aim of investigating the response to nitrogen on soils that have different histories of P application. Data on both crop phenology and yield of maize will be collected.

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The Role of Boma Manure for Improving Soil Fertility

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RUTHENBERG (1980) stated that 'hardly anything is as destructive in terms of maintaining a balanced environment as the expansion of impoverished smallholder farming producing unfertilised arable crops on depleted soils in a tropical setting'. Continuous cultivation without replenishment of nutrients must in time result in productivity declining to a low level. The only means of reversing this insidious process is through inputs of nutrients. For resource-poor subsistence farmers in the semi-arid areas of eastern Kenya, the principal source of nutrients that is available for their crops is farmyard manure (FYM) produced on their holdings. Its use provides a means of recycling nutrients and, where animals have access to forages outside the croplands, a means of collecting nutrients from surrounding areas.

Nutrient deficiencies are a major constraint to crop production in the semi-arid areas targeted by our project. Consideration must therefore be given to the effectiveness with which farmers use the manure they have.

In this paper we outline how farmers in the Machakos District of Kenya keep their animals and manage the manure on their farms, estimate how much manure is likely to be available on the farms, review previous studies in the region on the effectiveness of manures as sources of nutrients for crops, and present results for the amount and quality of the manure being applied by farmers and the accumulation of nutrients beneath the boma.

The Boma System

Farmers' animals are kept in small enclosures (bomas) overnight and at various times during the day. The animals are taken for watering and grazing in both the morning and afternoon, but spend the balance of their time (i.e. at least 16 hours per day) in the boma. Goats and sheep may be kept in separate bomas from cattle. For convenience and security, bomas are located close to the homestead. They are usually built cheaply of bush poles and/or thorn branches and once constructed may remain in use for many years. Excreta from the animals accumulate in the boma. Crop residues may be fed to animals in the bomas soon after the grain is harvested. Unconsumed stems and coarse residues are trampled into the soil and dung and to some extent are composted in the bomas.

Each year, usually at the end of the long dry season (August–October), the manure is dug out of the boma, perhaps stored temporarily in a heap to dry and (reputedly) cool, and then transported to the croplands using ox-carts, and less often wheelbarrows, where it is deposited in heaps. These are subsequently spread and ploughed in.

The trampling of the excreta and crop residues with the soil in the boma and the digging out of the manure each year, result over time in the boma area becoming a shallow pit. On some soil types at least, water collects in the boma for extended periods and animals may stand to their hocks in a slurry of mud and manure. These conditions could be expected to produce anaerobic soil zones conducive to denitrification. Furthermore, because there is no uptake of water from the boma (other than by evaporation), leaching of nutrients can be expected to occur. Both mechanisms will lower the nutrient content of the manure recovered from the boma and constitute possible inefficiencies in the recycling of nutrients.

The Effectiveness of Manure

Application of manure can have beneficial effects on both the physical properties (e.g. structure, infiltration rates) and chemical fertility of soils. A large part of the responses obtained is undoubtedly due to the nutrients that the manure contains. Some studies of the effectiveness of manure have been carried out previously in the area (Ikombo 1984; Kilewe 1987; Okalebo, unpublished data).

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The responses Ikombo (1984) obtained in the yields of maize at two sites are illustrated in Figure 1; at a third site (Katumani Research Station) there was no response to either manure or the fertiliser treatments and high yields were obtained on the control treatment.

The manure used in this study was collected from the dairy yards at Katumani Research Station and stockpiled prior to use (B.M. Ikombo, pers. comm.). It may not be typical of the manure available to farmers as it had been subjected neither to trampling and mixing with crop residues and soil, nor possible denitrification or leaching losses.

A feature of the results is the good residual effect obtained in subsequent seasons. Ikombo concluded that 'the application of FYM at the rate of 8 t/ha appeared to give high and consistent yields, close to that obtained by applying the standard rate of mineral fertilisers (this was 40 kg/ha of N and 17 kg/ha of P), indicating that this could supply maize plants with enough nutrients'. An application of 8 t/ha of the manure used by Ikombo (1984) would have supplied 130 kg of N and 40 kg of P. Bearing in mind that not all of these amounts would become available for uptake by the crop in the first season, they are reasonable rates of application in terms of the requirements of a maize crop. No conclusion was reached on how often the manure should be reapplied. Because of the residual effects, it would not be expected that applications of this magnitude would be required every year. The findings of this study are the basis of current recommendations for farmers of the region concerning the use of manures (B.M. Ikombo, pers. comm.).

Kilewe's (1987) results are illustrated in Figure 2. They

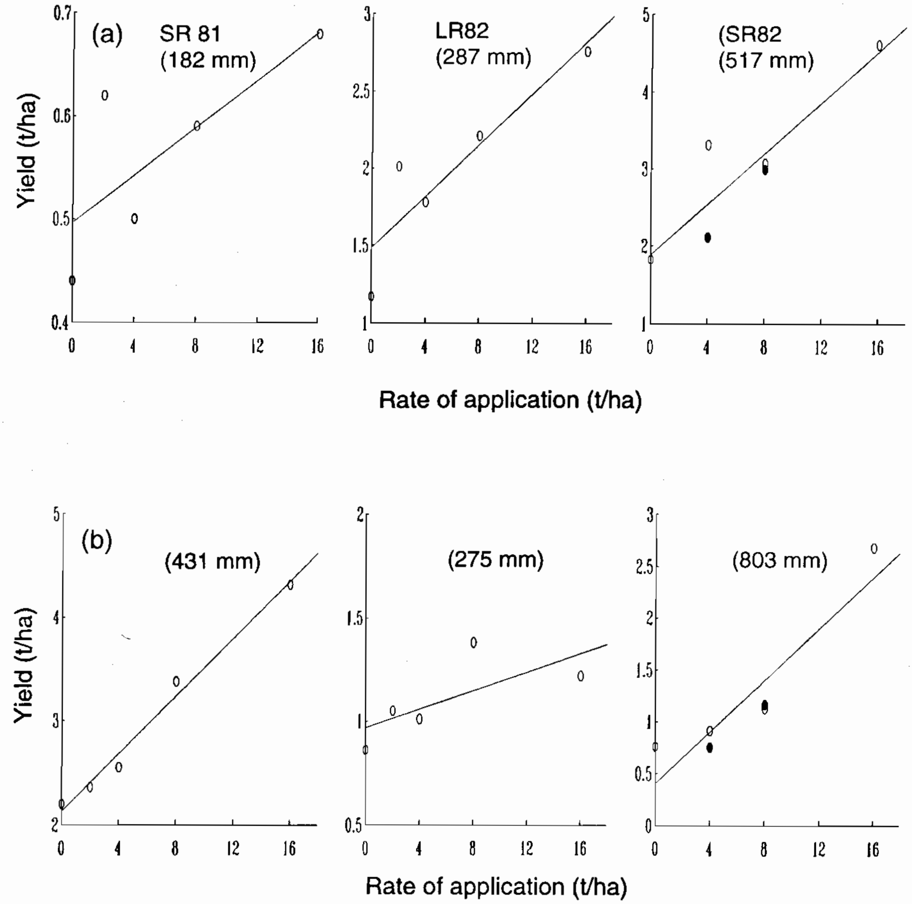

Fig. 1. Effects of application of farmyard manure on grain yields of maize at (a) Kampi ya Mawe and (b) Ithookwe. Initial applications of manure were made to the crop in short rains (SR) 1981, residual effects were determined in long rains (LR) 1982, and some fresh applications (denoted by solid symbols) were made for the SR 82 crop. Seasonal rainfall (mm) is shown in parentheses. Adapted from Ikombo (1984).

show that 40 t/ha of air-dry manure yielded a crop at least as good as that from the highest input of fertiliser, which supplied 120 kg N and 40 kg P per hectare. The two lower rates of application of manure did not give a full crop yield. No information on the source or nutrient content of the manure was given.

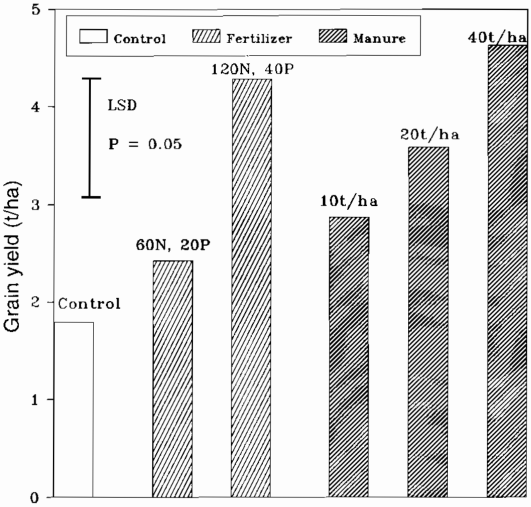

Fig. 2. Effects of fertiliser and manure on the yield of maize. Data from Kilewe (1987) are the means of the treatments that had zero or 3 cm of surface soil removed. The rates of application of manure are on an 'air dry' basis.

In these studies no effort was made to identify the nutrient(s) responsible for the response. Manure provides both N and P (and other nutrients), but they present in less soluble forms than in commercial fertilisers. The response obtained will thus depend upon the deficiencies that occur in the soil and the rate at which the nutrients in the manure are made available. The nutrient responsible for residual effects will not necessarily be the same as that causing responses when freshly applied.

In studies carried out by Okalebo (unpublished data), an attempt was made to separate the effects of N and P by including treatments that compared their effects (alone and combined) with those obtained with poultry manure and FYM; however there were only single rates of application of each fertiliser material. The results from the three sites were similar and the means are presented in Table 1.

In no instance was the response to separately applied N or P significant, making it impossible to determine which of the nutrients in the manure caused the responses. When N and P were applied together, yields were similar to those obtained with the FYM and poultry manure. Residual effects following a single application of the fertiliser materials tended to be greater for the manures than the inorganic sources, but yields were below what could be achieved with fresh application of the manures.

Table 1. The effects of fertilisers and manures on the yield of maize grain (kg/ha) averaged over three sites. Data of Okalebo (unpublished).

Treatment	First season	Second season	
		with fresh application of fertilisers	initial application only
Control	2340	1507	1336
CAN (60 kg N/ha)[a]	2378	1332	1046
TSP (40 kg P/ha)[a]	2228	1769	1432
CAN + TSP	3212	1876	1392
FYM[b]	3084	2212	1767
Poultry manure	3998	1972	1788
s.e.	109	91	95

[a] Sources of N and P were calcium ammonium nitrate (CAN) and triple superphosphate (TSP)

[b] The farmyard manure used was not the same at all sites. Rates of N and P applied (kg/ha) in the FYM treatment were: at Kathonzweni and Kampi ya Mawe 103N and 44P, at Kimutwa 215N and 49P. The poultry manure supplied 106N and 58P.

How Much Manure Could Be Available on Farms?

The amount of dry manure that can be expected to be deposited in bomas has been estimated by workers at ILCA (P.N. de Leeuw, pers. comm.) at 1 t/year/tropical livestock unit. This would be of good quality and, based on the nutrient contents assumed by S. Sandford (unpublished data), would contain 19 kg N and 3.5 kg P.

Data presented by Ockwell et al. (1991) show average figures for seven farms in Mwala, Wamunyu and Makueni locations as follows: crop area 3.4 ha, grazing area 5.1 ha with 2.4 oxen, 7.7 cattle, 8.1 goats and 1.3 sheep, which converts to 8.7 livestock units. Applying the figure above for the yield of manure, an annual rate of application of 2.5 t/ha of cropland would be possible, containing 50 kg of N and 9 kg of P.

Thus, if there were no inefficiencies in the system, the potential annual inputs of nitrogen and phosphorus on an 'average' farm are enough to support a yield of about 2 tonnes of maize grain per annum. This must be viewed as the upper limit of productivity determined by the return of nutrients in manure. It assumes that all the nutrients in crop residues are fully recycled via manure, that there are no losses of nutrients from deposited manure, and that the nutrients in manure can be fully utilised by the maize crop. These are obviously unrealistic assumptions but there is no information available that permits one to ascertain just how unrealistic they might be.

Where the numbers of animals kept by a farmer are fewer, as they are in more closely settled areas nearer to Machakos, the potential for maintaining soil nutrient status with manure will be even lower.

The On-farm Situation

Studies carried out in the Mwala location before the short rains 1990–91 addressed the following two issues.

- The rate and quality of the manure being applied by farmers. This was achieved by counting the number of heaps of manure placed on a given area and measuring the mass of selected heaps. The heaps were subsampled and analysed to determine the quality of manure.
- Accumulation of nutrients beneath bomas. Soil samples were collected from beneath bomas after the farmer had removed the manure and from nearby areas (within 20 m) where soils were judged to be similar but unaffected by the bomas. Unless prevented by stoniness or other impenetrable layers, samples were collected to 2.1 m. Samples were air-dried, sieved and analysed.

Some observations made while carrying out the sampling in the field are pertinent. There is a considerable discrepancy between when farmers expect to clean out their bomas and move the manure to the croplands and when they actually do so. Ten farmers were contacted in July who agreed to permit us to sample manure on their farms. They all asserted they would move manure in August or early September. Yet when we concluded sampling on 4 October several of these had not yet removed their manure from the boma. The presence of pigeon peas awaiting harvest is a major constraint to the operation as it inhibits the use of ox-carts to carry the manure to the terraces. The delay in moving the manure creates a bottle-neck in that it has to be moved, spread and the land ploughed, and as a consequence the farmer may miss the opportunity to plant early, which is recognised as being of benefit in this environment. We encountered one farmer in our study who recognised the importance of the timeliness of the job; even though he had pigeon peas on the area where he wanted to apply his manure he had decided to get the job done by using a wheelbarrow! On one other farm that was sampled, a wheelbarrow had been used to move manure to the portion of the terrace closest to the boma and an ox-cart to the more distant part.

Ockwell et al. (1992a,b) in discussing the labour requirements of various farm activities indicate that harvesting of pigeon peas occurs in July–August and manure is moved in August–September. This closely corresponds to when our farmers expected to move their manure, yet the reality was rather different. We have no reason to suspect that the season when we conducted our sampling was unusual in that pigeon peas were harvested later than normal.

Rates of Application of Manure

Because of the small number of heaps that were measured — in most instances only two per sampled area — the sampling strategy was less thorough than it might have been. The estimates of the rate of application of dry manure are considered correct to within 20% as ascertained from agreement between the masses of duplicate heaps.

The data in Table 2 show that estimated rates of application varied widely, from 38 to 168 t/ha. It is very noticeable that the larger the heaps in the field, the higher the rate of application. Rates of application were higher than those found in two areas of Zimbabwe (Magwira and Shumba 1986) where the estimated application rates ranged between 14 and 72 t/ha, the average being very close to the recommended rate of 37 t/ha every four years. None of the farms studied had sufficient manure to apply to the whole crop area. One farm had applied manure to one of ten terraces, another to half of a terrace out of three. On this limited evidence the frequency with which croplands might receive manure is less in the Mwala district than in the Zimbabwe study. All of the farmers visited asserted that they practice a policy of applying manure to different terraces each year. However, in our study of the fertility of farmers' terraces (Okalebo et al., these proceedings), higher soil P levels were found on terraces closer to the homesite. It is likely that this effect is associated with these terraces receiving more frequent applications of manure.

Table 2. Measured rates of application of manure.

Farmer	Area sampled (m^2)	Number of heaps	Average mass of heaps (kg DM)	Rate of application (t DM/ha)
John Nzioka	472	18	110	42
Matenge Mbaki	290	65	17	38
Gregory Ngao	840	35	322	134
Mrs Kasiva Ngului				
(i) small heaps	127	18	55	78
(ii) large heaps	185	14	222	168
Dominic Makuti	384	22	156	89

The Quality of the Manure

The manures sampled from the heaps on the farmers' croplands were air-dried, ground and analysed. The results are given in Table 3 together with some other published data on the analysis of manures.

The most obvious feature of our results is the extremely high ash content of the samples. This corroborates the impression gained in the field that the manures contained substantial amounts of soil. A consequence of the mixing of the manure with soil is that the nutrient content of the manures that farmers carry to their croplands is poor. The N content of the manures we sampled is only about one-third of that used in the field experiments of Ikombo(1984). Even the materials used by Okalebo, collected from farms where he carried out his studies, contained higher concentrations of nitrogen than we found on farms in the Mwala location.

Because the materials sampled contained so much soil, we have also performed some analyses using routine soil analytical methods (Walkley-Black organic carbon, mineral-N and Bray No. 2 extractable P). No strong relationship between the ash content and organic carbon was found. Mineral N and extractable P levels in the FYM samples were high compared with the levels usually found in soils, indicating that they would be expected to be useful sources of these nutrients.

Averaged across the five farms where data on rates of application of manure and its nutrient content were obtained, inputs amounted to 280 kg N, 91 kg P and 448 kg K per hectare. Despite the low nutrient content of the manures, farmers are applying it at rates that provide high inputs of nutrients, considerably above those that have been used in the experiments of Ikombo (1984) and Okalebo (unpublished).

Accumulation of Nutrients in Soil Beneath the Bomas

Soils were sampled from the floor of bomas and from adjacent areas on seven farms. Results of nutrient analyses are summarised in Table 4. There was very clear evidence that the soils beneath the bomas had become enriched with nutrients. This showed up especially in the data for mineral-N and extractable P, K and Ca.

The soils beneath the bomas also had a much higher pH. The only exception was on Farm 1 where the soil on which the boma was located was a vertisol and the adjacent soil already had a high pH. Typically, the soil

Table 3. The nutrient content of boma manures from the Mwala location and other African data.

Reference	Ash	C	N	P	K	Ca	Bray 2 P (ppm)	Mineral N (ppm)
	(%)							
This study[a] (Farmer's name)								
Nzioko	94	4.4	0.63	0.14	0.84	1.24	648	81
Mbaki	92	5.1	0.55	0.16	1.10	1.94	727	47
Ngao	94	1.6	0.17	0.08	0.26	0.58	185	81
Ngului	88	3.4	0.33	0.13	0.66	0.96	473	87
Makuti	89	4.4	0.50	0.14	0.68	0.84	214	87
Kioko	91	3.0	0.35	0.20	0.78	1.47	894	135
Kioko — ex goat boma	79	5.3	0.62	0.25	1.56	3.09	946	124
Ikombo (1984)			1.62	0.50	1.34	0.26		
Okalebo (unpublished)								
Kimutwa			1.33	0.30	2.11			
Kathonzweni			0.81	0.34	2.44			
P.N. de Leeuw (ILCA) (pers. comm.)								
fresh cattle manure	53		1.28	0.45	2.65	1.26		
old cattle manure	81		0.49	0.31	1.65	0.85		
small stock manure	74		0.59	0.57	0.57	1.76		
Magwira and Shumba (1986)								
Chiota communal area			0.98	0.13	0.99	0.48		
Svosve communal area			1.05	0.19	1.47	0.58		
Mokwunye (1980)								
Range for various samples from west Africa			0.48 to 1.95	0.06 to 0.57	0.39 to 2.62			

[a] For the present study the analyses were performed on air-dry samples but results are reported on an oven-dry basis.

in the floor of the boma had a pH in water of 8.5–9.5 and these high pHs extended to depths of more than 0.5 m. These high readings indicate the presence of carbonate in the soils, and some of the potassium and calcium measured will be present in the soil solution rather than as exchangeable cations. The high pHs beneath the bomas are likely to have arisen from the oxidation of organic anions added to the bomas (K.R. Helyar, pers. comm.). Once such high pHs are created, conditions will be conducive to loss of N by ammonia volatilisation.

The differences between the soils beneath the bomas and the adjacent areas were not as marked in the organic carbon or total N data. This is probably because a variable amount of soil had been removed with manure during the time that the bomas had been in use, so that comparisons are being made between what was once subsoil and the surrounding surface soils.

The mean values of mineral N, Olsen P and extractable K are shown in Figure 3. For both mineral N and extractable K the enrichment extended to the full sampling depth (2.1 m), but for extractable P the effect was restricted to the layers closer to the surface. The data for mineral N and extractable K suggest there is a downwards flux of these nutrients, so that unknown quantities of these nutrients may have leached beyond the depth of sampling.

The boma areas are reasonably small: the range for the farms sampled was approximately 50–300 m^2 depending on the numbers of animals being kept. Nonetheless, there is an accumulation of nutrients beneath the bomas and these areas are acting as sinks for nutrients that have been removed from farmers' soils and are no longer being put to any use.

Needs for Further Research

The studies reported here indicate that the nutrients in manure that are available for use on farms in the semi-arid region of Kenya are not being used as effectively as they might be. There can be no doubt that the continuous cropping system has resulted in a decline in the fertility of the soils, and that this process is continuing. Recycling of the nutrients within the farming system has the potential to retard the decline in soil nutrient status thereby making the system less demanding on the input of nutrients from other sources. Any inefficiencies, due to loss of nutrients from the system, must contribute to the impoverishment of the soils.

The studies that have been made identify a number of causes for concern. Firstly, the quality of the material that is being recovered from the bomas and applied to the croplands is poor. In particular the N content of the manure is very low. This arises partly from the fact that the manure is mixed with much soil, but there is also evidence that processes are occurring within the boma system that will lead to a loss of N from the system. Direct evidence is provided of leaching losses as shown by accumulation of nutrients beneath the bomas. The high pH of the soils under the boma was unexpected and will be conducive to ammonia volatilisation. The very wet conditions that sometimes occur in the bomas can be expected to cause losses through denitrification.

The second issue relates to the rates of manure being applied by farmers. This is a scarce resource and there will never be enough of it to satisfy the nutrient requirements of all the croplands. We found that some farmers were applying what seemed to be extraordinarily high rates, especially when one considers that they had only enough manure to treat a small fraction of their crops. One would suspect that better returns would be obtained by a lower rate of application to a larger area. Unfortunately, there is a lack of information on the responses that farmers can expect to see to the nutrients in boma manure and which could form the basis for recommendations on its rate and frequency of application. There would seem to be a role for incubation studies to measure the rate at which the N and P in manure become available, and also for field studies to measure the

Table 4. Comparison of soil analyses for samples collected beneath bomas and from adjacent areas; + indicates that the values are higher under the bomas.

Farmer	Soil property							
	pH in H_2O	C (%)	N (%)	Mineral N	Olsen P	Bray 2 P	Extr. K[b]	Extr. Ca[b]
1. Matenge (5)[a]				+	+			+
2. Nzioka (18)	+	+	+	+	+	+	+	+
3. Muinde (~30)	+			+	+	+		+
4. Ngao (~10)	+	+	+	+	+	+	+	+
5. Ngului (~20)	+			+	+	+	+	+
6. Makuti (~10)	+		+	+	+	+	+	+
7. Kioko (>10)	+			+			+	+

[a] Numbers in parentheses indicates the time (in years) that the boma had been in use.

[b] Extractable K and Ca using the ammonium lactate–acetic acid solution of Egner at al. (1960).

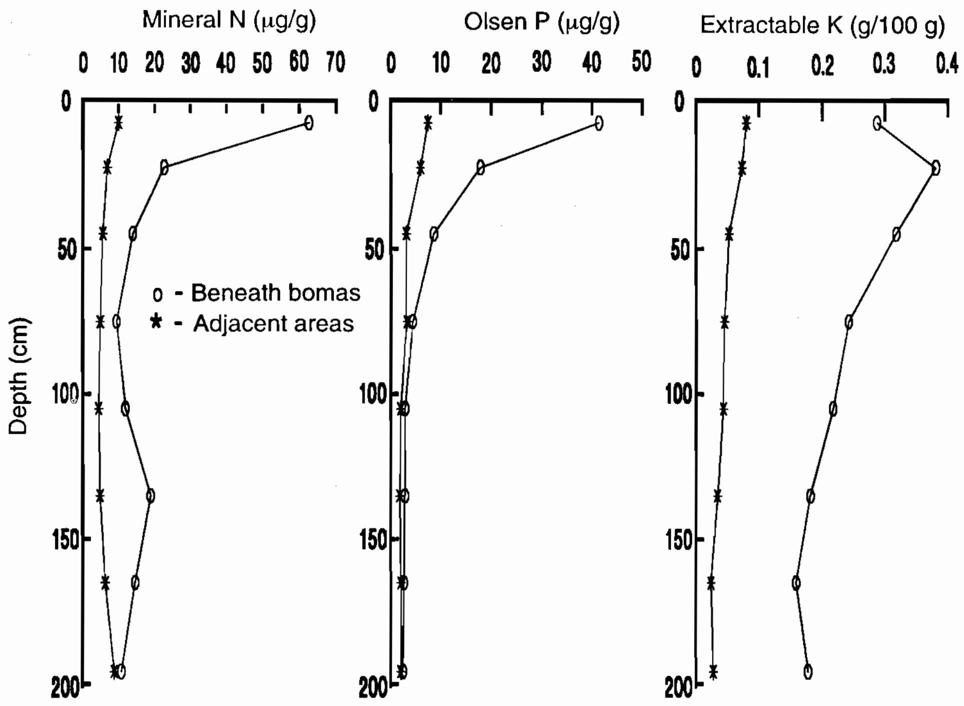

Fig. 3. The accumulation of nitrogen, phosphorus and potassium beneath bomas. Data plotted are means for the seven bomas that were sampled.

immediate and longer-term effects of application of manure. Any such studies should involve 'typical' manure as used by the farmers. In field experimentation it is imperative that the nutrient(s) responsible for the effects are identified and their effects separated. Other issues that could be addressed relate to the manner in which manure is applied. Would it be more effective if it were localised below or along the rows as it is sometimes applied around tree crops such as citrus or coffee?

Our studies have shown that enrichment of the soils beneath the bomas does occur, but gaseous losses of nitrogen, as ammonia volatilisation or via denitrification, may be of even greater importance than leaching losses. While it would be of interest to have better information on the conservation of nutrients in the boma system (a direct comparison of what goes in as crop residues and excreta and what comes out as manure), such information could not be directly applied to the benefit of the farmers. Of more fundamental importance is to question the suitability of the current boma system as a means of recycling nutrients. It might be preferable to locate the boma in an elevated position so that it sheds rather than gathers water thereby reducing the likelihood of losses of N by denitrification and leaching, though losses in runoff from the boma might then become an important process leading to loss of nutrients. Perhaps the dung could be removed from the boma more frequently during the year so that it is less exposed to the anticipated loss mechanisms. How would this affect the yield of manure and its quality? Are there alternatives whereby the animals could be enclosed temporarily on different, rotated areas of cropland thus enriching these directly for the benefit of subsequent crops? Answers to such questions might lead to better conservation and recycling of nutrients in the mixed farming systems of the semi- arid regions.

Acknowledgment

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Exploring Strategies for Managing Runoff and Erosion

Assessment and Alleviation of the Impact of Runoff and Erosion on Crop Production

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THIS paper concerns management of the important processes that lead to loss of resources in an already resource-poor farming system. To the degree that rainfall runs off rather than enters the soil, a problem of inadequate rainfall for crop water supply is exacerbated. In that part of Kenya of interest in the KARI/ACIAR/CSIRO study, where landscapes are predominantly sloping and where fields generally have low soil cover, cumulative runoff relates closely to cumulative soil erosion. However, not only does runoff cause erosion, but there is positive feedback through the effect of erosion increasing subsequent runoff. The surface of fields whose topsoil has been eroded tends to crust and shed an even larger proportion of rainfall.

Positive feedback is similarly important in the relationships between erosion, soil fertility, soil cover, and infiltration/runoff. Reduced soil fertility is the first production-reducing casualty of erosion. Reduced fertility results in less biomass production and, consequently, less surface cover and less soil macrofaunal activity. These result in reduced infiltration, higher runoff and soil loss, and further reduction in soil fertility.

The complexity of these interactions has important implications for improved soil surface management strategies and the research and development activities that pursue them. This paper scans past research in the region, explores the principles of improved management, and describes a new research program aimed at improving the Kenyan research and development capability to pursue strategies for more sustainable agriculture.

Some Earlier Studies in Kenya's Semi-arid Regions

The study of soil and water conservation in Kenya's semi-arid lands dates back to the era prior to independence. Studies on the design and maintenance of terraces and waterways were carried out and/or reported by the following: Maher (1936a, 1939, 1943); Barber and Van Eijnsberen (1981); Barber et al. (1981); Thomas (1983); Thomas and Barber (1979; 1983); Thomas et al. (1980); and Thomas and Biamah (1989). Work on land use and cropping systems has included that by Maher (1937a,b,c,d); Moore (1979); Pereira (1979); Pereira et al. (1958); Pereira et al. (1961); Thomas (1974, 1975, 1980, 1982). There has been an extensive range of studies concerning tillage, soil structure and general soil surface management, with Barber (1979, 1980), Barber and Thomas (1981), Kilewe (1984), Kilewe and Mbuvi (1987a), Kilewe and Ulsaker (1984a,b), Liniger (1988a,b, 1989), Maher (1936b, 1943, 1946, 1972), Marimi (1977, 1978), Moore et al. (1979), Muchiri (1985, 1989), Muchiri and Gichuki (1983), Pereira (1956), Pereira et al. (1958, 1961, 1967), Thomas and Barber (1983), Thomas et al. (1981), and Ulsaker and Kilewe (1983) reporting much of what is presently known.

The effects of erosion on productivity of arable lands has received only limited attention in Kenya. Much of the available information is from the more recent work in the Machakos district of eastern Kenya by Kilewe (1984, 1988), Kilewe and Ulsaker (1984a,b), and Kilewe and Mbuvi (1992). Prediction of runoff and soil loss has also received little attention, mainly coming from Pratt (1962) in earlier days, and Kilewe (1987), and Kilewe and Mbuvi (1987a,b) more recently.

While this list of investigators is by no means exhaustive, it points to the fact that a great deal of research work has been done in Kenya's semi-arid environment to control the high levels of runoff and soil losses that are characteristic of the region. It is evident that past research has been concerned largely with static analyses of the problem. While such static analyses are useful, they tend to be restricted in capacity to deal with processes that vary markedly both in time and in space. There is need for more dynamic analyses of the processes involved in the management of the complex rainfall–infiltration–runoff–soil and nutrient loss problem. Better understanding and management of these interactions are the keys to ecologically sustainable production in Kenya's semi-arid environment.

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Agronomic/Biological Management Strategies to Increase Infiltration and Reduce Runoff and Soil Loss

The Effects of Tillage

The management of the soil surface modifies surface storage capacity, infiltration, and susceptibility of soil to detachment. Tillage has been shown to improve the infiltration capacity of soils (Larson 1962), but such improvements are often very short-lived as the soil settles into a dense compacted medium under the influence of raindrop impact. More serious is the fact that tillage may, in the long run, decrease the soil infiltration rate through increasing the rate of organic matter oxidation (Baeumer 1970), thus reducing soil structure and infiltration capacity. Brams (1971) reported that a five-year continuous cultivation of ferrallitic and alluvial soils, originally under bush, reduced the organic matter contents of these soils by 50%. The effects of these reductions of soil organic matter under continuous tillage are seen in the deterioration of soil physical condition resulting in surface seals, crusts and hardpans leading to accelerated soil erosion even on gentle slopes (Larson 1962).

Conservation tillage conserves soil and water by (a) preserving stable transmission porosity, (b) minimising particle detachment, and (c) retaining mulch cover on the surface of the soil. The importance of stable soil aggregates in a soil's resistance to erosion is set out by Rose (1960, 1961). Any practice or factor that stabilises the soil aggregates will indirectly increase water infiltration into the soil. The effects of tillage are to reduce aggregate stability and cohesion of the soil mass and thereby increase soil loss, while conservation tillage favours stable aggregates. Infiltration is usually maintained at high rates under conservation tillage. Studies have shown improvements in soil hydraulic properties under conservation tillage, although the existence of certain interactive effects between these hydraulic characteristics and seasonal weather patterns have yielded some negative effects (Edwards and Amerman 1983; quoted in Bristow and Williams 1987). In general, where improvements in hydraulic properties have been reported, the effects have been a reduction in runoff and soil erosion losses, an increase in crop water storage, and in some instances an increase in deep drainage beneath the root zone.

The Effects of Mulch

The application of crop residues as surface mulch can improve the hydraulic properties of a soil. Surface mulch stabilises soil aggregates and favours high infiltration rates (Black 1973; Smika and Greb 1975; Suwardjo and Abujamin 1985). Freebairn and Wockner (1986a,b) also reported that mulch maintained higher infiltration rates through absorption of raindrop energy and reduction of aggregate disruption and surface crusting. Various investigators have also reported significant reductions in soil bulk density with increasing and continued use of surface mulch (Black 1973; Brawand 1964; and Johnson 1950), and that lower bulk densities favoured high infiltration rates. Studies by Lal (1975) showing higher infiltration rates under mulch, as compared with unmulched plots, indicated that this increase was due to increased earthworm activity in the soil due to surface mulch. Suwardjo and Abujamin (1985) reported an increase of aeration from 18% to 20% following surface mulch application. The higher aeration favoured higher infiltration rates, and reduced runoff losses.

Lal (1975) reports, after a series of experiments on an Alfisol in Western Nigeria, that mulching with straw effectively prevented runoff and soil loss on slopes ranging from 1% to 15%. Mensa-Bonsuh and Obeng (1979), in comparing bare fallow and mulched plots at Kumasi, Ghana, found that mulching reduced runoff by between 11 and 35 times, and erosion by 188 to 750 times. At the National Dryland Farming Research Centre, Katumani, Kenya, work by Kilewe (1987) showed that 3 t/ha maize stover, applied as mulch (providing over 50% cover) significantly reduced runoff and soil loss, leading to the conclusion that mulch application was 'the best soil conservation practice for this region'. The overall effect of surface mulch on soil erosion is the combination of how it affects the amount and velocity of water flowing on the soil surface, and the sediment-yielding processes of rainfall detachment and runoff entrainment. As infiltration rate increases compared to the rate of precipitation, less water flows on the soil surface as runoff, thereby reducing the shear stress and stream power of the flow, and less entrainment takes place.

Cogo et al. (1984) list four ways in which surface mulch may reduce soil erosion: the protection of the soil surface against direct raindrop impact; the reduction of flow velocity and hence an increase of flow depth which then protects the soil against falling raindrops; the reduction of the erosive forces of runoff (shear stress/stream power effects); and the creation of ponded runoff which enhances sediment deposition. Foster et al. (1985) point out that the effect of contact cover is to increase the hydraulic roughness and thus increase flow depth and lower flow velocity.

Experiments on Podzolic and Krasnozem soils of northern Queensland, Australia, showed that surface mulch provided by sugarcane residues delayed runoff initiation, decreased runoff rates, and reduced soil loss (Prove and Troung 1985). These effects of mulch on surface hydrology have a direct bearing on sediment yield and transportation. Under simulated rainfall conditions, Okwach (1988) reported a reduction in rainfall detachment and efficiency of net entrainment under maize residue cover, leading to corresponding reductions in sediment concentration in runoff and total soil loss. Palis et al. (1990) reported an increased proportion of fine materials and reduced amounts of coarser fraction in the eroded sediment under maize residue cover. They reported a corresponding reduction in total nitrogen loss and attributed this more to the reduction in sediment loss under cover than to the often observed corresponding reduction in enrichment ratio for the nutrient. Laursen (1958) reported that the transport capacity of flowing water is roughly proportional to v^5, where v is the flow velocity. Hence, by reducing v, mulch significantly reduces the transport capacity of a flow, thus reducing soil erosion.

Problems of Adoption of Conservation Tillage/Mulch Retention

Retention of crop residues as mulch is an important soil management strategy and its effects in reducing runoff losses and soil erosion are well documented. However, a major constraint to its applicability is the alternative uses of crop residues for feed, fencing or fuel. Farmers clearly value stover as a stock feed far more than for soil conservation. It was this factor that led Kilewe (1987) to conclude that mulching is not a feasible recommendation in the semi-arid regions of Eastern Kenya.

The typical farmer in this region is caught up in a vicious circle (Fig. 1). As the soil is mined of nutrients and organic matter by removing the crop residues, surface runoff and soil and nutrient erosion are increased. These losses lead to degraded soils which are capable of only low crop yields for food, and provide little crop residues. The available residues are barely able to sustain livestock, leaving no option for retaining some on the arable farm. Under these circumstances, the seasonal production of food in semi-arid Kenya is bound to decrease with time and indeed has. The all-important question is whether it is possible for a farmer to break this vicious circle? What are the options, considering the technical and socioeconomic limitations?

The downward trend of soil productivity needs to be reversed and land degradation halted if these regions are to continue supporting the increasing human population. Some dramatic changes in land and crop management are essential if improvements are to be made. Organic matter contents of soil will have to be steadily increased: this is the only way in which soil physical structure can be improved and the rate of infiltration increased. Returning more crop residues to the soil would be a most effective way to accomplish this but farm animals need these crop residues for food. Mulching can be practiced only if stover production is increased above the traditional levels, or if there are sufficient alternative sources of fodder. McCown (1987) pointed out the need for more critical research on the economics of mulch retention in systems intensified by soil fertility inputs resulting in plant production above the low traditional level. Such an increase provides some 'extra' stover which may be returned to the soil as surface or stubble mulch, while retaining, and setting aside, the equivalent of the traditional stover production for livestock feed. We emphasise that this strategy seems feasible on degraded soils only with inputs of nutrients to the soil, either as farmyard manure or chemical fertilisers, to increase crop production.

Residues retained on the soil reduce runoff and soil erosion. In the long run, residue retention improves soil physical condition through increased organic matter content of the soil. Infiltration of rainwater into the soil is then increased, and water redistribution greatly enhanced, further reducing surface runoff and soil loss. Tillage, ridging and surface residue retention would provide an effective soil surface roughness that would further reduce the runoff. Tillage causes temporary increases in infiltration rates, which decline rapidly under raindrop impact. On the other hand, as stated earlier, tillage is counterproductive as it increases the rate of organic matter oxidation and decomposition, thus decreasing the infiltration rate of the soil, in the long run. For this reason, a conservation tillage practice may be a viable option. Reducing tillage may require some form of chemical weed control but, in the interests of sustainable cropping, these costs need to be weighed against the above-mentioned benefits.

The KARI/ACIAR Soil and Water Management Research Program

Conceptual Framework

Crop productivity is determined largely by the physical, chemical and biological conditions of the soil. The physical conditions drive the hydrology (infiltration, soil water, runoff), while the chemical and biological conditions determine soil nutrient availability. These soil properties and conditions are not static. They vary with time and with management options, and are dependent on the duration of prevailing weather conditions, particularly rainstorms. Thus, both interseasonal and intraseasonal changes need to be considered.

Soil surface management systems, such as tillage options, cover (mulch) application, cropping systems (including density), and fertiliser application, all influence the physical and chemical conditions of the soil. Moreover, the influences of such management systems are themselves subject to time variations. For example, a friable, loosely tilled and highly pervious soil at the beginning of the season will soon, under the impact of raindrops, settle into a dense, less pervious medium as the season progresses. Similarly, an initially bare arable

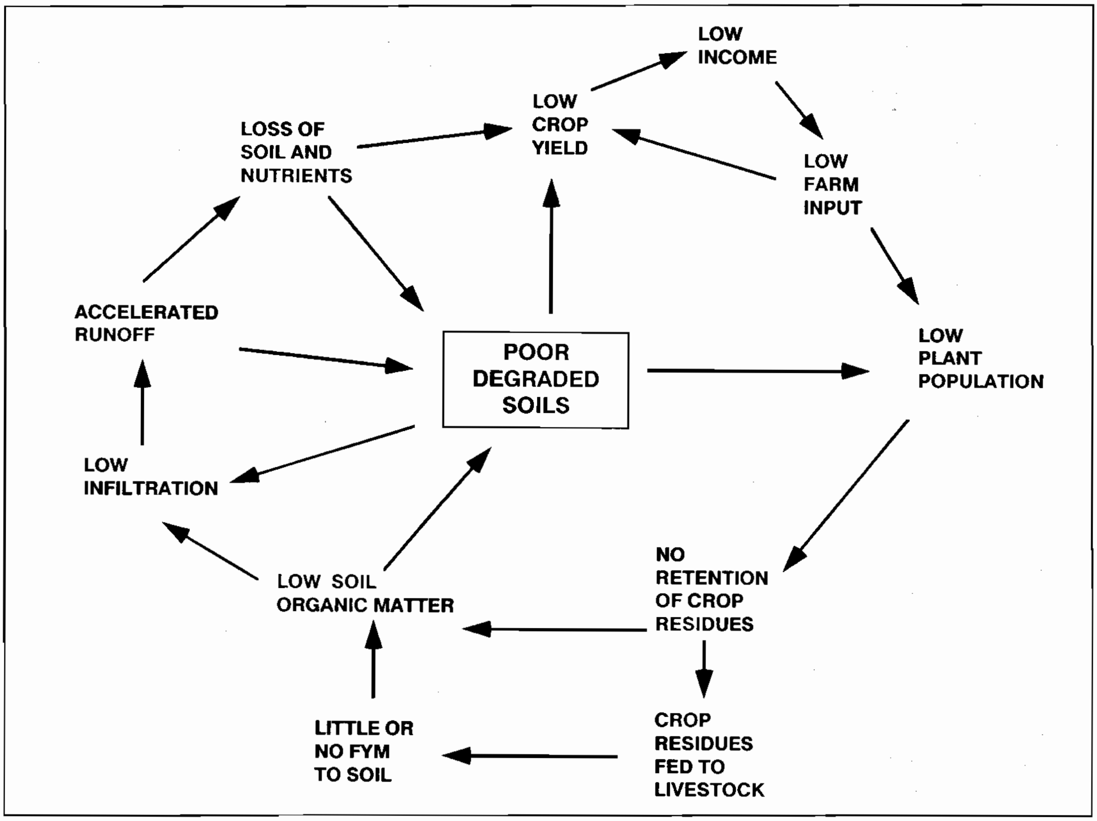

Fig. 1. The conflicts that lead to unsustainable land use for a typical subsistence farmer in semi-arid Kenya.

land, at the beginning of a season, soon becomes increasingly covered by vegetation as the crop grows through the season. Under mulch there are bound to be changes in the proportions of the total cover that are floating above the soil surface or in contact with the soil. As the season progresses, it is to be expected that total mulch cover will decrease (due to decomposing activities of termites and other soil fauna) but, in proportion, contact cover would increase as floating cover decreases.

The broad objectives of this study are to gain an understanding and the ability to predict these changes in soil surface condition and their impact on both erosion and the crop water balance. Rainfall and runoff are monitored as a function of time. Analysis of these measurements (on an event basis) using proven methods will then allow interpretation of what the various surface management options are doing to soil infiltration rate, and soil surface stability, roughness, and water retention. It is expected that such analyses will provide a sound scientific basis for what may be done to control soil and water losses. It is recognised, however, that the complexity arising from the many possible combinations necessitates more than a simple experimental approach to research. Field experimentation forms the first of the two phases of this study. It is intended to provide the data relevant to Kenyan semi-arid mixed farming situations, taking into account the traditional soil and crop management practices and a limited number of possible improved systems. The information will be used in phase two to develop a simulation model for the relevant aspects of the crop–soil–climate situation of the region. With this tool it should be possible to simulate and predict the consequences of any management option on long- term soil productivity, given historical rainfall records.

Objectives

The specific objectives of this research program are to monitor the changes in hydrology, erosion and crop yield that accompany typical cropping practices, commencing with soil in good physical condition. A range of treatments is being studied, with a progressive increase in inputs in terms of water conservation, maize production and soil conservation. Infiltration rate and soil erodibility characteristics are being measured to determine how these change with time in response to soil management and antecedent moisture. Improved models for simulating the soil water balance and erosion that take into consideration soil surface management will be interfaced with the maize model, CM-KEN (Keating et al., these proceedings), and used to compare alternative soil management strategies in terms of productivity and sustainability.

Experimentation

The Site

The experimental arrangement comprises a set of 12 instrumented runoff plots installed at the National Dryland Farming Research Centre, Katumani. Each plot has been individually surveyed for slope, which ranges between 8.3% and 11%. The site was previously covered with pasture so that the initial soil condition is good. Plot size is 15 m × 7 m.

The soil is classified by Aore and Gatahi (1990) as a Haplic Acrisol, developed from biotite gneiss and granitoid gneiss. It is described as well drained and with a very deep effective soil depth. The soil texture grades from sandy clay loam in the surface layer (0–19 cm) to sandy clay at depth, with a gravelly stone line at approximately 125 cm. The surface soil has total N of 0.08% and a pH (in water) of 6.1; extractable P (by the Olsen method) is moderately high at 25 ppm.

Treatments

The seven treatments being studied are described in Table 1.

Treatment 1 is a cultivated bare fallow. This serves firstly as the control in as much as it presents the worst possible soil surface management option. Secondly, it has an important scientific purpose in that it generates data used for determining certain erodibility parameters in the Universal Soil Loss Equation (USLE), and other models. Thirdly, the bare soil surface may also be perceived as a feature of the existing system, since it corresponds to the condition of the farmers' fields during the first few days of rainfall, following cultivation and planting, but before seedling emergence.

Treatments 2 and 3 are features of the existing, traditional cropping systems representing monocrop maize and intercropping with beans. Plant populations are low, no fertilisers are used and no mulch applied.

Treatment 4 is the first step towards a higher input system. It is identical to Treatment 2 except that half of the stover produced is retained as mulch. Thus, the only cost is the value of the fodder that is no longer available for livestock.

Treatment 5 is a 'best bet' of what might be achievable. Input costs are higher due to fertiliser and increased plant density, but this treatment would provide the same amount of stover for consumption by livestock as the traditional system (Treatment 2). Fertiliser applications will be dependent on seasonal rainfall and will draw on expertise from completed studies of Response Farming at Katumani (Wafula et al., these proceedings).

Treatments 6 and 7, while unlikely to be adoptable now by farmers due to their higher inputs, are of research interest in the pursuit of a technology for sustainable cropping. Treatment 6 is the same as treatment 5, except that it uses conservation tillage. Only the planting rows are disturbed in order to accommodate the seeds and to effect good seed establishment. There is no inversion of the soil . Weeding is by herbicide application.

Treatment 7 is the highest input system. It is identical to treatment 5 except that all residues are retained, and a higher rate of nitrogen fertiliser will be used in good seasons.

Table 1. Treatments in runoff experiment.

	Treatment number						
	1	2	3	4	5	6	7
Mulch	Nil	Nil	Nil	50% of stover from previous crop	Stover produced by previous crop in excess of treatment 2		Return all stover from previous crop
Tillage[a]	Conventional	Conventional	Conventional	Conventional	Conventional	CT	Conventional
Nitrogen fertiliser (kg/ha)[b]	0	0	0	0	40+30	40+30	40+60
Maize (plants/ha)	0	22K	22K	22K	53K	53K	53K
Beans (plants/ha)			74K				
Number of reps	1	2	2	2	2	2	1

[a] Tillage Conventional = hand hoe to break soil into loose, friable, flat seed bed and remove weeds.
CT (Conservation Tillage) = plant with hand hoe and kill weeds with Roundup applied with rope wick.

[b] Nitrogen fertiliser 40 kg/ha at planting + additional N 30 days after planting depending on seasonal rainfall.

Data Collection

The strong emphasis on hydrological processes in this study requires measurements of the rate of rainfall and surface runoff as well as the total amounts. Rainfall rate is logged to a minute time base using a pair of tipping bucket rain gauges to provide measurements of rainfall intensity and amount. Similarly, runoff amounts and rate are logged using a tipping bucket at the outlet of each of the twelve catchment plots. Sediment traps and suspension sampling devices enable soil loss to be measured, which is analysed to provide data on nutrient (nitrogen and phosphorus) losses.

To complement the measurements of rainfall, runoff and soil loss, a number of other soil and crop characteristics are measured, including:

- soil surface roughness by use of a profile meter;
- estimates of contact mulch cover;
- canopy cover through estimate of leaf area index;
- hydraulic properties of the surface and the sub-soil layers;
- phenology of crops, yield of grain and stem, and uptakes of nitrogen and phosphorus; and
- other inputs needed for the running of the CM-KEN maize production model.

Early Experimental Results

The long rains (March–June) of 1990 was the first season in the experimental phase of this study. Although a single season's results are inadequate for the formation of any conclusions, they are, however, valuable as early indicators of where the study is heading and illustrate the approaches that will be used to analyse the data. For this purpose, some selected results are briefly presented.

Seasonal Data

The crop yields, runoff and soil loss for the first experimental season are given in Table 2. Increased inputs (improved systems) yielded higher and produced lower runoff and soil loss compared to the traditional cropping treatment. These effects are more marked in soil loss, where the bare fallow and the traditional monocropping system yielded six times more soil than under full mulch. The effect of ground cover is seen in the big reduction of soil loss under intercrop and under the stover mulch treatments.

Event Data Analysis

A detailed examination of each rainfall event allows interpretation of treatment effects. An example of such an event analysis is presented in Table 3 and Figures 2 and 3 for a 40.6 mm rainfall which occurred on 9 April 1990. Although no great difference in total runoff was observed under the various treatments, the time to runoff initiation and the computed infiltration rate showed significant differences (Table 3). Full mulching had the effect of nearly doubling the time to run off initiation, compared to the non-mulch, or less mulch, treatments. The infiltration rate during ponded conditions, which is the highest possible rate of infiltration that may be achieved under given conditions of soil moisture and surface crusting, show large variation with treatments. Ponded infiltration rate was lowest under bare fallow (9 mm/hour), reflecting the possible high surface crust formation in this treatment. As cover provided by mulch and/or the growing crop increased, infiltration rate also increased, reaching a value of 22.3 mm/hour under full mulch and high crop population. These increases in ponded infiltration rates appear to reflect reductions in crusting under these treatments. These values offer the possibility of predicting the performance of any subsequent rainfall events, should the plot conditions remain the same. Under these conditions, for example, a rainfall event of less than 9 mm/hour is not likely to produce any runoff in any of the treatments, while a 20 mm/hour rainfall will yield runoff under both the traditional and the conservation tillage treatments, but not in the full mulch plots, which would require more that 22.3 mm/hour rainfall to produce runoff. Such predictions, however, must be considered valid for only short time

Table 2. Crop yields, runoff and soil erosion during the 1990 long rains.

Treatment	Crop yields (t/ha)		Runoff	Soil loss
	Maize	Beans	(mm)	(t/ha)
Bare fallow	–	–	77[a]	42
Traditional	1.4	–	99	47
Intercrop	2.0	0.4	86	14
+ mulch	2.0	–	73	15
+ mulch + N	3.5	–	74	15
Reduced tillage + N	3.2	–	67	19
Full mulch + N	3.4	–	55	7

[a] Incomplete season figure

Table 3. Surface hydrology for rainfall event of 9 April 1990: total rainfall = 40.6 mm; peak rainfall rate (15 minute intensity) = 30 mm/hr.

Treatment	Total runoff (mm)	Runoff initiation time (min)	Ponded infiltration rate (mm/hr)
Bare fallow	26.3	5	9.0
Traditional	26.5	4	11.1
Reduced tillage	25.2	5	15.2
Full mulch	23.4	9	22.3

periods, because changes in soil conditions (such as soil moisture content and surface permeability) will cause changes in infiltration rates.

Figure 2 is a graphical representation of this event for the bare fallow treatment, while Figure 3 compares the infiltration under bare fallow with that for high crop cover (Treatment 7). Mulch and crop resulted in higher infiltration compared with the bare fallow treatment. Of greater interest in Figure 3, however, are the peaks marked X on the mulch + crop infiltration curve. This curve, derived from the difference between rainfall and runoff, indicates negative infiltration at two points in time. These perturbations represent water stored above the soil surface as a consequence of surface roughness. The high mulch present on the surface had the effect of collecting and retaining water on the surface, and releasing this slowly as runoff. It is expected, and can be shown, that the peaks correspond with the regions of sharp increases in the runoff rate curves. Here may be seen one other process by which cover reduces runoff and increases infiltration. Apart from its effect in reducing surface crust formation, cover acts by retaining

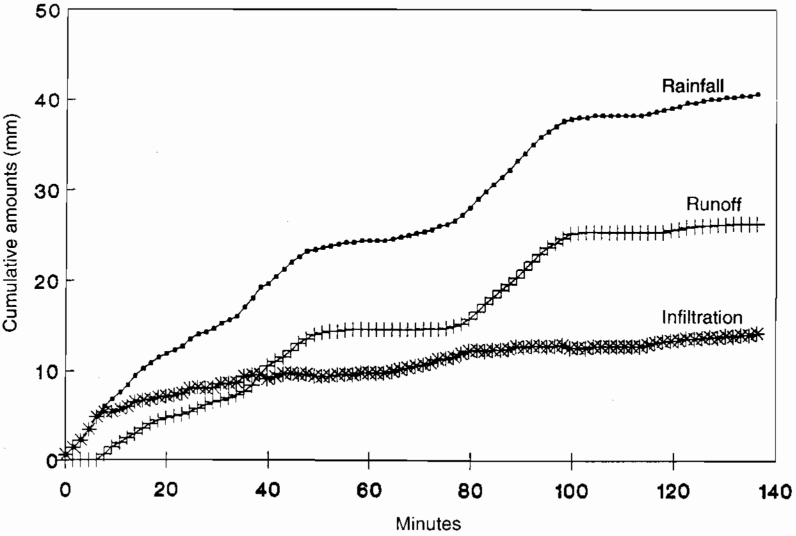

Fig. 2. Runoff and infiltration under bare fallow during an event on 9 April 1990.

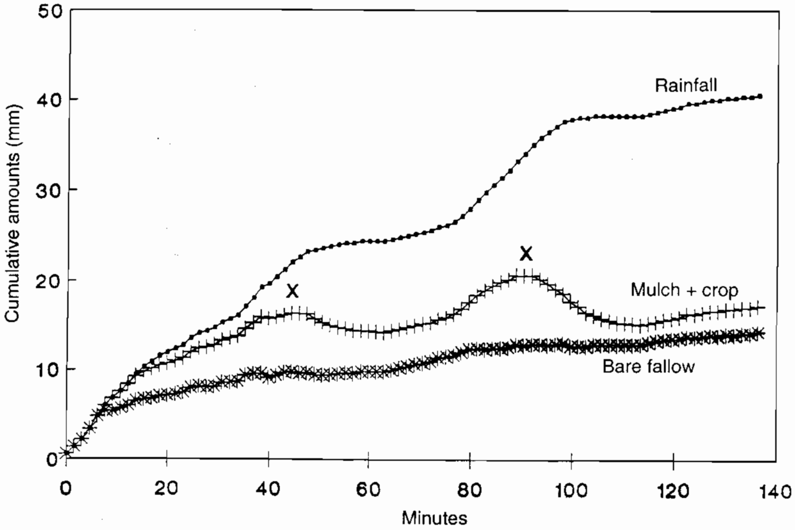

Fig. 3. Infiltration under two contrasting treatments (barefallow and mulch + crop) during an event on 9 April 1990.

water in situ on the surface for longer periods, thus providing more time for the infiltration process and causing a marked reduction in the velocity of the runoff and its power to erode soil.

Simulation

There is a need to predict the effects of the various land management options on soil loss and crop production (improved and traditional) that may be practiced within Kenya's semi-arid mixed farming conditions. The hydrological implications of the various improved systems that are now under test need to be known, predicted and extrapolated both in time and in space. We cannot afford another set of expensive, research station experiments that cannot readily be extrapolated to other sites and seasons in the Kenyan semi-arid cropping zone. The effects and implications of these management options on soil and nutrient loss in particular, and soil degradation in general, are important information in formulating land management policy and in drawing soil management recommendations for farmers in the semi-arid environment.

A number of effective and proven prediction tools is currently available. The CERES–Maize model developed in the USA has been adapted, enhanced, and improved to describe maize growth and yield in Kenya's semi-arid regions. The Kenyan version, CM-KEN, reported on elsewhere in these proceedings, is currently sufficiently adapted to justify its use in the analysis of system constraints and prospects for technical innovations. There is need for improvement of the hydrological component of both the original CERES–Maize, and its Kenyan version. Both models currently use curve numbers to partition rainfall between infiltration and runoff. These are empirical and there is need to improve the handling of water balance of CM-KEM in relation to soil management options. This may be done by interfacing good water balance models with CM-KEN. One such water balance model that is being used in this study in the newly formulated Soil Water Infiltration and Movement (SWIM) (Ross 1990).

CM-KEN, like its parent CERES–Maize, does not simulate and predict soil erosion and its effects. This study will therefore adopt a process-oriented, mathematically derived Griffith University Erosion Systems Template (GUEST) model. This will be interfaced with CM-KEN to enable the crop simulation model to predict erosion, given certain hydrological factors and conditions. The hydrology to drive both the GUEST and the CM-KEN models will be handled by SWIM, rather than by the curve number approach. The present experimental phase of the study is aimed at identifying and measuring the parameters that will be used in these model interfacing and formulating processes. Ultimately, we want a tool that can predict crop growth and yields given certain environmental and managerial conditions, and predict runoff and soil loss. Such a model would be capable of extrapolation to other soil types and conditions. Figure 4 illustrates a synthesis of proven models to arrive at an outcome that would fulfil this objective.

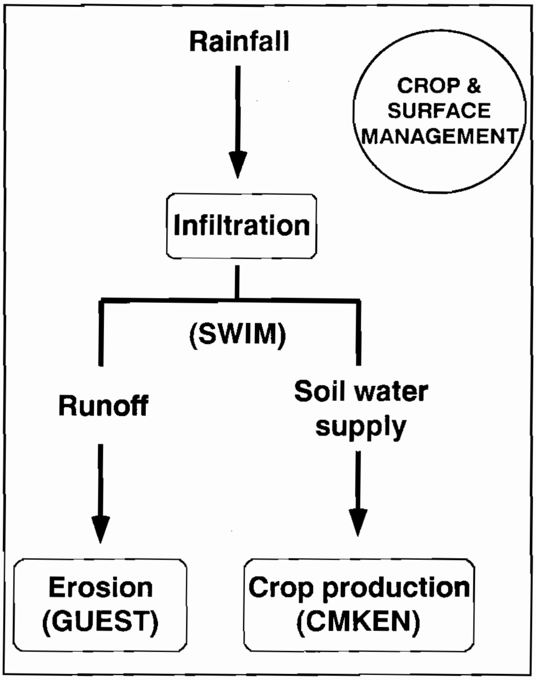

Fig. 4. The framework for generalising experimental results using three complementary models: SWIM for water balance, GUEST for erosion, and CMKEN for maize production.

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Rehabilitation of Degraded Grazing Lands Using the Katumani Pitting Technique

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MUCH of the grazing land in the smallholder subsistence farming areas in the 500–800 mm rainfall zone of eastern Kenya is being subjected to severe overgrazing and poor management, as pressure on the land resource from both humans and livestock increases. This overgrazing leads to the loss of plant cover on the soil surface, erosion of the more fertile topsoil, compaction and crusting of the newly exposed subsoil, and eventually to widespread sheet erosion and gullying. The productivity of the pastures declines as the perennial grasses are replaced by annuals, and water and nutrients are lost from the system. Without a dramatic change in the management of these lands, their productivity will be permanently reduced.

Livestock production is currently an important component of the mixed-farming systems practised in this region, and is directly affected by this loss of pasture productivity. As pressure on the land resources increases, however, it seems likely that cropping land will expand at the expense of grazing land. This scenario gives even greater urgency to the search for a solution which will preserve the vital soil resource for future needs.

Croplands in this area of eastern Kenya are almost always terraced to reduce runoff and soil erosion. Terracing of the grazing lands, however, is too expensive and labour intensive relative to expected returns to be contemplated by most farmers. A new technique was therefore needed to improve productivity and to protect the soil resource. This was developed from the work of Mututho (1989) in an Arid and Semi-Arid Lands (ASAL) project in the Kitui District, Kenya. He reported considerable success in revegetating eroded grazing lands by building small interlocking mini-catchments using a pitting and ridging technique, coupled with reseeding of the area with native grasses. We modified his approach to suit smallholder farms in the Machakos and Kitui Districts, principally by inserting a high value grain legume (cow pea) in the favourable niche created by the pitting process. The work was reported in more detail at the International Soil Conservation Organisation's Conference in Addis Ababa (Gichangi et al. 1989).

In this paper, we summarise the results of further experimentation and experience with the technique, and give revised recommendations for its use in the region.

An Overview of the Performance of the Technology

Experiments on five farms in the 500–800 mm rainfall zone of the Machakos and Kitui Districts have demonstrated the following.

(a) Stable micro-catchments, capable of withstanding normal rainfall intensities, can be constructed on badly eroded land at a labour cost of KShs 3000–4000 per ha. They prevent runoff, with the result that available soil water is greatly increased (Gichangi et al. 1989) and can be used to grow both grain and forage legumes.

(b) Cow peas (*Vigna unguiculata*) planted at the start of the season on the ridges around the pits benefit from the favourable moisture conditions of the micro-catchments and grow well, yielding 750–900 kg/ha of grain in good seasons. Bean (*Phaseolus vulgaris*) and pigeon pea (*Cajanus cajan*) grow less successfully.

(c) Competition of weeds and grasses with the introduced grain and forage legumes is of minor importance in the first season, but becomes considerably more serious in the second season. Thus, the 'window of opportunity' for cash cropping with cow pea, avoiding the cost of intensive weeding, appears to be restricted to the first season.

(d) Following emergence of the cow pea, a range of forage legumes of various growth habits has readily established and grow vigorously when sown in

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various positions within the pits. Pasture yields of 3-4 t/ha/season are achievable, with legume content of up to 50%.

(e) Good quality native grasses of the *Chloris* and *Cenchrus* genera successfully invade Katumani pitted land in the first, and particularly the second, seasons and may not require to be deliberately seeded in many locations.

(f) The total dry matter production on Katumani pitted land increases by a factor of 5 to 10 compared to untreated land. The increase in protein production per hectare is even greater through the introduction of legumes.

Results of More Recent Experiments

Optimum Sowing Time for Cow Pea

In 1989, a very low cow pea yield was obtained after a late preparation and sowing of pits (April) on a badly eroded site near NDFRC–Katumani. Recent experiments have explored the reason for this and the results indicate that careful timing of pit preparation and sowing is required to obtain maximum yields.

In an experiment during the short rains of 1990, a delay in sowing of as little as 10 days reduced plant survival, the number of pods per plant, and the yield of grain per pod, with the result that grain yield per hectare was dramatically reduced (Table 1). A delay of 20 days in sowing at the same site produced a similar result. In this particular season, the October–December rainfall was 367 mm but was poorly distributed, with dry periods of up to 10 days and no effective rain for cow pea after mid-December. Such a rainfall distribution is not unusual in this region. It seems clear that dry sowing or very early sowing of cow pea is essential, in order to minimise competition for water and nutrients by the natural vegetation which often recovers in the undisturbed 'catchment' area of the micro-catchment.

Table 1. Effects of sowing date on cow pea grown on newly pitted, eroded land near NDFRC-Katumani, Machakos.

	Sowing date[a]	
	Early[b] (24.10.90)	Late (3.11.90)
Plants established per pit[c]	19.2	13.2
Pods per plant	3.59	1.30
Yield per pod (g)	1.35	0.70
Grain yield (kg/ha)	465	60
Corrected[d] grain yield (kg/ha)	698	90

[a] Data are means for P fertilised and unfertilised pits.

[b] The early sowing was made three days before the first rains of the season.

[c] There were 20 sowing positions in the 2 m long strip sown.

[d] A concurrent experiment nearby showed that yields were directly proportional to populations, so all yields have been corrected to a uniform plant number and row length (3 m) per pit.

When to Sow Forage Legumes

One of the objectives of the pitting technology is to maximise cow pea yields so that a substantial cash flow is generated quickly to offset the labour costs. A consequence of this is that the sown forage legumes and any native grasses and weeds which re-establish, should grow at a rate slow enough to minimise competition with the cow pea for moisture. In previous work, *Lablab purpureus* sown at the same time as cow pea reduced cow pea yield by about 40% (Gichangi et al. 1989) when sown either across the middle of the undisturbed micro-catchment, or in the trench.

The pitting technique has now been modified by sowing the forage legumes and grasses about two weeks after the cow pea . Unfortunately, this could be expected to increase the risk of failure in establishing the forage species when they are sown during the long rains, as they have to survive the long dry season (June–October) which normally follows. Both for this reason, and to fit the availability of labour in the farming system, pitting is recommended as an activity for the long dry season, with the cow pea being sown at the onset of the short rains season (usually mid-October–early November) and the forage species sown two weeks later. The dry season between the end of the short rains and the beginning of the long rains is usually quite short (8–10 weeks). The forage species therefore have a reasonable chance of survival into the subsequent season.

The Need for Fertiliser

On sites where the surface soil has been removed by erosion, severe P deficiency is likely (Bray No. 2 extractable P 4–10 ppm; see Okalebo et al., these proceedings) since subsoils usually have a lower P content than surface soils. In several recent experiments, responses to P of 40–100% in cow pea yield have been recorded. In these, the usual rate of application of P was 10 kg per ha. However, as the undisturbed micro-catchment was not fertilised and all the fertiliser was concentrated on the disturbed ridge which occupied about 20% of the microplot area, the effective rate of application would have been about 50 kg P per ha. This raises the question of whether lower rates of P would have been as effective. There was no clear evidence of poor nodulation or need for nitrogen fertiliser by the legumes.

Costs and Benefits of Pitting

Simple calculations of the gross value of the cow pea grain crop, conservatively estimated at 600 kg/ha and selling for about KSh 8 per kg, indicate that most of the hired labour cost of pitting (KSh 4000 per ha) and fertiliser (approx. KSh 400 per ha) can be recovered after one season. This leaves the costs of fencing, of any cut-off drains and other works, and of forage legume seed, to be recovered from future income generated by improved fodder production and grazing capacity and products (e.g. fruit, nuts or firewood) from a planted tree crop. As land use becomes more intensive, much of the land currently used for grazing will probably be converted to cropland, pitting such lands should preserve the soil resource for this future use and have the potential for large long-term effects on the economy of the farm or region.

Katumani Pitting: Revised Procedures for Success

1. Pitting should start at the top of the eroded slope or below a cut-off drain which will intercept all runoff water from above. Pits should be dug to form interlocking micro-catchments, each about 2 m^2 in area, varying in shape with the micro-topography (see Fig. 1). Pitting can be extended progressively down the slope, as convenient, during the long dry season (June–October). The first digging can be quite rough and should be done early in the dry season, before the soil dries completely. Its purpose is merely to loosen the soil and to allow any out-of-season rainfall to infiltrate. Final embankments should be about 30 cm high around crescent-shaped trenches 15 cm deep and 20 cm wide. Animals can be excluded at low cost with a thorn fence made from branches of *Acacia* species in order to avoid damage to the fresh pits. Construction of pits and micro-catchments must be consistent down the slope, so that a continuous matrix or mosaic of micro-catchments is formed. Details of pit construction are given by Gichangi et al. (1989) and in Figure 1.
2. Cow pea should be sown on the ridges at the onset of the short rains (late October), or dry planted just prior to it. A high sowing rate should be used to establish a minimum of 20 plants per pit (approx. 100 000 per ha). This can be achieved by planting two seeds every 10 cm, and later thinning to one. If the site is badly eroded and a phosphorus deficiency is suspected, phosphatic fertiliser should be placed near the seed to provide up to 10 kg of P per ha (i.e. 20 g single superphosphate per pit, or 10 g diammonium phosphate). The fertiliser should be kept roughly 5 cm below and away from the seed to avoid damage to germinating seeds. At this rate of application, fertiliser cost should be less than 10% of the cost of the whole operation and could probably be further reduced.
3. A mixture of forage legumes should be sown soon after the cow pea plants have emerged, by broadcasting the seed across the micro-catchment area and into the trench. A little loose soil can be brushed across to cover the seeds to a depth of 2–5 mm. A suitable forage legume mixture for agro-ecological zone IV in Machakos and Kitui Districts is shown in Table 2.

   If seed is scarce or expensive, the seeding rate could be reduced or the seed sown in every second or third micro-catchment only and encouraged to spread as the pasture develops. *Stylosanthes scabra* (cv Fitzroy or Seca) and *Desmanthus virgatus* are two promising additional species which could be tried. The *S. scabra* cultivars, sown across the micro-catchments have produced well and persisted for three years under moderate grazing at a site in Kitui district. They require a little more care in initial establishment but are hardy, grazing-resistant legumes. They should be sown at 2 kg/ha (0.4 g/2 m^2). *Lablab purpureus* cv Rongai forms a prolific cover when sown across the micro-catchments in a shallow furrow. However, it will compete vigorously with the cow pea plants unless its sowing is delayed until well after cow pea emergence. Oversowing with grasses such as Rhodes grass (*Chloris gayana*) or Buffel grass (*Cenchrus ciliaris*) may not be necessary, as they are indigenous to this region. A decision on whether or not to oversow with grasses should therefore be delayed until the second season.
4. Grazing should be delayed until the end of the long rains; that is, until about nine months after pitting. By this time, a substantial vegetative cover should have been produced, and the soil from the pit construction phase should have compacted and stabilised. In this and subsequent seasons, grazing pressure should be sufficiently light to prevent a return to the mismanaged condition which gave rise to the original degradation.
5. After pitting and sowing, suitable portions of the pitted area can be demarcated for tree planting — for fuelwood, fruit, fodder or timber. Slight depressions within the slope, or around cut-off drains, are the

Table 2. Adapted species for use in Katumani pitting of eroded grazing lands in Machakos and Kitui districts, Kenya.

Species	cv	Suggested seed rate kg/ha	g/2 m^2
Macroptilium atropurpureum	Siratro	10	2
Macrotyloma axillare	Archer	8	1.6
Cassia rotundifolia	Wynn	5	1
Stylosanthes guianensis	Cook	7	1.4
Stylosanthes hamata	Verano	7	1.4

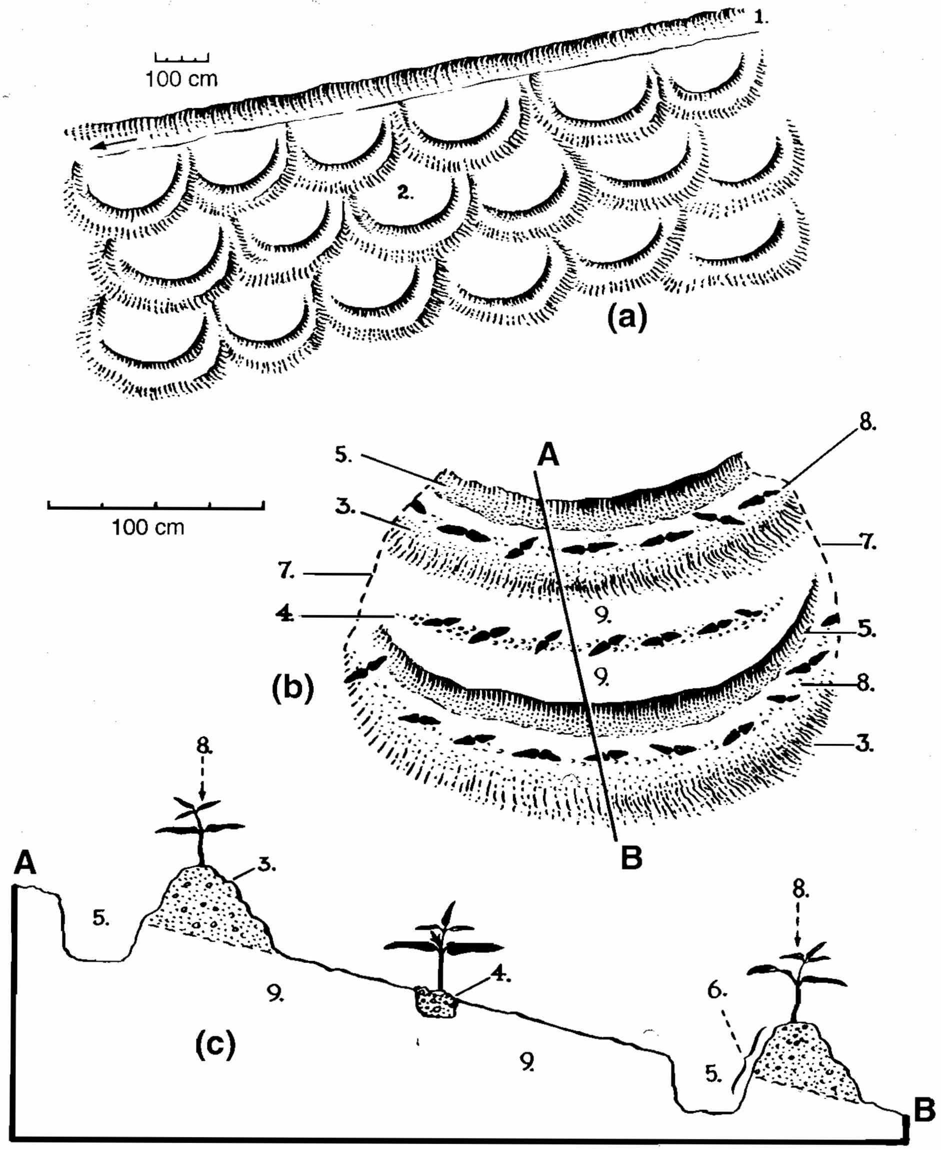

Fig. 1. Stylised representation of Katumani pits in plan (a and b) and cross-sectional view (c). 1. Cut-off drain (where necessary) to prevent runoff water from land above the site from running onto pitted land. 2. Interlocking Katumani pits shaped to account for local variations in microtopography. 3. Bank of loose soil from excavation of the trench. 4. Narrow cultivated strip roughly on the contour across the centre of the otherwise undisturbed micro-catchment. Forage legumes can be sown in this strip. 5. Trench to act as reservoir for runoff water and soil. 6. The location of the fertilised zone. 7. Approximate positions of the side boundaries of the pit; these are naturally occurring boundaries of adjacent pits. 8. Upper and lower boundaries of the pit on the tops of the loose soil banks. 9. Undisturbed soil.

most suitable sites. Pitted areas planted to trees should not be grazed until the trees are large enough to withstand grazing, but forage can be cut-and-carried to livestock. Weeding of the micro-catchment immediately around each tree will be necessary in the first two seasons or until the trees are well established, to reduce competition for water and nutrients.

The Future

Feedback on the utility of Katumani pitting is now urgently required from government officers in agricultural extension and soil and water management. The response of farmers who have tried the pitting technique should also be studied, so that adjustments can be made according to their comments and suggestions. A wide diversity of farmer responses to the technique, and the grazing provided, has already been obtained. Farmers appreciate some of the benefits of the procedure, but while one was keen to obtain more pasture legume seed and improve additional areas of his grazing land, others did not make effective use of the forage provided. This may be due to lack of knowledge and skill in managing grazing for optimum utilisation (factors which probably led to the degradation by overgrazing in the first place).

The challenge is now to extend testing of the Katumani pitting technique to a larger group of farmers, soil types and environments in the zone. As feedback from this is received, the technique may have to be modified by changing the method of pit construction, the plant species used, or the way in which the enhanced dry matter production is utilised. Such changes can all be accommodated as long as the basic concept of retaining the soil and water in situ is not compromised. Better data are needed also on the economics of the technique under farmer management, and its impact on the whole farming system.

We anticipate that the production of crops and animal feed from previously unproductive land will impact on the rest of the farming system in various ways. There should be less need to feed stover and other residues from the croplands to animals in the dry season, thus freeing these materials for use in mulching, runoff control, and direct nutrient recycling (see McCown and Keating, these proceedings). Animal manure produced from the extra grazing will also improve the cropland on which it is spread. Draught animals should be in better condition at the end of the dry season when they are required for early ploughing of the cropland. These and other possible effects of Katumani pitting on the whole farm need to be assessed through 'paired farm' studies in representative areas. The studies need to continue for at least five rainy seasons in order to document the magnitude and longevity of the effects.

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Exploring Production Strategies for Maize

Exploring Strategies for Increased Productivity — the Case for Maize in Semi-arid Eastern Kenya

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MANAGEMENT and genotype options which increase productivity through more efficient use of limiting water and nitrogen resources have been the focus of much of the past research in the semi-arid cropping lands of Kenya (Keating et al., The impact of climate variability, these proceedings). Field experimentation aimed at optimising management strategies and evaluating technical innovations has been hampered by the highly variable climate of the region. In addition, the potential for multiple interactions between management, soil and climate variables has limited the value of experiments dealing with only single factors.

Another paper in this proceedings (Keating et al., Development of a modelling capability) has shown that it is possible to simulate crop growth and yield in relation to the important climate, soil and management variables.

This paper uses this model in conjunction with historical weather data, to assess the longer term prospects for a range of options relevant to maize production systems of the region. Issues investigated include: planting date, plant population, crop improvement (altered phenology), sensitivity to reducing runoff losses and prospects for nitrogen fertilisation. This assessment is conducted in terms of both the average productivity and the variability or risk of particular strategies. The analysis presented will be focused on a particular site (the National Dryland Farming Research Centre – Katumani), although the approach is generally applicable where realistic soil parameters and climate data are available.

Standard Methods and Assumptions

This comparative analysis has been conducted under a standard set of soil, genotype and management conditions, described in Appendix 1. The analysis focuses on grain yields, except in the case of strategies that involve substantial input costs (e.g. fertiliser nitrogen) in which case a simple gross margin was calculated using assumptions outlined in Appendix 1. In general, conditions selected are those thought to be typical of current practice or recommendations. The analysis focuses on the climate of the National Dryland Farming Research Centre at Katumani (lat. 1°35' S ; long. 37° 14' E ; alt. 1601 m) where much of the past experimental crop research for the region has been conducted. This paper is presented as a case study for the agroecological zone (AEZ) represented by the Katumani site (Upper Midlands Zone 4 — Jaetzold and Schmidt 1984), and different conclusions may be drawn for other agroecological zones in the region. This is illustrated in the analysis of genotype phenology, which has been conducted both at Katumani and the lower altitude, drier site of Makindu (lat. 2°30' S, long. 37°50'E, alt. 997 m) which is representative of AEZ, LM5 (Lower Midlands Zone 5).

With the exception of the study of residual benefits of nitrogen fertiliser application, the analyses consider crops grown in separate fields of the same initial water and nitrogen status each season. Hence, the need to make assumptions about the management of a field over a long time sequence is avoided. Because of limitations in current models, the long-term impact of erosion and soil fertility changes has not been considered.

Planting Date Studies

Planting at or before the onset of the rains is generally recommended but little is known about the yield penalties associated with delayed planting. In this study, planting was assumed to take place at onset (defined in Appendix 1) or to be delayed by periods of up to 25 days from onset. Mean grain yield simulated over the 63 seasons examined at Katumani declined from 1750 to 1300 kg/ha as planting was delayed 0 to 25 days after onset (Fig. 1a). The losses associated with delayed planting were, in general, greater in the long rains (LR) than in the short rains (SR). On average, losses of 1.2% of grain yield per day delay in planting were simulated over both seasons, rising to 2.5% per day delay in the long rains. Variation in response from season to season was great (Fig. 1b) and while losses were

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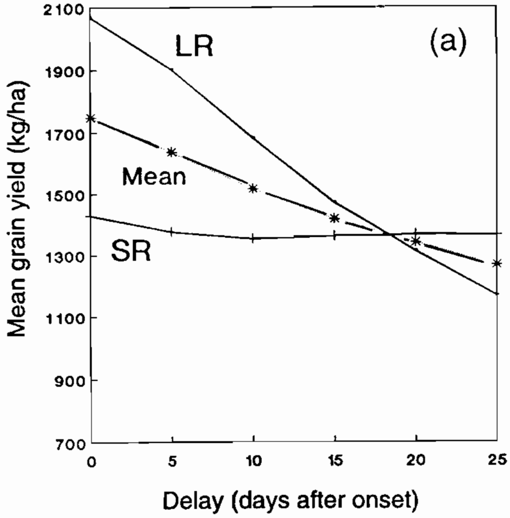
generally recorded, some short rains crops actually benefited from delays in planting. This occurred in situations where out of season rain was recorded in the January to February short dry period. While such positive responses to planting delay boosted mean yields from late planted short rains crops (Fig. 1a), variability was greater under delayed planting and median yields declined progressively with delays in planting in both seasons (Fig. 1c). A 20 day delay in planting after onset was estimated to lead to yield losses in 80 per cent of long rains seasons and 60 per cent of short rains seasons (Fig. 2).



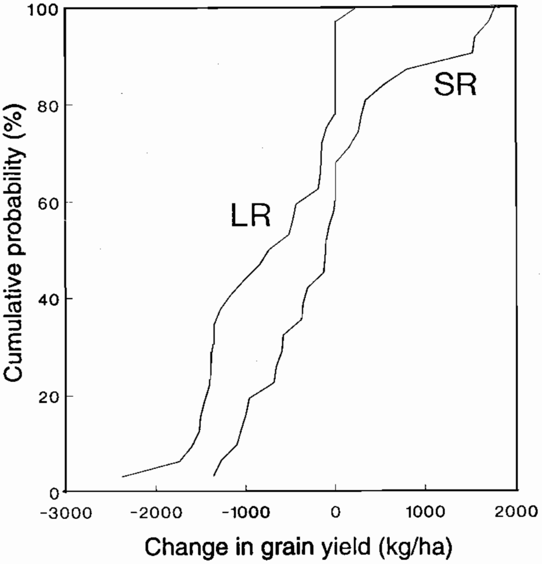
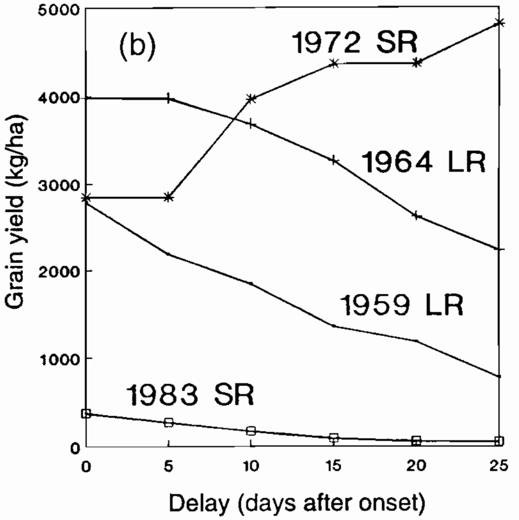


Fig. 2. Cumulative distribution function for loss of grain yield associated with a 20-day delay in planting after onset of the long rains and short rains at Katumani.

This analysis highlights the value of planting early when opportunities arise. Earlier experimental work had suggested that yield losses of the order of 5% per day delay in planting occurred (Dowker 1964). Our analysis shows that while losses of that magnitude or greater can occur,



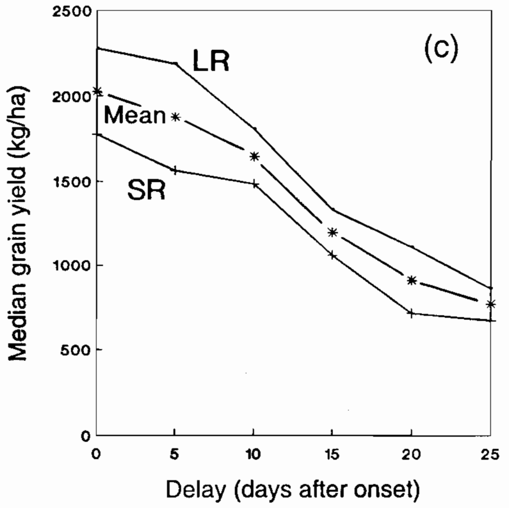


Fig. 1. Effects of a delay in planting after onset simulated at Katumani.
(a) Mean grain yield over the 1957–1988 period.
(b) Variation in response of grain yield to delay in planting simulated for a range of seasons (as indicated).
(c) Median grain yield over the 1957–1988 period.

variability from season to season is great and that such generalisations are of limited value. Losses associated with delays in planting can be attributed to inefficient use of both nitrogen and water resources and hence other factors which influence nitrogen and water supply or demand (for example, fertilisation, plant population, and genotype) will influence the outcome of delays in planting.

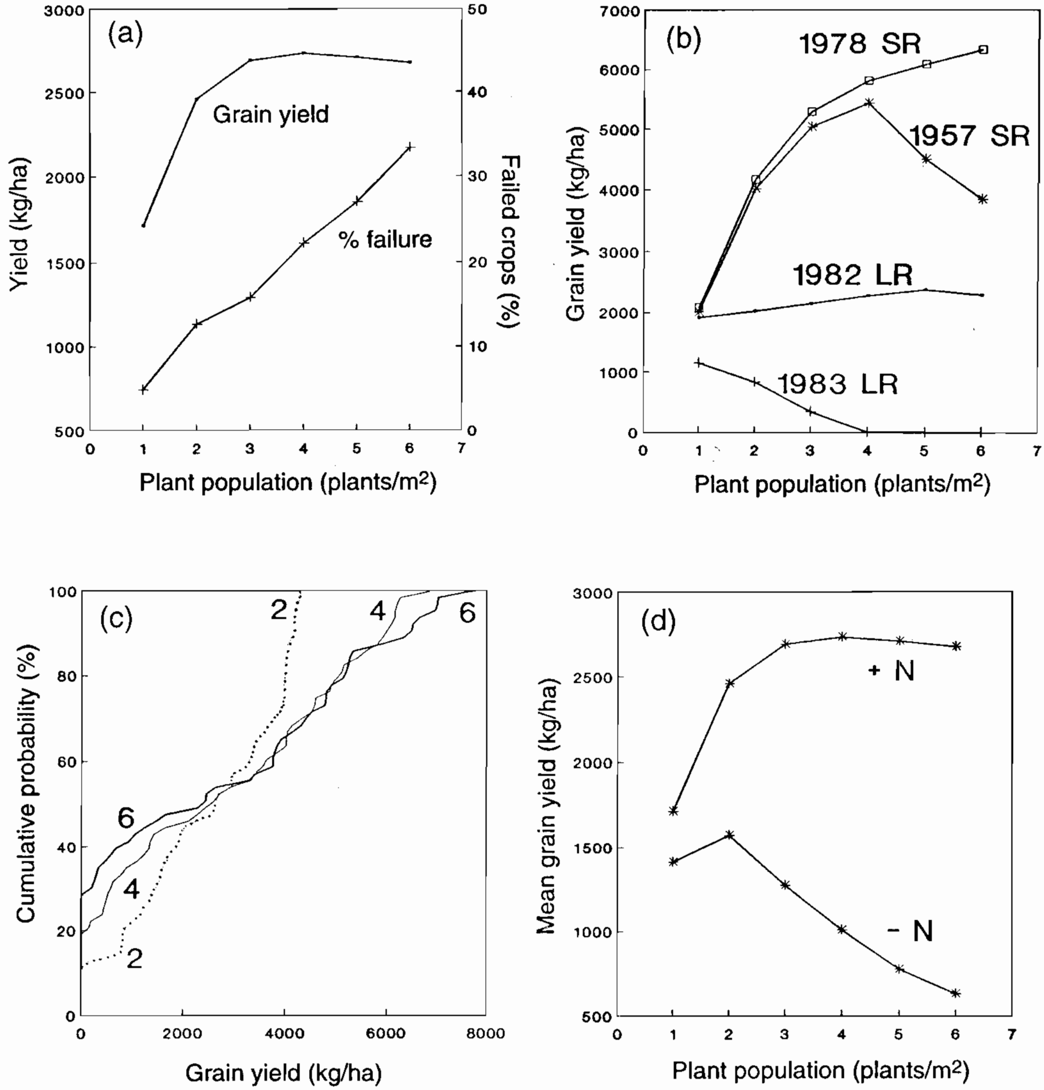


Fig. 3. Effects of plant population simulated at Katumani.

(a) Mean grain yield over the 1957–1988 period. Per cent failure rate is also shown with a failure defined as a yield less than 300 kg/ha.

(b) Variation in response of grain yield for a range of seasons (as indicated).

(c) Cumulative distribution function for grain yield associated with plant populations of 2, 4 and 6 plants/m^2.

(d) Mean grain yield over the 1957–1988 period for non-limiting nitrogen supply (+N) and strongly limiting (–N) nitrogen conditions (54 kg mineral-N at planting and no fertiliser additions).

Plant Population Studies

Farmers can manipulate plant population at minimal cost but with a potentially large effect on the risks and returns from their cropping activity. In this study, plant populations over the 1–7 plants/m^2 range were simulated over the rainfall record for Katumani in the absence of nitrogen limitations.

Mean grain yield at Katumani was maximised at plant populations in the order of 3–4 plants/m^2 (Fig. 3a). Plant populations above this level did not increase average yields, and resulted in a higher proportion of crop failures (Fig. 3a), assuming yields less than 300 kg/ha represent failed crops. Variability in the shape of the response of yield to plant population was great (Fig. 3b), a result consistent with field experience (Nadar 1984). Median yields were similar at 2, 4 and 6 plants/m^2 (Fig. 3c), but the higher plant populations were associated with higher probabilities of high yields at the cost of greater chances of low or zero yields. Plant populations found in the district tend to be in the 2–4 plants/m^2 range and the 10–20% of seasons simulated with zero yield under such circumstances is consistent with local experience.

The foregoing analysis was conducted in the presence of adequate nitrogen. A different picture emerges in the presence of a strong nitrogen constraint (Fig. 3d). Nitrogen deficiency, which is widespread in the region, lowers both the general yield level and the optimum plant population. This effect has been confirmed experimentally (Watiki and Keating, unpublished data) and results from the inefficiencies arising when the high N demand at high plant population exceeds N supply. An increase in the proportion of plants not forming an ear with grain is a symptom of such an imbalance.

Earlier experimental studies (e.g. Nadar 1984) focused on the advantages of high plant populations (that is, > 6 plants/m^2) in good seasons. The interaction with nitrogen had not been previously considered and past plant population work had almost certainly been conducted under adequate to high nitrogen status.

When taken in the context of the climatic record for Katumani, intermediate plant populations (in the 3–4 plants/m^2 range) were found to maximise productivity. Under strong nitrogen constraint, there was evidence that these levels should be reduced (approx. 2 plants/m^2). The former is close to current recommendations and the second value is effectively what many farmers already achieve with their low maize populations intercropped with N-fixing grain legume species. Other potentially important factors that will interact with plant population include planting date, genotype maturity class and soil water holding characteristics. Further studies are warranted to examine these interactions.

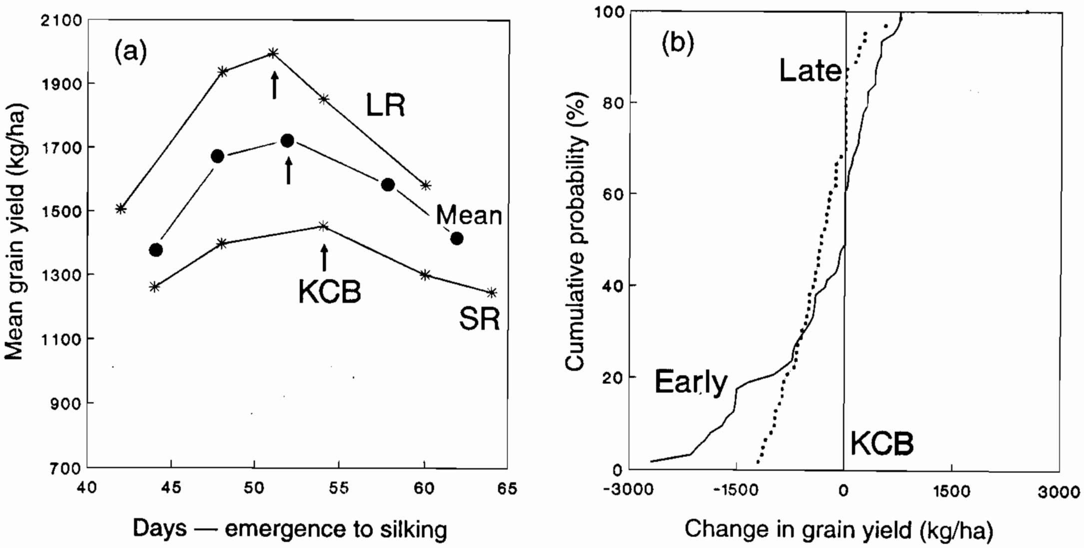


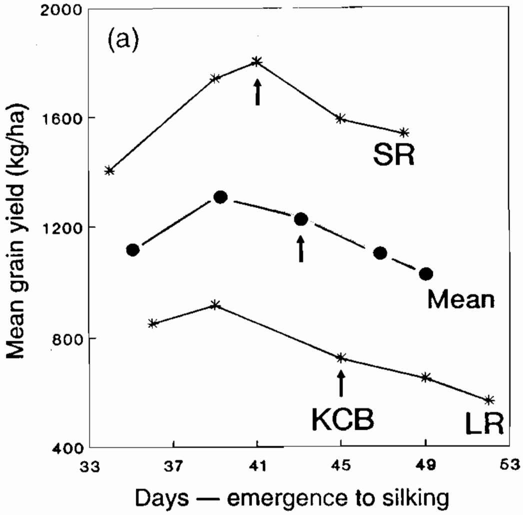
Fig. 4. Effects of the duration of vegetative growth (emergence to silking) simulated at Katumani.
(a) Mean grain yield over the 1957–1988 period for the long rains, short rains and mean over both seasons. Arrows indicate duration of the current cultivar (KCB).
(b) Cumulative distribution function for the difference in grain yield relative to KCB for genotypes simulated to flower 8 days earlier or later.

Genotype Maturity Studies

While germplasm improvement is a costly activity for research agencies, improved cultivars do not generally represent a major input cost for farmers. This is particularly true in semi-arid eastern Kenya, where open-pollinated composite cultivars are extensively used. Throughout the semi-arid areas of the world generally, and this holds true for Kenya, much of the improvement in germplasm has come from a better matching of crop phenology with the rainfall pattern. The impact of flowering time on productivity and variability in yields is examined in this section.

The growth duration of the current cultivar, Katumani Composite B (KCB), was found to be optimal in terms of long-term average yield at Katumani (Fig. 4a). Simulated yields were higher in the long rains than the short rains, but in both cases the time to silking for KCB [median of 52–55 days from emergence to silking (E → S)] was optimal. The early experimental work that led to the development of KCB (Dowker 1971) showed that the optimal time to flowering varied greatly from season to season, depending on the rainfall pattern. This was also the case in the simulations. Late flowering genotypes (median of 62 days E-->S) were simulated as giving higher yields than KCB in 15% of seasons and lower yields in 70% of seasons (Fig. 4b). Likewise, early flowering genotypes (median of 45 days E → S) were estimated to yield more than KCB in approximately 40% of seasons and less than KCB in 50% of seasons (Fig. 4b).

At the drier and hotter Makindu site, the short rains were shown to have almost twice the maize yield potential under dryland conditions than the long rains (Fig. 5a). This result supports the outcome of the agrometeorological analysis of season potential reported by Musembi and Griffiths (1986). The shorter growth



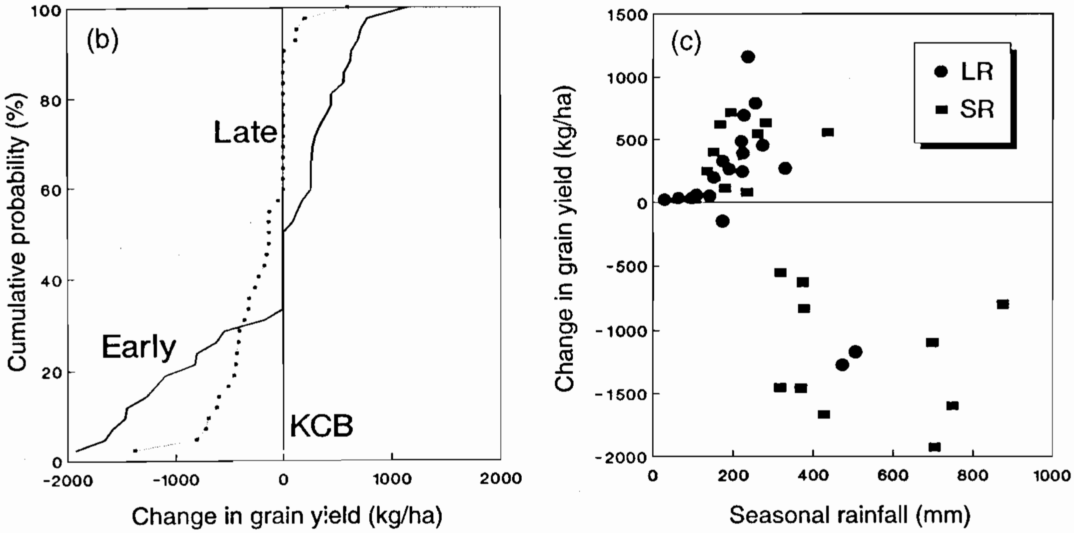


Fig. 5. Effects of the duration of vegetative growth (emergence to silking) simulated at Makindu.

(a) Mean grain yield over the 1961–1983 period for the long rains, short rains and mean over both seasons. Arrows indicate duration of the current cultivar (KCB).

(b) Cumulative distribution function for the difference in grain yield relative to KCB for genotypes simulated to flower 8 days earlier or later.

(c) Relationship between the yield increase due to an early flowering cultivar (relative to KCB) at Makindu and seasonal rainfall in the long (LR) and short (SR) rains over the 1961–1983 period.

durations at this site compared with Katumani reflect the warmer temperatures at Makindu. The yield potential of the short rains at Makindu was similar to the long rains at Katumani and the optimal time to flowering in terms of long-term average yield was also found to be that of KCB. The long rains at Makindu have a low yield potential and there is evidence that average yield could be increased by approximately 30% by a cultivar that flowered a week earlier at this site. Such a genotype was predicted to give higher yields than KCB in 55% of long rains seasons and lower yields in only 13% of long rains' seasons (Fig. 5b). Earliness at Makindu (relative to KCB) was predicted to be largely of benefit when seasonal rainfall was less than 300 mm (Fig. 5c).

Soil Surface Management

Prospects for irrigation are limited in semi-arid eastern Kenya, but potential exists to improve water supply to crops by better managing the soil surface to reduce runoff losses. Retention of surface residues or topographic modification of the soil surface (e.g. tied-ridging) will reduce runoff but at considerable cost in terms of reduced fodder for animals or labour, respectively. While we were not in a position to fully evaluate the feasibility of these strategies, the sensitivity of maize yield to changes in the magnitude of runoff losses was examined, as it will have a major influence on the profitability of any surface management strategy.

Rainfall is partitioned in the model between infiltration and runoff using a curve number approach (USDA 1972). Curve number (CN) was varied in order to vary the amount of rainfall lost to runoff (Table 1). As expected for a water-limited site, mean grain yield at Katumani was very sensitive to runoff losses. A reduction in mean runoff from 58 mm (CN 80) to 37 mm (CN 70) almost doubled maize yields (from 1200 to 2000 kg/ha) (Fig. 6a) and reduced the proportion of crops where zero yield was simulated from 42 to 24% (Fig. 6b).

Quantitative data are not yet available for relating surface management to curve numbers or to runoff. Current research described elsewhere in this volume (Okwach et. al. 1992) is directed at predicting the impact of various surface management strategies (mulch, ridges etc) on runoff losses.

Table 1. Curve numbers (USDA, 1972) examined and associated mean and median runoff simulated.

Curve number	Mean runoff (mm)	Median runoff (mm)
40	4	0
50	10	1
60	21	10
70	37	20
80	58	35
90	79	63

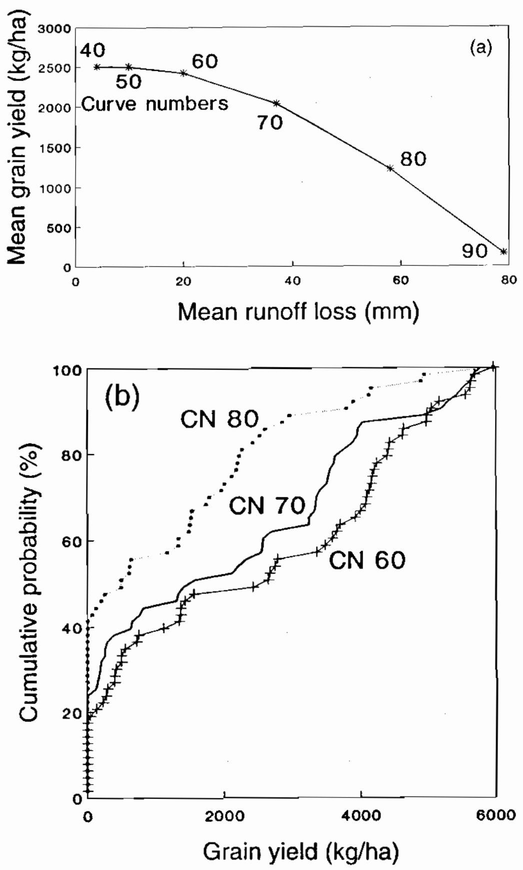


Fig. 6. Effects of runoff losses simulated at Katumani over the 1957–1988 period.

(a) Mean grain yield as a function of mean runoff (in mm). Numbers on the graph refer to the curve numbers used to simulate runoff.

(b) Cumulative distribution function for the grain yield associated with three levels of runoff simulated by curve numbers of 60, 70 and 80.

Nitrogen Fertiliser

The use of purchased fertiliser inputs is limited in the region, but there is strong evidence that availability of nitrogen and, in some cases, other nutrients, strongly limits the productivity of the maize production system. This limitation will increase as cropping continues in the absence of nutrient inputs. Hence, the prospects for nitrogen fertiliser use have been a major focus of our analyses. Emphasis has been placed on the general level of response to nitrogen fertiliser, and variability in returns to fertiliser use. Soil and management factors that influence fertiliser response and the magnitude of residual benefits of fertiliser nitrogen have also been assessed.

Long-term average grain yields increased from 1000 to 2700 kg/ha as seasonal N fertiliser additions increased from 0 to 160 kg/ha (Fig. 7a). Gross margins under the same standard inputs described earlier were on average maximised (6400 –6600 Kshs/ha) at N rates between 40 and 80 kg N per ha (Fig. 7b). Variability in response to N was extreme, ranging from positive increases in gross margins of 11 000 Kshs/ha (above the crops receiving no fertiliser) in some seasons, to losses of 2600 Kshs/ha associated with high rates of fertiliser use in other seasons (Fig. 7c). In general, response to added N was correlated with seasonal rainfall levels (Fig 7d). The two seasons which showed the largest losses from N fertiliser (Fig. 7d) were situations when crop death was simulated under N fertilised conditions. Large leaching losses were simulated in the two seasons where rainfall exceeded 800 mm and as a result yields and gross margins fell short of the general relationship with rainfall (Fig. 7d).

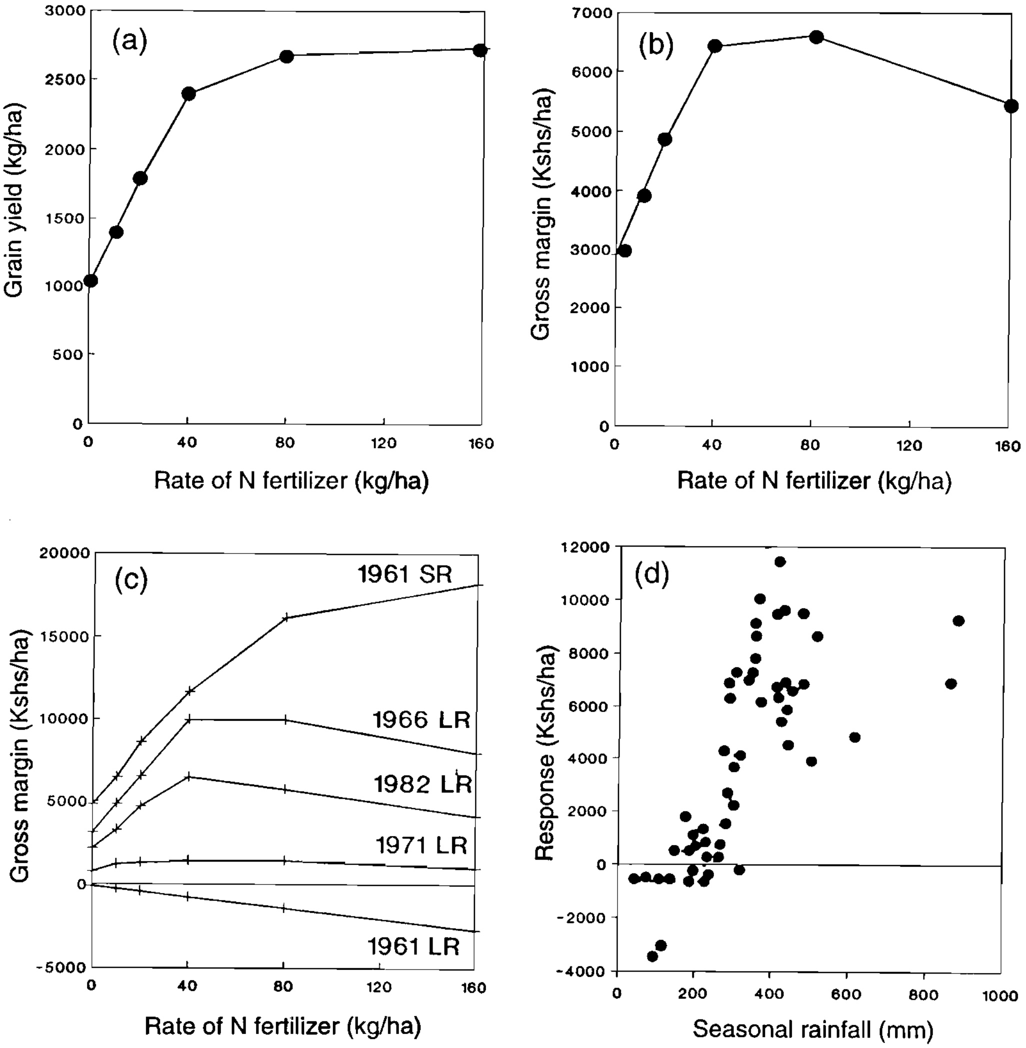


Fig. 7. Effects of nitrogen fertiliser simulated at Katumani over the 1957–1988 period.
(a) Mean grain yield.
(b Mean gross margins.
(c) Variation in response in gross margin for selected seasons (as indicated).
(d) Relationship between additional gross margin resulting from the application of 40 kg N per ha and seasonal rainfall.

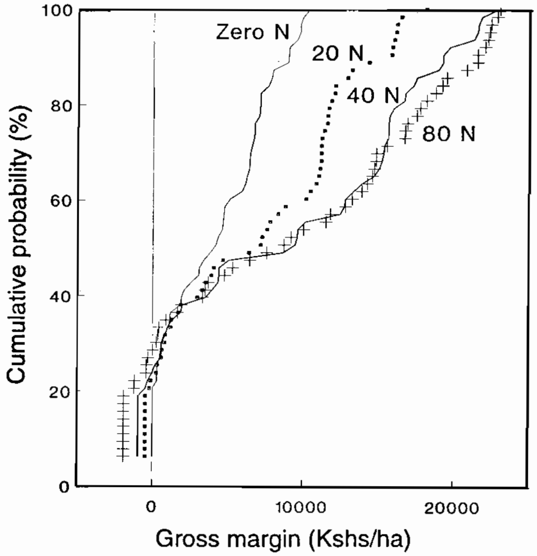


Fig. 8. Cumulative distribution function of gross margin simulated for maize at Katumani (1957–1988) at different rates of N fertiliser (as indicated in kg N per ha).

Under the standard soil and management conditions, the 40 kg N per ha strategy appeared to offer a greater probability of high returns, with only marginally increased risk of greater losses compared with lower rates of N (Fig. 8).

Effects of Initial Soil Nitrogen Status

The quantity of mineral-N present in the profile at planting strongly influenced the mean response to fertiliser N (Fig. 9a). There was little to be gained from using fertiliser-N in situations when mineral-N present in the profile at planting exceeded 100 kg N per ha (Fig. 9b).

Effects of Management Factors — Plant Population

The optimum plant population increased from below 2 plants/m^2 in the absence of fertiliser, to above 3 plants/m^2 when 40 kg N per ha was included in the simulated management (Fig. 10a). Lower plant populations reduced failure rates considerably, but at the cost of lost yield potential in the wetter years, assuming N was available (Fig. 10b). Plant population in this region therefore can be seen as an important low-cost tool available to farmers to manipulate demand for water and N resources. Optimum production will be achieved when this demand most closely matches supply.

Many other soil and management factors will influence the response to nitrogen fertiliser. The maize model has proven useful in evaluating the value of split nitrogen applications and the frequency with which some residual benefit of nitrogen fertiliser will be carried over from one season to the next (Keating et al. 1991). In addition, all strategies examined here have been fixed (i.e. the same

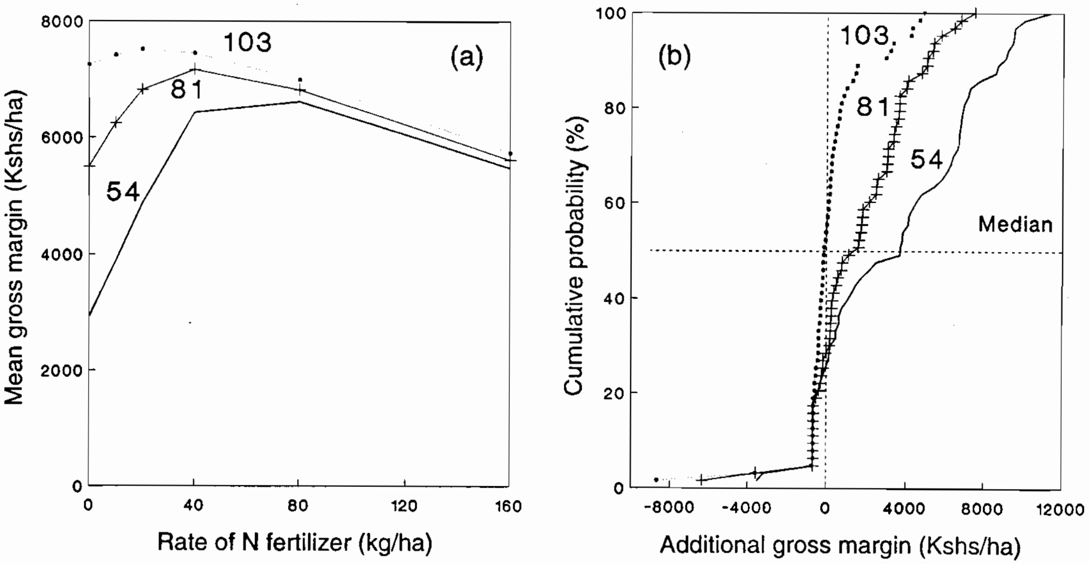


Fig. 9. Effects of initial mineral N (in kg N per ha as indicated) on response to fertiliser-N.
(a) Mean gross margins.
(b) Cumulative distribution function for change in gross margins resulting from application of 40 kg N per ha.

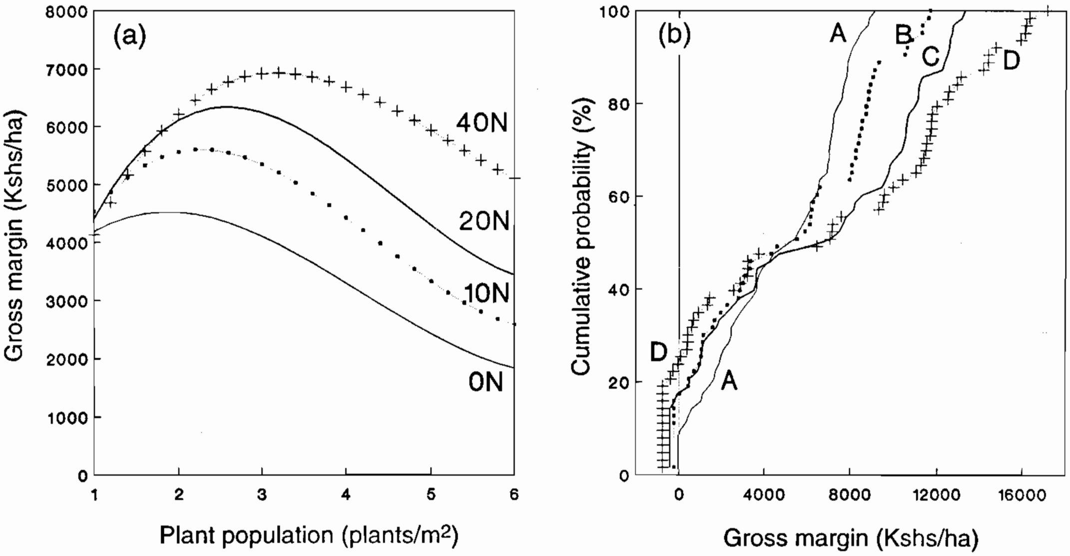


Fig. 10. The interaction between plant population and nitrogen fertilisation simulated at Katumani over the 1957–1988 period.
(a) Mean gross margin versus plant population at four N fertiliser rates (as indicated in kg N per ha).
(b) Cumulative distribution function for gross margin for optimal combinations of plant population (plants/m^2) and rate of N fertiliser (kg N per ha: A = 2.2 plants/m^2 and zero N; B = 3.3 plants/m2 and 10 N; C = 3.3 plants/m^2 and 20 N; D = 4.4 plants/m^2 and 40N.

in each season) while potential exists for tactical use of nitrogen fertiliser in relation to seasonal prospects. An example of using a model in the evaluation of tactical adjustments in input of nitrogen fertiliser is given by Wafula et al. (these proceedings).

Comparing the Options

Yields achieved by farmers in Machakos district have been reported to average 850–900 kg/ha (Jaetzold and Schmidt 1984) in the absence of fertiliser application. This compares with the long-term average yield of approximately 1000 kg/ha simulated at Katumani without fertiliser. Our estimate of yield potential with adequate nitrogen, little runoff losses, appropriate plant population, early planting and optimal phenology is in the region of 2800 kg/ha.

We were unable to undertake a formal analysis of the difference in yield between the farm averages and our estimate of potential. Nevertheless, some generalisations can be made. There appears to be little to be gained from breeding for altered phenology at Katumani (AEZ UM4), and only very modest gains seem possible from earlier flowering germplasm in the long rains at Makindu (AEZ LM5). Existing recommendations and farmer practices relating to plant populations and planting date are generally appropriate and no major gains can be expected in these areas. Improved water supply from reduced runoff is of considerable value, but nitrogen supply must be reasonable if crops are to benefit from increased infiltration. Productivity is predicted to be sensitive to improved nitrogen supply, and future research should give high priority to investigating how this might be achieved. The place for nitrogen fertilisers in these farming systems is considered in the final chapter of these proceedings (McCown and Keating).

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Appendix 1. Standard Inputs and Assumptions Used in the Modelling Analysis

Standard Inputs

The analysis assumes that pests, weeds and nutrients other than nitrogen are not limiting.

Unless otherwise specified, the following inputs were assumed. The maize cultivar, Katumani Composite B was simulated at a plant population of 4.4 plants/m^2. The standard soil profile used was that of a chromic luvisol which is typical of the region (Table A1).

Planting was assumed to occur once onset of the season was detected. Onset was defined as the receipt of in excess of 40 mm of rain within an 8-day period with no more than one consecutive dry day (0 mm). Onset windows during which planting could take place were defined as from calendar day 276 to 320 and calendar day 62 to 120 for the SR and LR, respectively. Planting was simulated at the end of the onset window in those seasons when onset according to these rules was not detected.

The standard soil profile had an organic carbon content of 1.1% in the surface layer, an initial mineral N content of 54 kg/ha at the beginning of the onset window and an available water-holding capacity of 173 mm over its 130 cm depth. Soil water was initialised at one-fifth of the available range and initial values of mineral N are given in Table A1. The fertiliser response investigated was to 0, 10, 20, 40, 80 and 160 kg N per ha applied at planting as calcium ammonium nitrate. Each season was modelled independently of other seasons with reinitialisation of input parameters at the start of the onset window unless otherwise specified.

Gross Margin Calculation

In situations when the scenarios simulated involved different input costs, yield output was converted to a gross margin in Kenyan shillings (Kshs/ha), using the following assumptions. Grain was valued at 3 Kshs/kg and fertiliser was assigned a value of 16.3 Kshs per kg N. Seed costs varied with plant density and gross margins were adjusted to reflect this, assuming that seed for planting was valued at 4 Kshs/kg and two seeds of average weight of 0.32 g are planted per planting position, prior to thinning to one plant. Planting, harvesting and weeding costs were not likely to be influenced in any predictable way by the scenarios investigated and these costs have been excluded.

Table A1. Profile information for the standard soil used in the case study.

DLAYR is the layer depth in cm, LL is the lower limit of plant extractable soil water (volumetric), DUL and SAT are the corresponding drained upper limit and saturated water contents respectively, WR is a weighting factor for root growth, BD is the layer bulk density in g/cm^3, C is the organic carbon (%), NH_4 and NO_3 are the ammonium and nitrate mineral-N (in µg/g) at onset of the season.

DLAYR	LL	DUL	SAT	WR	BD	C	NH_4	NO_3
10.0	0.140	0.250	0.300	1.00	1.35	1.10	1.0	2.0
10.0	0.140	0.250	0.300	0.86	1.35	1.10	1.0	3.0
10.0	0.140	0.290	0.320	0.64	1.35	1.00	1.0	3.0
20.0	0.150	0.300	0.330	0.47	1.40	0.80	1.0	2.0
20.0	0.170	0.300	0.340	0.35	1.40	0.70	1.0	1.0
20.0	0.170	0.310	0.350	0.25	1.40	0.65	1.0	1.0
20.0	0.170	0.310	0.360	0.15	1.40	0.60	1.0	1.0
20.0	0.170	0.310	0.370	0.08	1.40	0.60	1.0	1.0

Whole profile properties :
SALB, the soil surface albedo = 0.13
U, the soil evaporation coefficient for stage 1 = 9 mm
SWCON, the whole profile drainage coefficient = 0.50
CN2, the runoff curve number = 60

Prospects for Improving Maize Productivity Through Response Farming

B.M. Wafula,[*] R.L. McCown[†] and B.A. Keating[§]

STRATEGIES considered in the previous paper involved management practices that were fixed, irrespective of seasonal prospects. In contrast, farmers frequently vary their management either consciously or subconsciously in response to their perceptions of the rainfall prospects for the current season. 'Response farming' was a scheme developed in Kenya to forecast the potential of the pending growing season using rules based on time of season onset and early cumulative rainfall (Stewart and Hash 1982; Stewart and Faught 1984; Stewart 1988, 1991). The scheme included tactical responses, such as adjustments in crop densities and nitrogen fertiliser, to better match agronomic management with seasonal potential. In seasons forecast as having a high yield potential, high plant populations and nitrogen fertiliser side-dressings were recommended. In seasons forecast as having low yield potential, recommendations were to thin plant stands to reduce demand for soil resources and not add additional nitrogen fertiliser.

Although the concepts embodied in response farming are intuitively attractive, there had been no means by which its value in terms of increased productivity or reduced risk could be assessed. This is because the value of response farming can not be determined experimentally, given the interseasonal variability in rainfall that characterises semi-arid Kenya. Stewart and Kashasha (1984) present the results of an evaluation conducted on seven farms in one season. Clear benefits of nitrogen fertilisation were obtained, but it is not possible to separate the value of fertilisation from the value of the response farming forecast per se. In addition, it is impossible to derive general conclusions on the value of response farming from one season's experimentation. The availability of a model that simulates maize growth in relation to climate, soil and management factors provided a unique opportunity to quantify the value of response farming. With the model, we can separate the value of fertilisation from the value of the response farming forecast and can assess variability in response over the historical rainfall record.

The details of response farming and our evaluation have been extensively reported elsewhere (Stewart 1988, 1991; Stewart and Hash 1982; Stewart and Faught 1984; Wafula 1989; McCown et al. 1991; Keating et al. 1992). In this paper we attempt to summarise the key outcomes of our analysis.

General Methods

The standard inputs used and assumptions made throughout the simulation study have been described in detail elsewhere (Keating et al., Exploring strategies for increased productivity, these proceedings; McCown et al. 1991). Briefly, all simulations were conducted using daily rainfall data for the National Dryland Farming Research Centre, Katumani, Machakos, Kenya (lat. 1°35'S; long. 37°14'E; alt. 1601 m). In general, conditions selected are those thought to be typical of current practice or recommendations. Two crops per year were simulated over the 1957–1988 period. The short rains (SR) occur from October to January and the long rains (LR) from March to July.

Onset of the long rains season was deemed to occur when 40 mm of rain was recorded within an 8-day period, with no more than one contiguous dry day. The onset rule for the short rains was similar but based on 30 mm instead of 40 mm. Onset periods or 'windows' were defined from calendar days 289 to 327 and 38 to 106 for the SR and LR, respectively. Unless specified otherwise, sowing was assumed to take place immediately season onset was detected within the window. If onset was not detected in any particular season, the crop was assumed to have been sown into dry soil at the end of the onset window. These onset criteria are based on the agroclimatic analysis of Stewart and Faught (1984) but are to some degree arbitrary and bound to be specific to regions. Nevertheless,

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the concepts of planting windows and minimum rain needed to initiate planting activity are consistent with farmer behaviour in this region (Ockwell et al. 1992) and are likely to be more generally applicable.

The maize cultivar, Katumani Composite B, was simulated throughout this study. The standard soil profile assumed was that of a chromic luvisol, which is typical of the region. This soil has an organic carbon content of 0.8% in the surface layer, an initial mineral-N content of 54 kg/ha and a potential available water content of 173 mm over its 130 cm depth. Each season was modelled independently of other seasons with reinitialisation of input parameters at the start of the onset window.

The performance of alternative fixed and response farming strategies involving different input levels (for example, studies involving different rates of fertiliser) were compared using gross margin per hectare. The assumptions made in terms of prices of inputs and outputs are given in McCown et al. (1991). Monetary values are in Kenyan shillings (Kshs) and as a guide, 100 Kshs is equivalent to US$4. Variable costs included seed, fertiliser (30 Kshs per kg N) and harvest costs. The price assumed for nitrogen is twice the purchase price, to allow for variable costs of transport, application and additional weeding costs. A constant sale price of 3 Kshs/kg for maize grain was assumed.

Strategies Examined

Fixed. Rates of N fertiliser (ranging from 0 to 80 kg N per ha) applied at sowing as calcium ammonium nitrate were examined. Other studies have shown that plant population needs to be varied to match nitrogen supply if optimum production is to be achieved (Keating et al. 1991). Hence, these N rates were combined with plant populations ranging from 22 000 to 55 000 plants/ha (Table 1a).

Response farming. The schema devised by Stewart and Faught (1984) incorporated two levels of predictor. Predictor I was based solely on date of onset of the rainy season. Predictor II used date of onset together with a second stage predictor, consisting of the cumulative rainfall over the 30 or 35 day period following onset. Analyses reported elsewhere (McCown et al. 1991) have indicated that the second stage predictor is of limited incremental value only in the short rains (SR) season. For simplicity, this paper will focus on an evaluation of Predictor I, the date of season onset.

Seasons in which onset occurred before 18 March (calendar day 77) and 2 November (calendar day 306) for the long rains and short rains, respectively, were classified as early. Seasons starting after these dates within the defined onset windows were said to be late. These definitions of early and late onset were those developed by Stewart and Faught (1984). In the period studied, 47% of seasons started early, 53% were late. Two levels of management were evaluated, each with specific tactics for early and late onset (Table 1b). No low input level was considered since tactics are only relevant when at least some inputs are in use. The tactics evaluated can be thought of as a reduction in N fertiliser rate and plant population when a poor season is forecast on account of a late onset.

Table 1. Nitrogen fertiliser and plant population levels used in the simulation study of (a) fixed strategies, and (b) response farming strategies using forecasts based on season-onset date.

(a) Fixed strategies

Fixed strategy	Plant population ('000 plants/ha)	N rate (kg/ha)
S1	22	0
S2	27	15
S3	33	30
S4	37	45
S5	44	60
S6	55	80

(b) Response farming strategies

Strategy	Predictor onset date	Plant population ('000 plants/ha)	N rate (kg/ha)
R_1 – medium inputs	Early	33	30
	Late	33	0
R_2 – high inputs	Early	44	60
	Late	33	30

Results

Performance of the Predictor

Three classes of season (good, fair and poor) were identified by Stewart and Hash (1982) and Stewart and Faught (1984) in terms of rainfall amount (Table 2a). Stewart and Faught (1984) showed that the date of season onset was negatively correlated with the amount of rainfall received, particularly in the long rains (Fig. 1). This is a reflection of the phenomenon that the date of cessation of the rains is less variable than that of onset, making season duration dependent mainly on date of onset. As a consequence, the prospects for the different classes of season are influenced by the date of onset predictor (Table 2b). For example, while 37 percent of all long rains seasons were rated as good using Stewart's criteria (Table 2a), the probability of a season that starts early being good, rises to 65 per cent. Likewise, while 15 per cent of all short rains seasons were poor in terms of

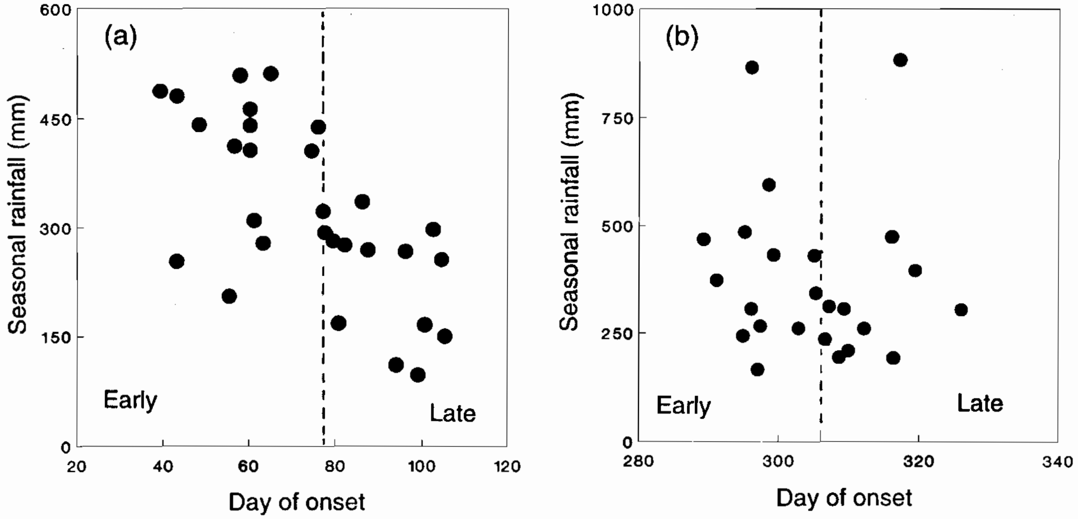

Fig. 1. The relationship between total seasonal rainfall for (a) long rains and (b) short rains), and date of rainy season onset. Classification into early and late onset based on the criteria of Stewart and Faught (1984).

seasonal rainfall, the probability that a season that starts late will be poor is increased to 25 per cent.

McCown et al. (1991) have examined forecasting rules devised by Stewart and his colleagues in more detail than is possible here. They conclude that the rules developed for Katumani are close to optimal and that they substantially reduce uncertainty in the prediction of seasonal rainfall. Predictor II (early season rainfall and onset date) provided an improvement over Predictor I (onset date alone) in the accuracy with which good seasons were forecast, particular in the short rains. Poor seasons were predicted little better by Predictor II than by Predictor I.

Table 2a. Classification of season classes based on rainfall received between season onset and maize maturity.

Season class	Rainfall between season onset and maize maturity (mm)	
	Long rains	Short rains
Good	>280	>330
Fair	150–280	230–330
Poor	<150	<230

Table 2b. Performance of the first-stage predictor (date of onset) for the long (LR) and short rains (SR) at Katumani over the 1957–1988 period. Proportion of seasons in different rainfall classes (specified in Table 2a) over all seasons, and when classified according to date of onset.

Season	Rainfall class	Percent of seasons		
		All seasons	Early onset	Late onset
Long rains	Good	37	65	0
	Fair	41	29	58
	Poor	21	5	42
Short rains	Good	40	53	25
	Fair	44	40	50
	Poor	15	7	25

The Impact of Response Farming on Productivity

Large increases in the productivity of maize production were found to be associated with the use of nitrogen fertiliser and appropriate plant populations, for both fixed and response farming strategies (Fig. 2). Simulated grain yields averaged over both seasons and over 1957–1988 increased from 1106 to 2794 kg/ha as the input level in the fixed strategies increased from S_1 to S_6. Mean gross margin was maximised at N rates of 45 kg N per ha and a plant population of 37 000 plants/ha (S_4 — Fig. 2).

For the same input cost, averaged over the period studied, the response farming strategies (R_1 and R_2 on Fig. 2) linking fertiliser use to onset dates resulted in gains in the expected gross margin. However, the average size of these gains was small (300–500 Kshs/ha) in comparison with the large impact of the unconditional use of fertiliser (up to 2500 Kshs/ha).

The Impact of Response Farming on Risk

While the overall impact of the tactics examined on average profitability was small, reductions in the risk associated with fertiliser use also need to be assessed.

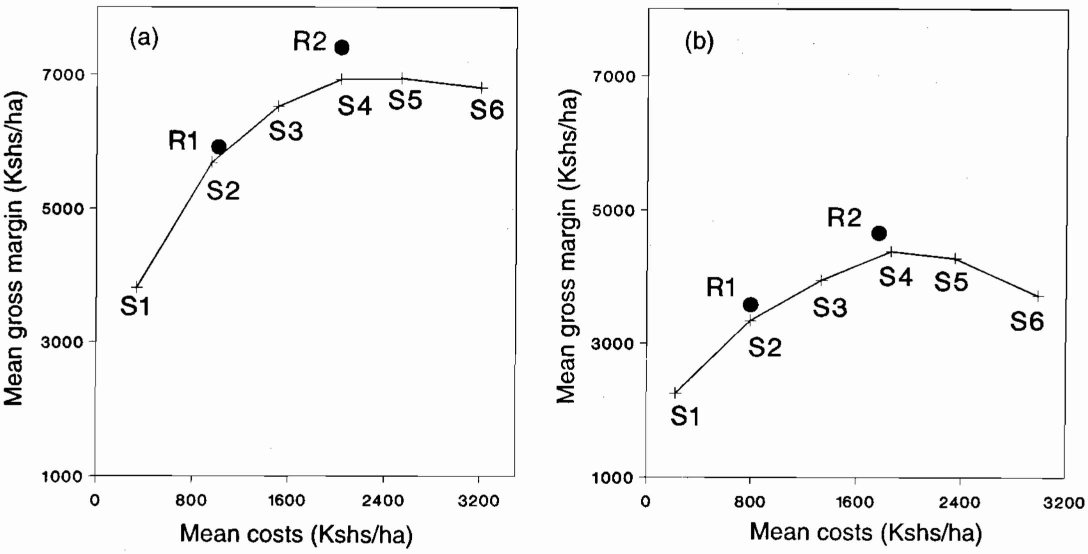

Fig. 2. Average gross margin and costs over the 1957–1988 period simulated at Katumani for a range of fixed (open symbols) and response farming (R_1,R_2) strategies specified in Table 1. (a) Long rains and (b) Short rains.

The high input conditional strategy (R_2) provided benefits over and above a comparable fixed strategy (S_4) in 67% of seasons simulated, but had a negative impact in the remainder of seasons. Such negative effects arose mostly from situations when an early onset was indicative of a good season and inputs were increased accordingly, but subsequent response to these additional inputs was poor.

Efficiency frontiers in Mean (E)–Standard Deviation (SD) space. McCown et al. (1991) have compared conditional strategies with fixed strategies in terms of E–SD space. The technique portrays production in terms of the long-term average gross margin (E) and risk in terms of the standard deviation of gross margin (SD) over the historical period simulated (Fig. 3). Compared with a corresponding set strategy (S_4), the high input conditional strategy (R_2) resulted in higher mean returns with the same or slightly reduced risk, insofar as standard deviation is an adequate measure of risk. The strategy using moderate input levels conditional on onset-date (R_1) fell below the efficiency frontier generated by fixed strategies and is of no further interest. A 2:1 rule of thumb has been suggested (Ryan 1984) as a first approximation to the attitudes of farmers on smallholdings to incurring added risk in conjunction with increased gross margin; that is, such farmers would not be averse to using inputs or technologies provided they did not increase the standard deviation of the gross margin more than twice the increase in mean gross margin. Such a rule would suggest that the S_2, S_3 and S_4 fixed strategies and the R_2 conditional strategy are realistic options for risk averse farmers. The E–SD plot also highlights the large gains in efficiency achievable through the use of inputs (S_4 vs S_1) and conversely, the small benefits of tactics associated with their conditional use (for example, comparing R_2 with S_4).

Stochastic dominance analysis. The cumulative distribution functions (CDF) for the gross margin (Fig. 4a) compare the low-input (S_1) and high-input (S_4) fixed strategies with a high-input conditional strategy (R_2). A closer examination of the lower third of the probabilities for gross margin (Fig. 4b) highlights the large increase in risk of a negative gross margin associated with use of fertiliser inputs (S_4 compared to S_1) and the significant reduction in this risk that was achieved with a conditional strategy using information on date of season onset as a predictor (R_2 vs S_4).

Safety first (mean (E)–negative deviation (ND) space). The desire of farmers to achieve some threshold production level needed for survival is easily envisaged. In the case of decisions concerning fertiliser inputs, the desire of farmers not to lose money (that is, to avoid recording a negative gross margin) can be viewed as a requirement for financial survival or 'safety-first' goal-setting. Strategies can be assessed in terms of such goals by plotting the expected returns against the probability weighted sum of deviations below some target, in this case, below a gross margin of zero (Fig. 5). Such a plot in mean–negative deviation space (E–ND)

(K.A. Parton, University of New England, Australia, unpublished data) has obvious parallels to E–SD space considered earlier (Fig. 4). E–SD space uses all variability in returns as an indicator of risk (that is, deviations both up and down) while E–ND space considers only the down-side risks. While response farming raised expected returns slightly, it had little impact on risk as assessed in the E–SD plot (Fig. 3). Tactics linked to an onset-date

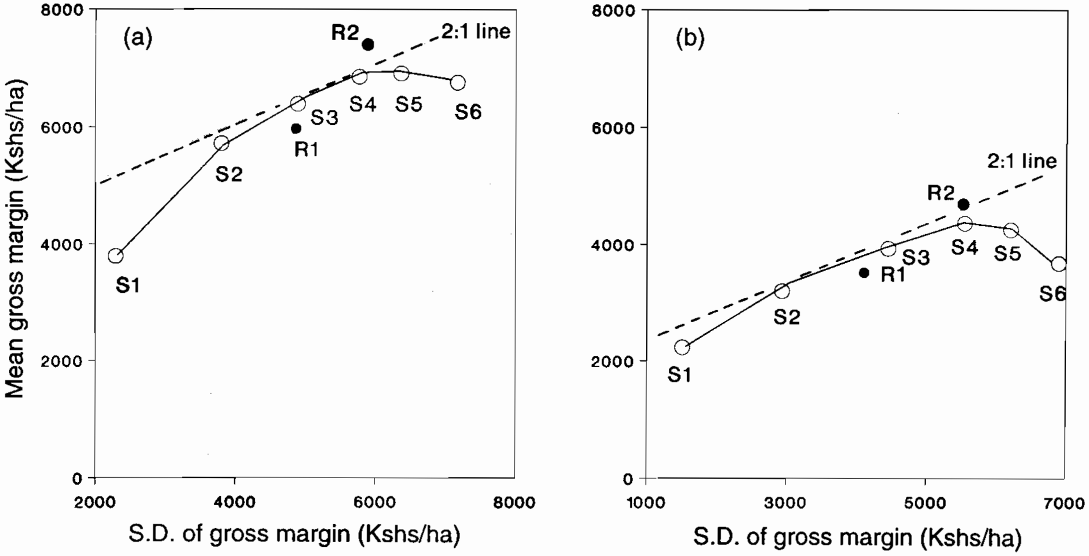

Fig. 3. The outcome of various fixed (open symbols) and response farming (R_1, R_2) strategies, specified in Table 1, plotted in mean-standard deviation space. The broken line represents the slope of the 2:1 line. (a) Long rains and (b) Short rains.

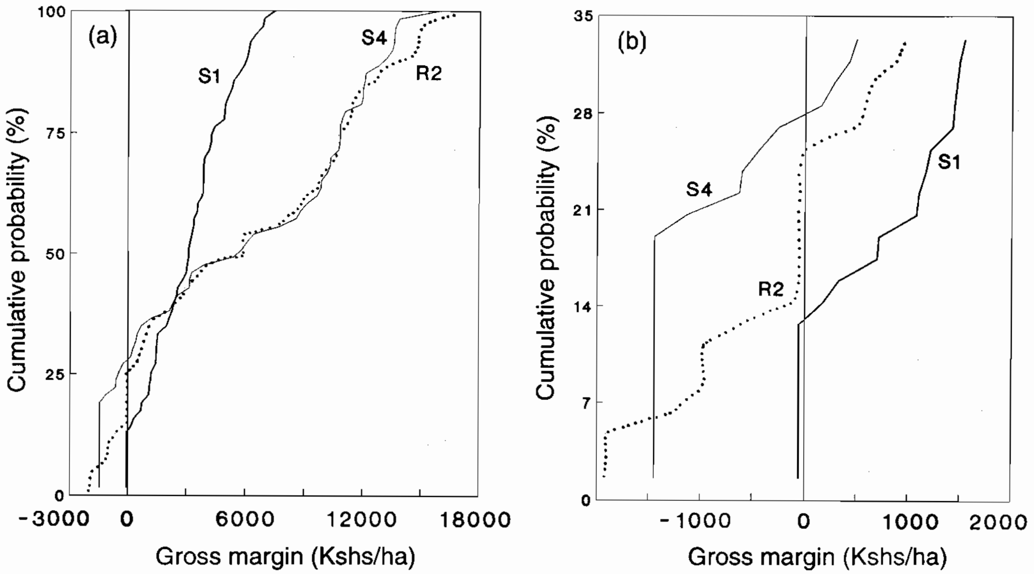

Fig. 4. Cumulative probabilities of gross margin for fixed (S_1, S_4) and conditional (R_2) strategies of N fertilisation over both long and short rains. Details of strategies are given in Table 1.

(a) Full range of gross margin.

(b) Lower 33% of the range in gross margin.

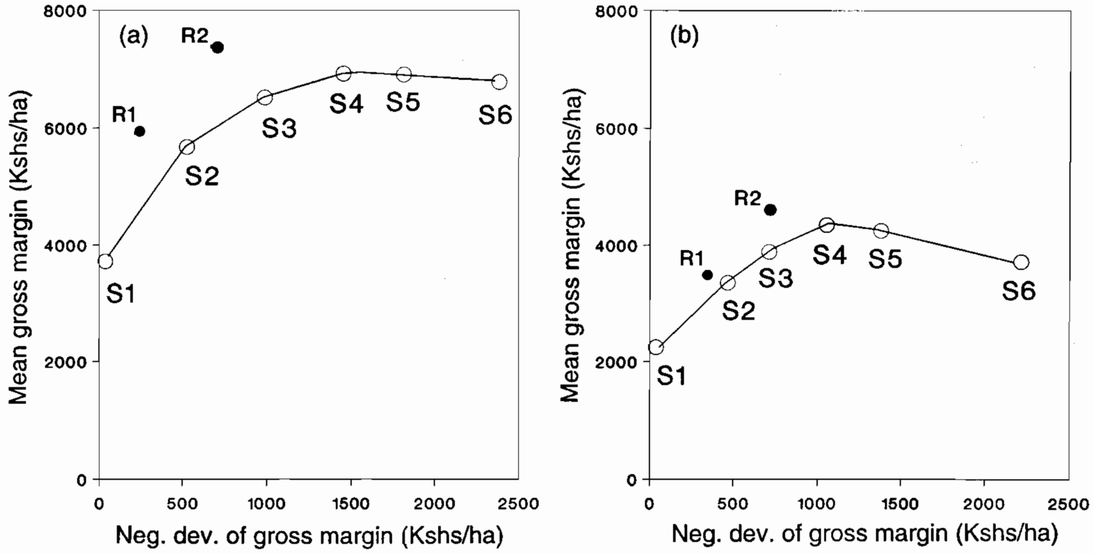

Fig. 5. The value of various fixed (open symbols) and response farming (R_1, R_2) strategies, specified in Table 1, plotted in mean–negative deviation space. The negative deviation refers to outcomes with a gross margin less than 0 Kshs/ha. (a) Long rains and (b) Short rains.

forecast did however have a substantial benefit in reducing negative deviations (Fig. 5) and may be attractive to farmers pursuing strong 'safety-first' goals.

Discussion

The date of the start of the rains at Katumani can be a useful predictor of potential yield, and hence of the capacity of crops to respond to inputs. Adjustment of N input levels and plant populations to better match the season potential is a logical response with a sound biological basis. How much value to place on the forecast is more difficult to assess. In terms of average returns, its value is small relative to the large benefits from using fertiliser irrespective of a forecast. In terms of minimisation of risks, it can be of value, substantially reducing the number of occasions when fertiliser is purchased and rainfall is insufficient to obtain a return in the year of application.

Information presented elsewhere (Keating et al., these proceedings) on variability in rainfall and response to fertiliser additions shows that anything less than 20 to 30 years would not provide an adequate picture of the variability in net benefits associated with a particular tactic. Experimental evaluation of the conditional management strategies (examined in this paper using simulation) would not have been feasible.

Recognising that farmers change their practices incrementally, the results indicate that the most important step is increased use of nitrogen fertiliser, irrespective of any formal system to forecast seasonal potential. While this and earlier studies (Keating et al., these proceedings) in the region highlight the potential economic value of fertilisers, we observe few farmers using them. Possible reasons are considered in other papers in these proceedings (Muhammad and Parton; McCown and Keating).

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Exploring the Human Side of Change in Production Technology

Socioeconomic Modelling of Decision Making with Respect to Choice of Technology by Resource-poor Farmers

K.A. Parton*

ONE objective of socioeconomic investigation is to obtain information that will direct research activities to relevant areas. Many mistakes have been made in the past by attempting to introduce innovative ideas without proper recognition of a socioeconomic perspective. An example in a Machakos context was the recommendation of the Kenyan Land Commission (1933) that there should be a policy of removing cattle from the land to enable closer settlement and hence solve the overpopulation problem. In 1938 a meat-packing plant was established and the government tried to use compulsion to get the Akamba to sell their cattle (Lynam 1978, p.49). The Akamba resisted and the government was forced to accede to their demands. This rather misguided government policy happened as a result of a misunderstanding of the role of cattle, particularly as a source of wealth and prestige.

While there are fewer such gross errors nowadays, various, more subtle mistakes are still made by misconceiving the socioeconomic context. The problem highlighted by Roling (1989) is widespread. This is that we tend to view farmers as passive recipients of technologies developed by other people and, at best, farmers' reactions to new practices are considered merely in terms of fine-tuning the technology. In fact, farmers are active problem-solvers who develop for themselves most of the technology they use. In addition, many off-farm innovations are modified by farmers by a process that Rogers (1983, p.16) calls 'reinvention'. While technically the potential for such modification may seem to be limited in cases like new maize varieties, socioeconomic variables may still be influential in preventing the application of the ideal level of fertiliser input, so that the complete technology package remains unadopted. Once processes like reinvention are recognised, the appropriate mode of farmer participation becomes collaborative or collegiate rather than consultative method (Biggs 1989).

In the remainder of this paper, attention is given sequentially to (a) those socioeconomic factors to be considered by researchers when designing innovations, (b) an economics approach that makes the issues both more tractable but more obscure, (c) a hybrid (socioeconomics) method that attempts to overcome some of the problems inherent in the economics approach, and (d) a synopsis of the type of results that flow from application of this method.

Socioeconomic Factors to be Considered by Researchers when Designing Innovations

Researchers often express concern about what they term the 'non-adoption' of innovations that have favourable technical characteristics. The act of innovating seems to be heavily laden with positive value (Downs and Mohr 1976), so that farmers who do not adopt are considered in some sense to be irrational. Generally, it would be more appropriate to view farmers as extremely rational decision-makers who have sound social or economic reasons for using or not using the innovation.

Another issue to be aware of is that concern about non-adoption should really be viewed as concern about the low rate of diffusion. Even innovations that have outstanding technical characteristics can take considerable amounts of time to diffuse. Rogers (1983) presents the example of hybrid maize in Iowa. The newly developed maize had a 20 per cent higher yield than the previously used open-pollinated varieties, was more drought-resistant and better suited to mechanical harvesting. On average, farmers took 9 years from awareness of this innovation to trial use, and then a further 3–4 years before they individually reached 100 per cent adoption. In other words, even for innovations that will eventually become the standard technology, there will be considerable introspection and testing by farmers before full adoption. In addition, the rate of adoption is likely to be less rapid in traditional societies where attitudinal resistance has to be overcome.

Following Rogers and Shoemaker (1971), a classification of the variables that influence the rate of adoption is shown in Figure 1. The most significant point

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about the figure is that from this sociological perspective there are a large number of explanatory variables. Moreover, for each of the variables listed, subcategories of supporting variables can be contemplated. For example, advantage of an innovation is measured relative to the currently used technique, and has a number of dimensions including financial gain, social prestige, and release from hard or tedious labour. In contrast to this, the economics approach of the next section tends to collapse its analysis into as few variables as possible.

Rogers and Shoemaker (1971, p.138–160) describe at length the remaining variables in Figure 1. In summary, the rate of adoption would tend to be directly related to the degree of relative advantage, compatibility, trialability and observability, and inversely related to complexity. With respect to the type of innovation-decision, it is expected that decisions made by a single authority would be adopted most rapidly unless the authority is tradition-bound. Innovations dependent on collective decision-making would generally be adopted relatively slowly. On communication channels, interpersonal channels have been found to be more effective where awareness already exists, and for complex decisions. Finally, the nature of the social system and the extent of the change agents' promotional efforts, particularly the timing of those efforts, have been observed to be significant.

Another aspect revealed by examining the work of social science disciplines other than economics in the context of poor farmer decision-making is the observation that farmers' objectives are represented by a hierarchical goal system. The arguments supporting the use of such a lexicographic want system in LDC agriculture were reviewed by Parton (1987). The basis of the theory in economics was presented by Georgescu-Roegen (1954) in terms of a hierarchy of wants that is fulfilled by individuals in a lexicographic manner. Not until the most basic wants (e.g., thirst, hunger and shelter) are satisfied will less basic wants (e.g., social esteem) appear. Research in other disciplines, from psychology (Maslow 1970; Lutz and Lux 1979) to economic anthropology (Sanday 1976; Barlett 1980), provides evidence to support this view. However, such a discrete ordering of wants is in complete contrast to the mainstream economics model,

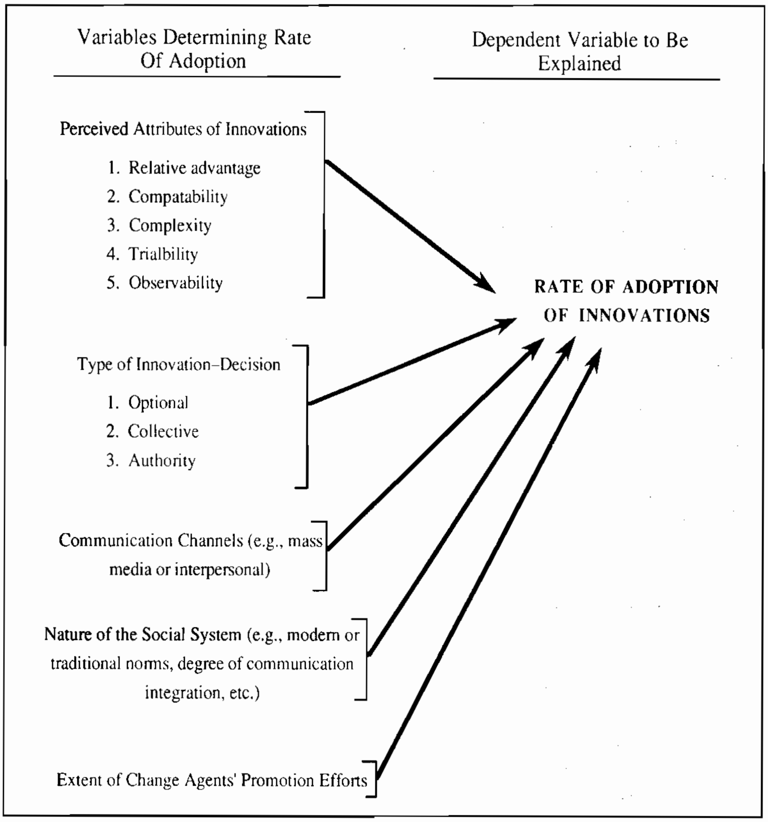

Fig. 1. Variables determining the rate of adoption.
Source: Rogers and Shoemaker(1971).

which converts all wants to single, continuously distributed want, called 'utility'. Choice in this latter model is across a continuous indifferent surface where utility measures the degree to which overall wants are met. Support for this model rests on the argument that it is tractable and provides a reasonable approximation of the real-world decision context even where choice is between wants at different levels of a lexicographic system.

Clearly, this is an empirical issue which varies depending on the circumstances under investigation. However, preliminary work in Kenya (Ockwell et al. 1991a,b) suggested that a richer model that incorporated a hierarchical preference system would be a significant improvement, both in analysing adoption decisions of individual farmers and in identifying and comparing the motives of different farmers. Support for the notion that there are diverse motives across the regional populations of farmers is provided by Roling (1988, p.69). He criticised the traditional role of extension which involved (a) interacting with the innovative farmers at the top of the hierarchy, and (b) expecting the message to trickle down to the other farmers once the innovators adopt the new practice. He argued that the farm population of a region should be viewed as being stratified into groups, with little interaction between them. As a consequence, there would be little trickle-down effect and each group of farmers might require a different extension program tailored to its own circumstances and goals. Thus, knowledge about such circumstances and goals would be required before an effective extension program could be designed. In addition, such knowledge would be crucial input to the type of model that is discussed later in this paper.

An Economics Approach

In contrast to the aforementioned complex description of the innovation process, economic analysis of adoption is generally extremely simple. The overriding concern is to capture the key components of the situation in as few variables as possible. The dictum is elegance in achieving realism with simplicity. An example is the work of Goodwin et al. (1980), in which poor farmers in Brazil can select traditional activities (X) or take on various levels of new farm practices (Y). Maximisation of expected utility (U) is the motivation behind the decision, and utility is dependent on (a) income from traditional activities (CX) and its variability (G), (b) perceived income from the innovation (ΩEY) and its perceived variability (βH), and (c) the decision maker's level of risk aversion (ϕ).

$$\text{Max } U = CX + \Omega EY - \phi G - \phi\beta H \qquad (1)$$

Taking account of the level of risk aversion by the coefficient ϕ, an innovation is adopted by farmers if it achieves a higher ßlevel of utility than the existing technology.

This approach to the analysis of adoption issues is at the same time both more tractable and more obscure. The obscurity is related to (a) the normative nature of the model, so that the model shows, for example, the preferred technology if risk aversion is within a particular range of values, and (b) the fact that the real socioeconomic variables that lie behind what the economist measures as risk aversion and risk perception remain unobserved. An implicit link to these unobserved variables often needs to be made after the analysis, because policy intervention is designed to influence such variables rather than risk aversion and risk perception directly.

Expected value–variance (E–V) analysis can be used to elaborate further this tractable-yet-obscuring effect of this economics approach to adoption. The effect of perception alone is shown in Figure 2. Three hypothetical E–V frontiers are shown. In the centre, is the E–V trade-off for the traditional technology. In this case, the farmer's perception and the actual trade-off coincide because of the farmer's long experience with the technology. The upper curve is the actual E–V trade-off with a properly managed new technology. However, in the first year that the technique becomes available the farmer's perception is likely to be defective, so that his impression of this technology is represented by the lower curve. From the perspective of the farmer the innovation is less risk-efficient than the traditional technology, and adoption does not take place. Nevertheless, it would be expected that through time the lower E–V curve will be moving towards the upper curve as observation of the new practice on neighbouring farms and trials take place.

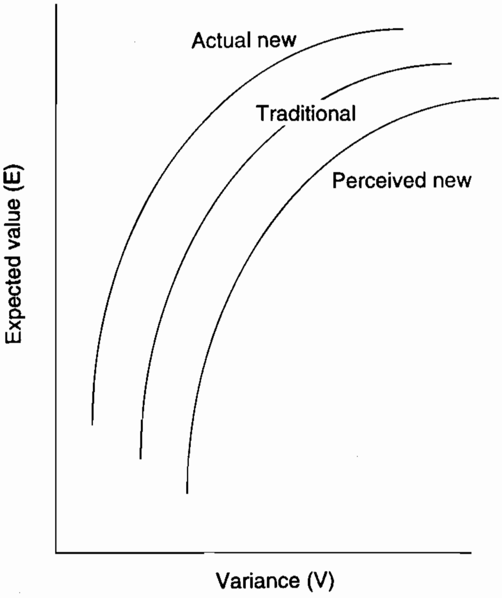

Fig. 2. E–V frontiers for traditional and new technologies.

Next, the effect of risk aversion must be considered. The first proposition here is that as long as the E–V curve is shifted up along its entire length (that is, the new technology dominates the old or is more risk-efficient than the old), the degree of risk aversion does not influence adoption. This is demonstrated in the two parts of Figure 3. The lower part of the figure represents the decision frame for a highly risk-averse decision-maker. The upper part is for a less risk-averse decision-maker. For both of these farmers the innovation provides them with maximum utility as evidenced by the points of tangency between the E–V curve and the highest utility contour.

However, this situation of complete dominance by one technology is unlikely. A more likely configuration, shown in Figure 4, is one in which at low levels of yield the traditional technology is superior to the new. This may result from an inherent problem in the new practice or from, say, a cash shortage that prevents adoption of a complete technology package. If the situation is as shown in the figure, then risk aversion again becomes important to the adoption decision, with higher levels of risk aversion causing non-adoption.

While the E–V model provides the basis for some powerful analysis, it still has the drawback that it does not explain the underlying influences that cause risk aversion and perception. The many sociological influences described in Figure 1 always remain in the shadows when using the E–V model. They are not within the actual analysis and the analyst must provide an intuitive link to them from the model results. This is significant because it is these underlying influences that are the targets of policy intervention and extension efforts. If such influences are considered in conjunction with an E-V analysis it must be by means of an implied (assumed) link from, say, on-farm trials to risk aversion and perception.

A Hybrid Method

The obvious next step is to make these implied links explicit. That is, the agenda is to commence with a risk-efficiency model (in our case a risk programming model) and build back into it some of the socioeconomic variables that are prevalent in the sociological approach. The objective is to capture the analytical advantages of the economics approach while giving credence to the attention to detail in the sociological approach. Muhammad and Parton (1991) describe the beginnings of the empirical part of this investigation.

At the outset it is clear that this type of method requires the introduction of more real-world detail into an economics framework, and hence much more intensive data collection. It requires attention to be focused on all the (many) significant circumstances that influence the adoption decisions of particular identifiable farms. The goal system of farmers must be understood more precisely than the risk aversion and risk perception models allow. Moreover, the socioeconomic constraints that operate on farm households must be given the same recognition that in the past has been given to the technical constraints of the farm.

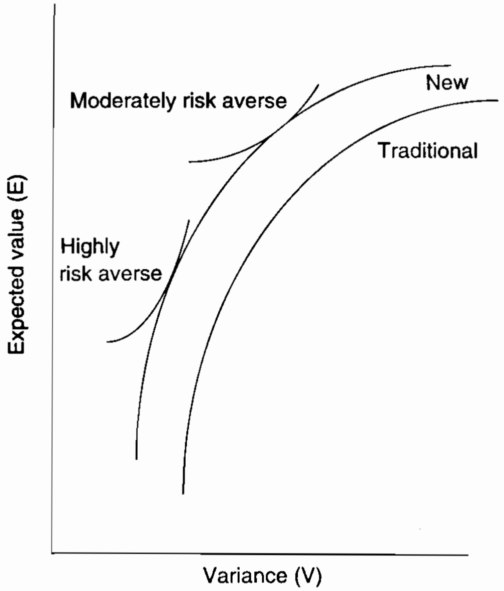

Fig. 3. E–V analysis showing that risk aversion does not influence technology selection where one technology dominates the other.

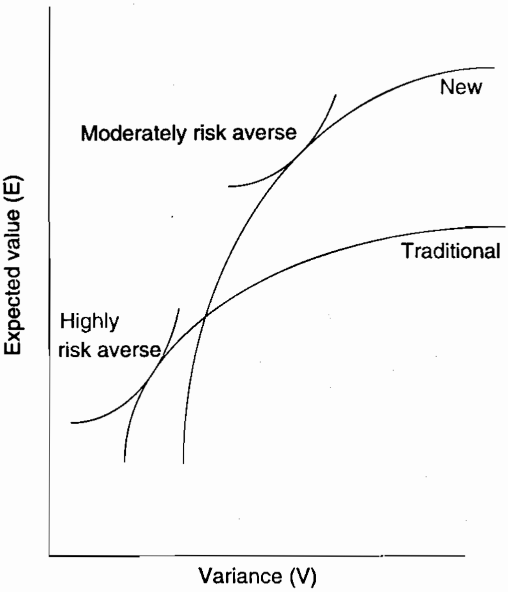

Fig. 4. The impact of risk aversion in a more realistic setting.

The main database for the hybrid analysis is a few carefully chosen case-study farms. While statistical surveys can be useful up to a point, the reasons for adoption and non-adoption are often too complex to be revealed by survey methods. For example, two farms from different villages may, using survey methods, be shown to be identical except that the first regularly applies fertiliser and the second does not. The reason for adoption could be the particular social organisation of the first village which involves an innovative leader on a farm other than the one being studied. Only an intensive examination of the case-study farm will reveal these influences. The challenge is to construct models that can capture the diversity of adoption, but still retain the ability to generalise about the causal processes (noting that the models are based on case studies that are probably statistically unrepresentative).

A Theoretical Framework

This subsection and the next describe in outline the development of such a model. A fundamental part of the model reported in Parton (1991) is presented. The method of applying this to resource-poor farmers in the Katumani District is then discussed, highlighting some potential reasons for non-adoption of improved practices.

The notion of representing decision-making by poor Kenyan farmers as a lexicographic ranking evolved while attempting to examine their preferences in a multi-attribute utility framework (Keeney and Raiffa 1976, ch. 6). On each new farm, the interview designed to elicit utility functions reached a certain point at which the farmer began to express his/her goals in terms of an ordering of attributes (Ockwell et al. 1991). From highest to lowest preference, many of the expressed rankings can be interpreted as family/farm survival, dietary preferences, education of children, and then (as a group in which trade-offs were significant) farm development and consumer expenditure. This suggested that a better description of decision-making by these farmers could be achieved using a lexicographic model (Georgescu-Roegen 1954), rather than the multi-attribute utility model from which the experiment began.

A lexicographic perspective for describing decision-making by these resource-poor smallholders is based on the assumptions that (a) there are three levels of goals, viz. survival, diet preference and cash, (b) the first goal is pursued until a survival level of consumption is achieved, after which the diet-preference goal becomes operative, and (c) there is a satisfactory level of the diet-preference goal which, once achieved, allows the objective of generating a cash surplus to operate.

The first (or lowest) level goal is the achievement of survival for the farm-family. Wharton (1971) provided a classification of types of subsistence. The term 'survival' used in this paper closely conforms to his 'minimum subsistence standard of living', and includes not only physiological requirements of the family group, but also sociocultural requirements.

Prior to the growing season, it is the survival goal that influences planning. It is operationalised by assuming that the farmer sows the combination of crops that he/she considers will maximise the chance of achieving the survival threshold of the farm-family. The farmer's decision-making can either be analysed in a situation where there is no market for the crops grown or, more realistically, where the food crops grown can be traded in a local market. The first requires the description of the production possibility set, while the second involves this set augmented by marketing activities.

As food production is dependent on weather, the production possibility set is defined stochastically. The line labelled *X* in Figure 5 shows the possible combinations of two foods that could be produced with a given combination of inputs and a given technology. Thus, a shift from one line to another could be either a change in technology, or a changed input combination within a fixed technology. A movement along the line represents the effect of weather. Lines *Y* and *Z* are similarly defined for a different combination of inputs or different technology. These three lines can be conceptualised as the planning framework of the farmer prior to the growing season in the situation where there is no market for the foods he/she produces. He/she must select one of the production plans *X* or *Y* or *Z*. (In the innovations context, *X* and *Y* might be improved technologies, and *Z* a traditional one.) Having made a selection, the actual weather

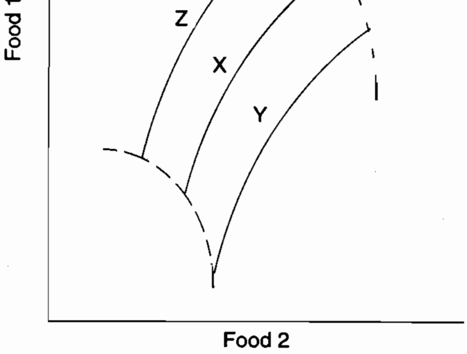

Fig. 5. Stochastic production sets.

that occurs during the season influences farm production and generates an outcome along the selected line. For completeness, the boundaries of these production sets are shown as the production possibility curves that apply to the best and worst weather situations, respectively.

These best and worst production possibility curves are carried forward to Figure 6. Also shown in this figure is a survival threshold. This represents the combination of the two foods which just ensure survival for the farm-family. Given that production is stochastic, the survival goal can be defined in terms of maximising the probability of its achievement. Hence, also shown in the diagram is a third production possibility frontier which has the characteristic that there is a given probability of obtaining outcomes to its north-east. Then at the point of tangency between the survival line and this final production possibility curve, the production plan that maximises the probability of survival is indicated. In Figure 6 this is plan *X*.

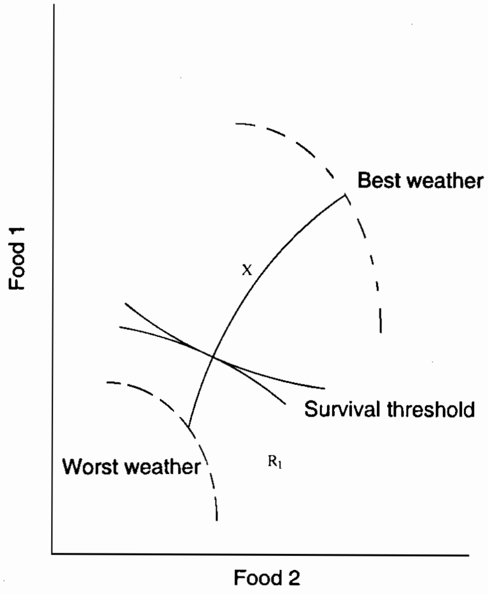

Fig. 6. Defining the plan that achieves survival with highest probability.

Extensions to this theoretical framework that include off-farm trading activities and higher level goals are included in Parton (1991). Of more interest in this paper is a practical application to a group of low-income farmers in the Katumani District. Over the seasons 1985 to 1989 this group seemed to be emphasising the survival goal. The technology in question is a new maize variety called Katumani Composite B. From the perspective of the agricultural research scientists, the two most significant components of the technology are improved seed and nitrogen fertiliser. This technology package offers farmers a substantial increase in yields and net returns over traditional varieties in all except very dry seasons. The perplexing issue facing researchers is that most farmers have adopted the new seed variety, but few apply fertiliser even though it can be purchased locally. To researchers such partial adoption of the technology package is a considerable loss of potential.

It is revealing to show diagrammatically the production from three alternative technologies: traditional; new maize without fertiliser; and new maize with fertiliser. Figure 7 indicates the combinations of two food crops produced under these different technologies for five weather patterns. Food 2 is maize, so there is a horizontal shift when moving from one maize to another. For example, the movement from A_1 to B_1 involves a rightward shift from an increased yield from the new variety and a leftward shift because of the cost of purchasing the new seed. Taken together they produce a shift to the right. In a similar manner, the movement from A_1 to C_1 is a net shift to the left, and is produced by a yield increase (to the right) and a cost of seed and fertiliser (to the left).

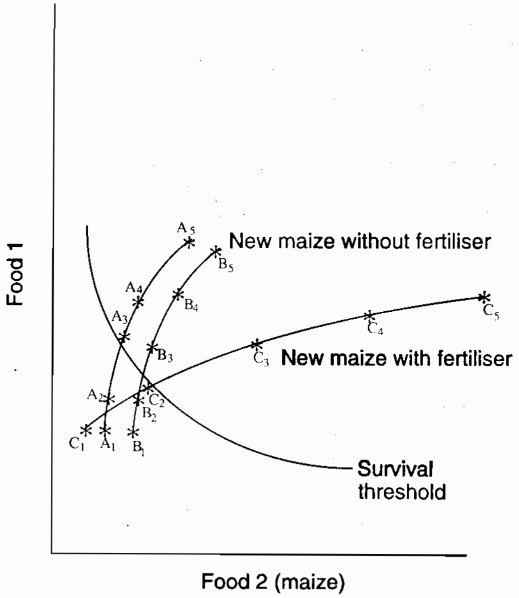

Fig. 7. Production relative to the survival threshold using different technologies.

The comparison that is emphasised in the consciousness of the agricultural researcher is that between the traditional variety (points A_1 to A_5) and the dominating points of the complete technology package (points C_2 to C_5). In contrast, the comparison that is in the mind of the farmer is between the traditional variety (points A1 to A_5), the dominating points with the new maize variety without fertiliser (points B_1 to B_5), and the inferior point using fertiliser (point C_1). In other words, the scientist tends to overlook the downside risk, whereas the farmer sees this of paramount importance when survival of the farm–family is at risk. From such a perspective, the adoption of maize without fertiliser is a rational choice.

It must be emphasised that this example is applicable to only those farmers pursuing the survival goal. A different response to the availability of technology can be expected for farmers higher up the want hierarchy. Hence, in designing technologies it may be useful to be aware of the proportions of the farm population that are, at a particular time, pursuing the different goals in the hierarchy.

A Target-MOTAD Representation

The target-MOTAD model (Pederson and Bertelsen 1986; Parton and Cumming 1991) offers a means of operationalising this analysis. Within this model, a higher-level objective (typically net revenue) is maximised subject to some probability of achieving a lower-level objective (like family living expenses plus fixed costs), and subject to the usual farm production constraints. It is easy to envisage adaptation of this model to the Kenyan situation in which farm survival forms the lower-level objective, and this is combined with a series of higher-level objectives.

To demonstrate target-MOTAD analysis, Figure 8 shows the possible outcomes from two farm plans, expressed as probability density functions. Also shown is a target level of the lower-level objective. Farm plan 1 is generated by fixing a tight constraint on the probability of obtaining an outcome above the target. It would typically have a lower mean (E_1) and a less dispersed distribution than farm plan 2 (mean E_2), which has a less rigorous constraint on the probability of remaining above the target.

By parameterising the constraint on the probability of remaining above the target, a series of such plans can be obtained. Plotting them, as in Figure 9, provides a mean–negative deviation frontier, where the negative deviation is the probability weighted sum of deviations below the target.

Having generated this frontier, one more step is needed to define a farmer's optimal position. Analytically this is shown at the point of tangency between the frontier and a mean–negative deviation utility function. More pragmatically the preferred position can be obtained by describing to the farmer the various farm plans along the frontier, and asking him to select one. If he/she was in fact maximising the probability of survival then this would be shown by selection of the farm plan with the lowest negative deviation.

A Synopsis

The main theme presented in this paper is that a hybrid approach is appropriate for modelling decision-making on innovations by resource-poor farmers. Such an approach would draw on a sociological perspective and highlight key socioeconomic variables, but by use of an optimisation framework it would also maintain the elegance of the economic modelling of farm decision-making. The use of the target-MOTAD method would enable both a broader array of variables than is usual to be captured in an economic analysis, and would permit a lexicographic preference system to be modelled.

Given that the type of work discussed above is just beginning it is not possible to report the results of this research. Nevertheless, some findings are reported in Muhammad and Parton (1991), and the work of Ockwell et al. (1991a,b) obtained results supporting the use of the method. The general conclusions of this latter work are worth re-emphasising as a demonstration of the type of information that is revealed even at the data collection stage.

First, Ockwell et al. (1991a,b) showed that the farm and household systems of the semi-arid tropics of eastern Kenya were highly integrated and complex. Second, clearer knowledge of the goal system of farmers was required for a reasonable understanding of the adoption process. Many farmers seem to have a hierarchical goal system, with survival being the dominant goal followed by education of children and then the purchase of goods for both the farm and the household. Third, livestock were a key part of farm activities. They were a store of wealth, an insurance against crop failure, a status symbol, and a source of draft power and manure. Next, off-farm work was widespread and the income generated from it facilitated adoption of innovations.

Finally, there seemed to be a distinct order in which new practices were adopted. Except for improved varieties of maize and beans which were in use by many farmers, the technologies that had widest use were non-cash using, followed by low-risk cash using and then high-risk cash using innovations. Hence, moving from lowest to highest adopter categories, the following progression in adoption was observed. The least innovative group applied farmyard manure to cropland, used improved fodder and maintained their terraces. The next group employed these practices and in addition prepared cropland before the onset of rains and had adopted improved maize and bean varieties. Further innovations adopted by the next group were the use of the oxplough and chemicals in crop storage. Then the most innovative group applied all of the previous new practices together with new varieties of crops other than maize and beans, and chemicals in the field. There was only limited use of fertiliser.

The challenge remaining is to develop a modelling

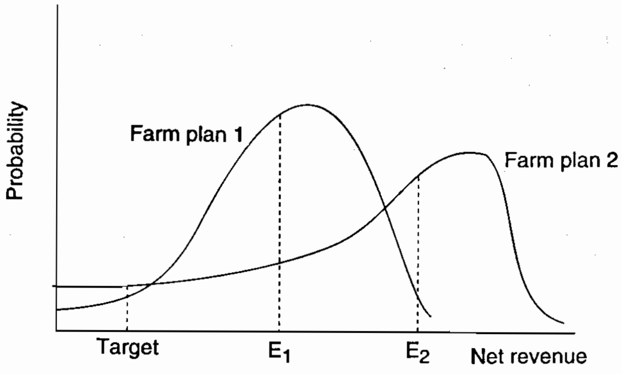

Fig. 8. Probability density functions of two farm plans relative to the target.

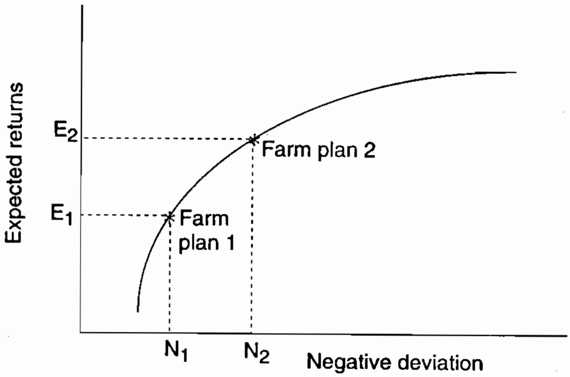

Fig. 9. A mean–negative deviation frontier.

framework that can explain these types of observations by revealing the significant components of farm-household decision-making. The first empirical steps towards such a model are described in a related paper (Muhammad and Parton, these proceedings).

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Smallholder Farming in Semi-arid Eastern Kenya — Basic Issues Relating to the Modelling of Adoption

L.W. Muhammad* and K.A. Parton†

THE farmers of Kenya are expected to lead the country in economic development for the rest of this century and beyond. Agriculture will have to provide food security and employment for a growing population and to stimulate growth of non-farm employment opportunities in the rural areas. The overall growth target for the agriculture sector is 5.1% per year (Government of Kenya 1990). In pursuit of this goal, three strategies related to farm innovation are being followed. In the first strategy, farmers are being encouraged to adopt more productive practices. Provision for research into higher yielding varieties and promotion of farm-level diversification into activities that generate higher incomes are the second and third strategies. For the semi-arid lands, the focus is on research into drought-resistant crops and suitable grasses to prevent soil erosion. All these strategies are to be supported through continued improvement in the extension services and an environment which offers adequate incentive for the expansion of private and public markets for farm inputs. This is designed to encourage rapid adoption by farmers.

Clearly the adoption of farm innovations is crucial to the overall development effort. To understand this process of adoption, knowledge about smallholder decision-making is required. By constructing a series of farm-household models (Parton, these proceedings) the objective was to evaluate this smallholder decision-making in relation to adoption of improved farm practices. Survey work supporting these models was carried out during 1990. In this paper, preliminary findings from the survey are outlined and discussed relative to the proposed and ongoing effort to develop options for enhancing the incomes of farmers in the semi-arid lands of Kenya.

Background

The most salient feature of smallholder farming in semi-arid eastern Kenya is the extremely high diversity in the portfolio of activities that farmers operate. Complementary, supplementary and competitive interactions among crops and livestock enterprises and the integration of the farm and household combine to underpin great complexity in the farming systems. It is mainly because of these considerations that the National Dryland Farming Research Centre (NDFRC) of the Kenya Agricultural Research Institute (KARI) has adopted a multidisciplinary approach to research for agriculture in the semi-arid lands. Previous farming systems research at the centre has provided a description of farm-level resource endowments and the constraints to higher productivity (Rukandema 1984). An in-depth study of the basis of non-adoption of proven innovations was subsequently undertaken following a case-study approach (Ockwell et al. 1991a,b). The roles of risk and other household characteristics were identified as being of importance in the making of decisions about adoption of new technologies. The farmer's goal system was clearly significant to the innovation process and knowledge about it was necessary to explain behaviour (e.g., farmers persisting with low yield/low risk traditional crop varieties). With respect to household and demographic characteristics, younger farmers tended to be the more innovative, and off-farm income tended to facilitate both adoption and the attainment of other goals like children attending secondary education. These findings provided the basis for the investigations that are discussed in the following sections.

Farmer Adoption of Innovations in Traditional Agriculture

The aim of investing effort in the development and dissemination of new farm practices is to bring about rural development through technical progress. Such progress can be said to have taken place only when the practice has actually been taken up by farmers. There is, however, considerable variation in adoption behaviour among smallholders. Some innovations spread rapidly among the farming community, requiring little promotional effort. Examples of this are cocoa in Nigeria in the 1940s (Roling 1988), hybrid maize in western Kenya (Johnson 1979) and new maize seed in the Machakos area (Dowker

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1961). In contrast, extension recommendations based on the applications of inorganic fertilisers appear to have encountered considerable resistance in traditional farming. Reluctance to innovate can, in general, be traced to either farmer characteristics, attributes of the innovations, off-farm factors or a combination of these. Our survey work examined each of these factors in turn.

Firstly, the innovation may not be known or understood by farmers. Lack of awareness among farmers about the relative advantages of an innovation or proper procedures for its implementation will reduce the chances of adoption. Lack of awareness may be a cumulative result of inadequate promotion and the farmer's inability to seek, acquire and utilise specialised information. Farmer's age, education and contact with the world beyond the confines of his own locality have been shown to be associated with innovation (e.g. Low 1982; Hunt 1978; Collinson 1983). Information on these variables was collected in the survey.

Secondly, if farmers lack the ability to innovate, the chances of a new practice being adopted will be reduced. Inability to innovate may be because of lack of resources or because the demands on available resources do not allow allocations to new undertakings. Factors such as wealth, income and ratio of producers to consumers in the household are usually relevant . Questions about these variables also formed part of the survey.

Thirdly, the innovation may not be technically viable or adequately adapted to specific conditions. Even if the technology is physically superior, it may not be economically attractive; that is, when the farmer assesses what is required by way of changes in the input mix against expected gain, the new technology is found wanting. Such expected gains and losses may not be measured in financial terms but rather in terms of, for example, labour hours required or how onerous the work is. Opinions of farmers on these issues were recorded during the survey.

Finally, the main off-farm factors relate to the availability of inputs. The usual practice is to promote innovations in 'packages' rather than individual components. Technologies which are embedded in physical items such as new seeds, fertilisers and equipment will call for the timely availability of these inputs for adoption to take place. These were also issues concentrated on during discussions with farmers.

Methods and Procedures

The design and conduct of the survey drew heavily on the work of Moser and Kalton (1971). A questionnaire was designed for the recording of various items of farm and household information, based on FAO's *Farm management data collection and analysis system* (Friedrich 1977). The FAO system was adapted to enable data to be processed by commercially available software. A second questionnaire was drawn up to elicit from farmers a subjective assessment of technology and related issues. The survey was conducted between December 1989 and April 1990. The plan was to utilise the sample that had been selected for participation in the baseline survey (Rukandema et al. 1981). This had been drawn, by a stratified random sampling procedure, from the register of land owners. Because of migration and other changes, the original sample of 100 households had been reduced to 93.

In the current survey, inventories of farm resources and descriptions of husbandry practices and the structural and functional organisations of farm households were recorded on the first schedule. Assessment of the current status of the farmers' understanding of the innovations, the extent of implementation and the farmers' views about advantages and disadvantages and constraints were recorded on the second schedule.

The focus of this study was maize production. Innovations considered were: timeliness of planting; use of improved seed (KCB); and use of organic and inorganic fertilisers for the improvement of soil fertility and plant nutrition.

Results and Discussion

As a first step, the information that was obtained was scanned for any deviations from the baseline data. This was to facilitate identification of innovations which have been adopted and the extent of adoption, providing a basis for further examination of the constraints stated by farmers. Factors which appear to have favoured or constrained adoption would be brought to the fore. Table 1 summarises these comparisons.

Overall, the results in Table 1 indicate a varied record of adoption of different innovations. Innovations requiring little direct cash outlays (organic fertilisers and early planting) are the most widely adopted. These comprise the poor person's technology. The inorganic fertilisers result is interesting. In absolute terms, adoption of this

Table 1. Uptake of selected components of the maize production package 1980–90.

Package	Adopters as % of all farms 1980[a]	1990	% change
KCB Seed	31	30	−3
Organic fertilizers	68	83	22
Inorganic fertilizers	8	18	125
Early planting date	n.a.	56	n.a.
Medium planting date	n.a.	37	n.a.
Late planting date	n.a.	7	n.a.
Pesticides	15	17	16

[a] Source: Rukandema et al. (1981)

innovation stands at 18%, up from 8% in 1980 but still low. Little change had occurred in the adoption of improved seed or pesticides.

Farm and Household Characteristics

As already stated, holding size, household size, gender, education and measures of wealth data were obtained. The results of this part of the survey are reported in Table 2.

Table 2. Farm/household characteristics.

Variable	Mean	Median	Mode
Wealth index[a] (Ksh)	20252.00	7645	2000
Wage earners/household	2.68	2	1
Farm size (ha)	7.13	5	3
Farmer's age	54.69	54	60
Years in formal education	6.01	6	8
Household size (no. of persons)	5.95	6	2

[a] The value of farm buildings was taken to represent the wealth level of the household.

The data suggest a preponderance of relatively mature household heads. Also worthy of note are the figures for participation in wage employment. Four in five households have at least one member in wage employment.

Most adoption studies (e.g. Roling 1988; Hunt 1978) have found education to be a relevant explanatory variable. More than half of the household heads (53.4%) have had no formal education at all. At the other extreme, about one third of the farmers have at least seven years of schooling and 16% have eight or more years of formal schooling. Women heads of households have the least formal education. Twenty-six per cent of households had women heads.

To test for possible cause–effect relationships, farm/household characteristics were cross-tabulated with innovations. Farmer's age, years of formal education and the wealth index showed some positive relationship with adoption of inorganic fertilisers. Other correlations did not reveal clear patterns of association. When the data were expressed on a per household basis, relationships between variables became clearer. Average age, producer to consumer ratios and wage income showed strong relationships with the adoption of inorganic fertilisers and improved seeds. Hence, as observed by Ockwell et al. (1992a), off-farm income possibly facilitates innovation by providing the required cash. In addition, family size was positively correlated with early planting and the use of organic fertilisers. Given that labour is the key constraint to the adoption of these techniques, this seems to indicate that labour provided by children facilitates their use.

Sources of Information on Farming

Rogers (1983) describes diffusion of innovations as a four-stage process involving knowledge, persuasion, decision and confirmation. At each of these stages, information is received by the farmer from a variety of sources. Lingamnini (1981) observed that different information sources were more relevant to some stages rather than others. For instance, mass media and cosmopolitan interpersonal channels were more important at the knowledge stage, whereas local interpersonal channels such as discussions with neighbours, friends and personally known extension staff are more important at the persuasion stage.

Farmers were allowed to discuss the various sources of information on innovations at considerable length. The results of these discussions are shown in Figure 1. Apart from their own experience, exchange of information within the local community is regarded highly by many farmers as a source of ideas. The official channels, especially radio broadcasts, also appear to be reaching a significant proportion of farmers. These observations tend to confirm other evidence that, even though diffusion of innovations has not progressed far, farmers have moved to the knowledge or persuasion stage in the innovations process.

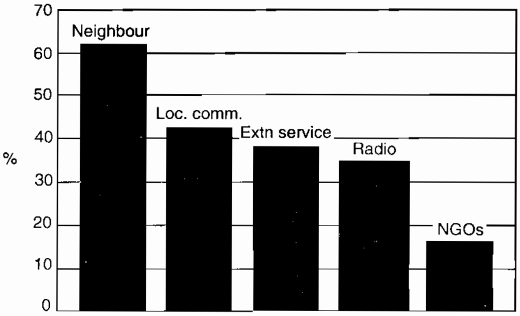

Fig. 1. Sources of information on farming.

As the official sources are likely to be the bearers of reliable technical information, the nature of farmer interaction with them was followed in greater detail. The agricultural extension process in Kenya utilises front-line workers to reach farmers through exchange of visits, farmer training, demonstrations and local meetings (Barazas). The perceived relative effectiveness of each of these methods is shown in Figure 2. A small minority actively seeks advice from the extension workers, but more frequently the extension workers visit the farmers. Overall, Barazas were considered the most important official source. As Figure 3 shows, crops account for most of the extension effort, followed by soil conservation and livestock.

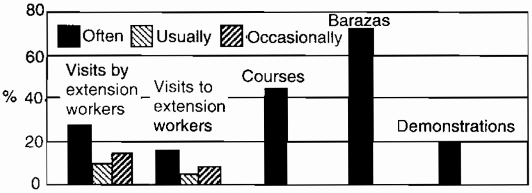

Fig. 2. Stated importance of various components of the extension service.

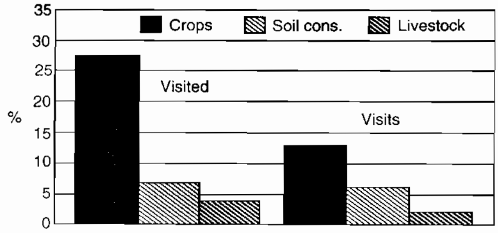

Fig. 3. Exchange of visits between farmers and extension personnel and subject of visit.

The New Technologies

Timing of planting

The current recommendation is that at least part of the crop land should be dry-planted, and that planting should be completed within one week of the onset of the rains (Weir 1985). Most farmers are aware of this recommendation. They see the main advantages as better plant establishment leading to higher yields (43%) and early availability of food (31%). On the other hand, the risk of losing seed (32%) and pest damage (30%) were seen as the main disadvantages of dry-planting. A surprisingly small proportion of farmers thought that weed management was a serious consideration in planting time decisions. This is an important consideration from an agronomic viewpoint.

Although well over half of the farmers in the sample were implementing the recommendation on time of planting, difficulties associated with the innovation were raised. Complaints about lack of sufficient labour were almost unanimous. Hence, availability of labour was seen to be, and usually is, a constraint to adoption of this practice. The relative cost of this constraint can be shown in the type of model outlined in the paper by Parton in these proceedings. In addition, although the awareness stage of the diffusion process has been reached, further interpersonal extension efforts are generally needed to overcome some misunderstandings about the effect of time of planting.

Improved seed

Virtually all respondents have had initial first-hand experience with the improved maize seed (KCB). Earliness (22%) and drought escape/tolerance (60%) emerged as the main stated advantages of KCB over local seed types. However, local varieties are considered to yield higher on average (62%) and require less by way of management. The price of seed was considered to be too high.

Less than one-third of the farmers had purchased some KCB for the 1990 long-rains season. Information obtained from the principal supplier of seed indicated that the quantities of seed purchased per annum are low and variable (see Fig. 4).

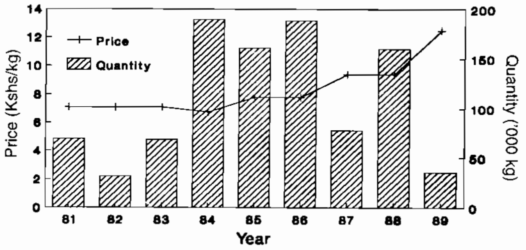

Fig. 4. Sales and prices of commercial seed maize (unpublished data KGGCU, Machakos).

The perception of poor yields using KCB seeds may reflect performance of the seed in poor seasons. Farmers are likely to overstate the frequency of occurrence and/or impact of such seasons. Hence, downside risk is probably important, and modelling of the adoption decisions of case-study farmers in the framework discussed by Parton in these proceedings should reveal the relative importance of such risk.

The survey showed that most respondents were aware that improved seed can be purchased from the local cooperative shop. However, the preferred source of seed was the farmer's own farm (52%). The local market was the second most common choice of source of seed. The usual practice is to select vigorous plants with big cobs and save the grain from these for next season's planting. These observations indicate some misunderstandings about the advantages offered by improved seed.

Fertilisers

Inorganic fertilisers. Like improved seed, all farmers in the sample have used inorganic fertilisers before. Most were aware that fertilisers could be bought at the local cooperative store. Unlike KCB seed, knowledge of different types of fertilisers, correct rates and timing of applications and proper storage and handling was virtually absent, even among those who are implementing the technology during the long rains of 1990. Possible side-effects relating to the use of chemical fertilisers were not recognised. Farmers themselves put forward lack of cash as the main constraint to the use of fertiliser technology. While this is probably a constraint for many farmers, it is clear that, of the techniques under consideration here, inorganic fertilisers have progressed least along the diffusion path.

Organic fertilisers. Increasing awareness of the value of this locally available resource is evident. Nearly all farmers that have livestock apply some manure to crop land. That no farmers apply all the available manure and that no farmer succeeds in applying it to all his fields are deemed to be significant findings of this study. The long dry season is when most farmers apply organic fertilisers; few farmers apply them in both seasons. As there are no standard recommendations, there is great variation in the methods of application, and the proposed modelling framework will highlight the returns from these different methods. Again, lack of labour was the main constraint to greater use.

Summary and Conclusions

In this paper, preliminary findings of a study of the adoption of innovations are presented and discussed. The study shows that, over the last 10 years, there have been increases in the adoption of organic and inorganic fertilisers but no change in the use of improved maize seed. Possible reasons for these developments are proposed. Farmer evaluations of most technologies were positive, except for seed. Despite this, there were numerous misunderstandings about the impacts of the various technologies. The findings of this study lead to the following questions, which form the basis of our current and future investigations.

- What is the relative importance of labour constraints to decisions about planting time?
- What implications does the farmer's behaviour with respect to KCB seed have for maize agronomy research and the pricing policy for seed?
- Why is lack of knowledge about the use of chemical fertilisers still widespread, despite of years of extension effort?
- Since most farmers appear to be conversant with the benefits of organic fertilisers, should the research effort go into finding ways and means of helping farmers with their critical delivery problem to the field, in addition to demonstrating its usefulness?

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Pathways for Development and Implications for Future Research

Looking Forward: Finding a Path for Sustainable Farm Development

R.L. McCown* and B.A. Keating†

THE challenges ahead in agricultural development for Kenya, in particular its semi-arid regions, are enormous. In real terms, population pressure on the land is among the most severe in the world. While Kenya ranks much lower than both Bangladesh and India (Binswanger and Pingali 1988) in terms of people per hectare, if land area is weighted by its potential productivity, the rankings change dramatically. Figure 1 expresses population pressure as people per million kilocalorie potential production and includes only people who work in agriculture: Kenya comes near the top. Pressure on land in the Machakos-Kitui districts of Kenya is particularly severe (Higgins et al. 1982).

The options for response to this problem, which have been presented in the introductory paper (McCown and Jones, these proceedings), are compared in Figure 2. Option A, out-migration to urban centres, generally precedes successful implementation of B or C. Remittances from urban workers provide security for the household and possible capital inputs to farm production. The future contribution of this option as a means of relieving pressure on land depends on the rate of employment growth relative to population growth.

The expansion of cropping into the dry marginal areas (Option B) can be expected to continue in the future, but certain trends are predictable. Because the carrying capacity of land available for settlement declines as the most productive land is settled first, the efficacy of this option declines proportionately. The downward spiral (Fig. 3 in McCown and Jones, these proceedings) ensures that without other options operating effectively, it is only a matter of time before the low-level state is reached again and another shift must be considered. As drier zones are settled, crop production becomes increasingly hazardous and relevant crop selection and breeding frontiers press up against biological limits. Remittances from urban workers will become increasingly crucial for financial security.

Option C concerns implementation of yield-improving technology that is necessary for making continuously-cultivated systems sustainable. The most important question concerning the production side of the problem of future food-security is whether yield-improving technologies are, or can be made, economically feasible. A number of technologies (new genetic attributes and various agronomic management strategies) have been examined by earlier papers in this volume. In general, new technologies do not bring about significant improvements unless the soil infertility constraint is first relieved. Our research findings indicate that chemical fertiliser of the appropriate type and amount is an ingredient of the management strategy which is economically optimum and consistent with risk preferences of many farmers in this region, in spite of climatic limitations (Keating et al. and Wafula et al., these proceedings). This is reinforced by our observation that a few farmers rely upon chemical fertiliser to augment traditional soil fertility maintenance strategies, and do so very profitably.

Analysis of Supply and Demand for a Fertiliser-augmented Soil Enrichment Technology

Why do so many farmers choose to retain a farming strategy that seems to be so far below the optimum for them? A helpful approach to analysis is provided by the model of induced innovations (Ruttan and Hayami 1984) which is portrayed in its simplest form in Figure 3 (simplified from de Janvry and Dethier 1985). New technology comes about as the result of demand 'pull' and supply 'push', but the rate and direction of technological change is strongly influenced by relative prices of land, labour, capital and associated risks. Comparative information available to the decision-making process of both users and suppliers of technology can be considered as a payoff matrix. This comparative information includes that concerning the costs, benefits, and risks of the

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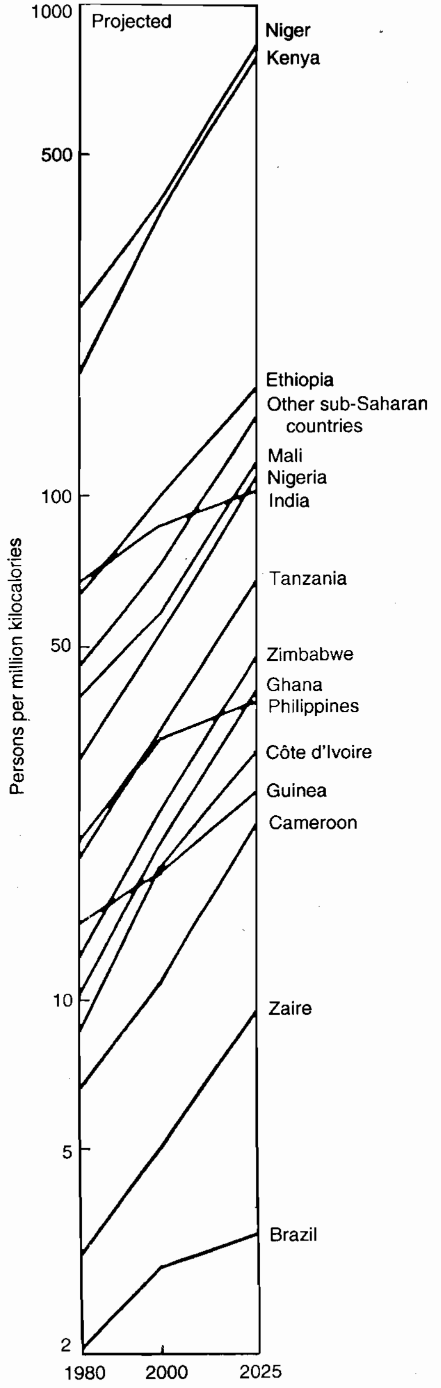

Fig. 1. Population pressure forecast in terms of rural people per million kilocalories of potential production, on a log scale (after Binswanger and Pingali 1988).

available alternative technologies. Not only does this influence producer choice, but it impacts upon supply of technologies by influencing research priorities; research institutions are rewarded for aligning research priorities with expected payoffs. From the demand side, the technology options are weighed against other options, for example, migration, or investment outside agricultural activities. The more variable the climate, the more difficult it is to compare alternatives in the payoff matrix and the more important it is to consider alternatives in the context of climatic risk.

From the fact that most farmers do not use fertiliser (even though it is available) it might be presumed that most farmers at present do not judge fertiliser as a contributor to the most profitable option in the expected payoffs matrix. Correspondingly, there is a strong tendency for Kenyan potential suppliers of innovations (researchers, extension workers) to accept this verdict. However, considering the human and ecological consequences of present technology remaining static as pressure of population continues to increase and soil fertility and production continues to decline, it is crucial that the option with the best technical prospects for sustaining yields is not dismissed prematurely.

Figure 4 shows a more comprehensive version of the induced innovation flow diagram. This 'structuralist model of induced innovations' (de Janvry and Dethier 1985) allows us to examine factors interfering with the market forces that underlie the supply of and demand for innovations. The elements corresponding with supply and demand in Figure 4 are qualified as 'latent' and the payoff matrix as 'expected'. Since we are focusing on the apparent lack of demand for a technology that we hypothesize is the optimum, we will begin with those factors that might influence latent demand (that is, what farmers think about this option) and the actual payoff matrix (that is, what they are able to do in implementing it). We believe that there are good reasons why many farmers would have an inaccurate perception of the probable benefits of this option because of the few opportunities for access to such information. This problem is compounded by the variability in yield response, often caused by variable seasonal water supply.

There is presently no well developed 'package' of recommendations for improving yields via soil enrichment through augmentation of scarce supplies of boma manure with chemical fertiliser. Even if a farmer realises the value of integrating fertiliser application into the existing system to avoid adverse effects on the soil (McCown and Jones, these proceedings), there may be supply constraints, including lack of capital to purchase fertiliser and poor access to supplies. These problems are compounded by any perception of investment risk due to poor rainfall, inadequate skill with the technology, or untimely supply.

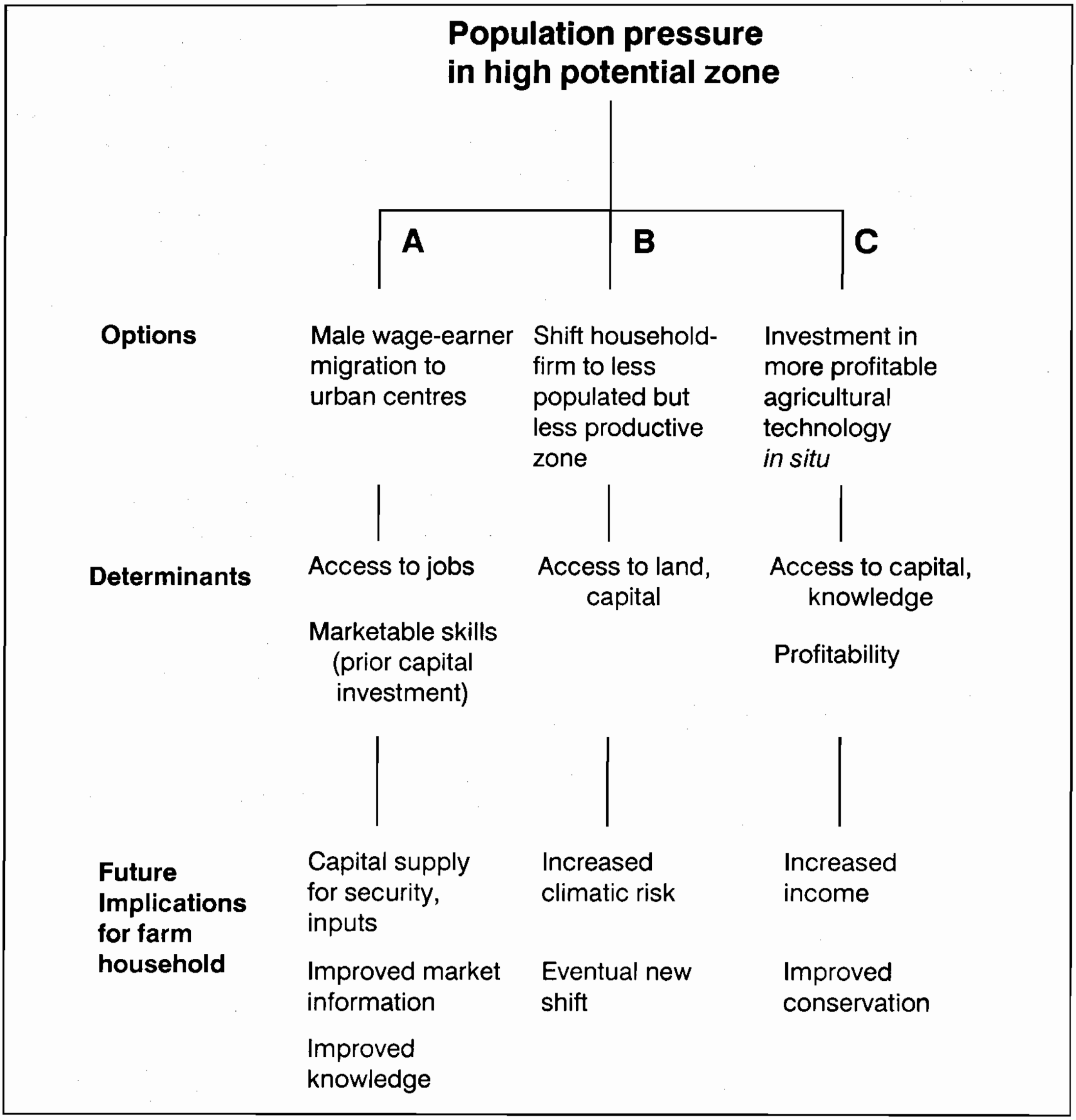

Fig. 2. Options open to farmers when faced with pressure for sustention induced by population growth, and their implications (after Mortimer and Tiffen, pers. comm.).

So far we have used Figure 4 to examine possible non-market explanations for non-adoption of fertilisers. We have not considered social payoffs from technological change and have not considered the state as a client of technology suppliers. It seems reasonable to question whether policymakers have either a realistic perception of the potential benefits of a fertiliser-augmented soil enrichment (FASE) strategy in Zone 4 (McCown and Jones, these proceedings), or of the risks and limitations of migration into the drier Zone 5. To date, agricultural science has provided little assistance to those seriously considering the policy option of encouraging fertiliser use. Information is needed on the potential of fertiliser use to increase incomes and improve food security for the highly populated, degraded areas in Zone 4, and on the risks that confront new settlers in yet uncultivated areas of the drier Zone 5 (Option B, Fig. 2).

An important result of this project is the placing of the FASE option in the expected payoff matrix in a more credible way. The requirement that, to be useful, credibility of FASE must be available in advance (ex ante) means that predictive tools are needed. Simulation

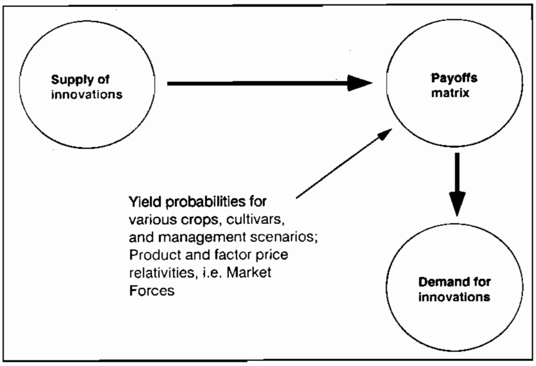

Fig. 3. Supply and demand for technological innovations (after de Janvry and Dethier 1985).

models, properly tested and validated, are a powerful tool for this purpose. Many of this project's resources have gone into field experimentation which provided such a tool for maize. This now provides the source of estimated yields for a wide range of relevant alternative production technologies. These are the data that enable economic analysis of costs and benefits for the expected payoff matrix. Economic analyses are shown in the lower left corner of Figure 4 in McCown and Jones (these proceedings) as the final task of the project.

Of the two potential beneficiaries of this research—farmers and policymakers—Figure 4 indicates that, in the usual situation where there are influences which distort market forces, policymakers are, in terms of action, 'upstream' of farmers. Government policy can be a tool for alleviating or compensating for factors which prevent farmers from adopting this technology. Ruthenberg (1980, p. 176) concluded that the fertiliser-driven soil enrichment option could be feasible in this farming system, but probably only if aided by some policy intervention . Mudahar (1986) indicated that this was likely to be in a form other than government fertiliser subsidies.

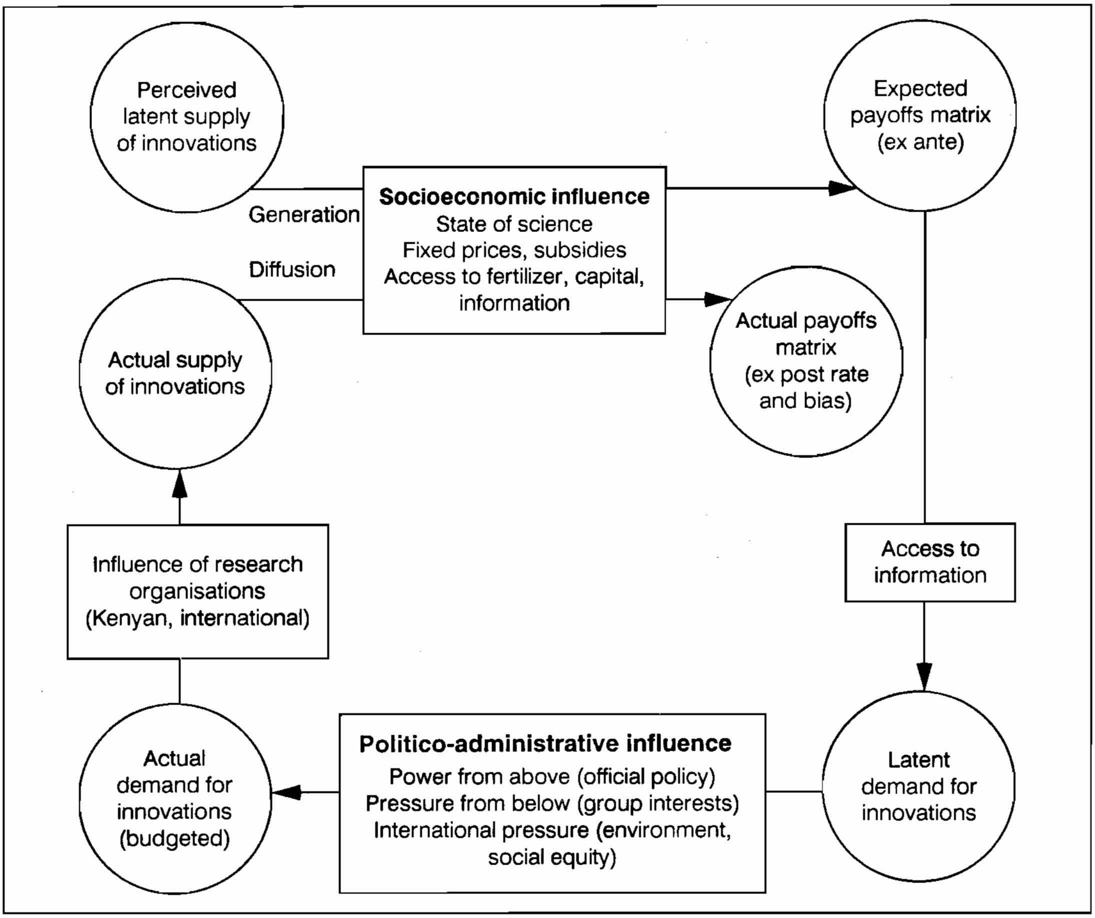

Fig. 4. Factors that interfere with the supply and demand for innovations within the context of induced innovations (after de Janvry and Dethier 1985).

Moving Towards a Sustainable Agriculture

There is a conflict that arises in the tailoring of a fertiliser strategy to a semi-arid environment. On the one hand, for a chemical fertiliser input to be technically efficient and not contribute to accelerated soil degradation, it needs to be part of a relatively complex package. On the other hand, as both the capital and management requirements of the package and the climatic risks are sufficiently large in relation to the expected improvement in returns, farmers are likely to resist adopting the entire package at once. In general, technology transformation attempts have a very poor success rate (Dommen 1988). Thus, it is necessary to conceptualise the ideal package in stages that can be implemented gradually without too much loss in total benefits.

In this, we have again turned to predictive models to examine the incremental progress that might be made from implementing different levels of inputs. These steps combine improvements in crop nutrition through N fertiliser application with improvements in crop water supply through return of crop residues. Plant population was optimised for each step (Table 1). While such steps would be, in reality, part of a progressive improvement in soil management, they are discrete for this analysis, since the long-term effects of fertilisation and residue return on soil fertility, structure and erosion losses are not considered. Neither have we explicitly modelled the impact of the return of crop residues on runoff, but have altered curve numbers within the model so that reductions in runoff of the magnitude shown in Table 1 were assumed. Effects of this magnitude are considered realistic (see Okwach et al., these proceedings).

Average maize yield at Katumani over the 1957–1988 period is predicted to increase from 970 kg/ha to 2740 kg/ha as inputs and associated management practices change from step 1 to step 4 (Figure 5).

Step 1 is a scenario that approximates the present system. Maize is grown at low plant populations without fertiliser nitrogen and with high runoff losses in the absence of the return of crop residues. The mean grain yield simulated (970 kg/ha) is on the upper side of the average reported for the region (700–900 kg/ha; Jaetzold and Schmidt 1983) but in our case we have not considered losses due to poor management, such as delayed planting, weeds or pests.

Step 2 involves small inputs of nitrogen fertiliser (10 kg N per ha), some increase in plant population and return of the 'additional' stover produced (that is, over and above Step 1) to the soil surface (Table1). Step 3 involves further increases in nitrogen fertiliser (20 kg N per ha), plant population and return of stover.

Step 4, with optimal N fertilisation (40 kg N per ha) and plant population (4.4 plants/m^2) and little runoff, is a scenario that approaches the production potential for this environment with excellent management (2740 kg grain per ha).

This analysis suggests that useful gains could be made with modest inputs of nitrogen, residue return and appropriate crop management (compare, for example, step 2 with step 1).

Being Realistic

We realize that to even suggest that a fertiliser-based strategy for smallholders in a climatically risky region might be feasible appears to many as naive. Nevertheless, we are faced with the certainty that the yields of a farming system which has increasing numbers of people continually taking more from the soil than they replace will not only decline to low levels, but also will respond little to any investment except soil enrichment. We argue that it may be even more heroic (or naive) to plan systems of production which increase intensity of cropping with no tested plan for compensating for additional extraction rates. For example, the nominal 'plan' for fertility maintenance in the Makueni project was for farmers to use manure, rotations and grass leys (Lynam 1978), and it has taken only about 20–30 years for the unsustainability of the strategy to become clear. Illusions of sustainable production of farms settled later may last longer, but the decline to a low-level equilibrium (Fig. 3 in McCown and Jones, these proceedings), is avoidable only by higher rates of replacement of nutrients than occurs with present technology.

Table 1. Management inputs and parameters of the soil water balance for the simulation of four possible steps towards enhanced productivity (see Fig. 5).

Step	Fertilizer N (kg/ha)	Plant population (per m^2)	Soil organic matter % (0–15 cm)	Runoff curve no.	Mean seasonal runoff (mm)	Soil evap. coefficient (mm)
1	0	1.6	0.9	80	62	9
2	10	2.2	1.0	70	40	7
3	20	3.3	1.1	60	23	5
4	40	4.4	1.2	50	12	4

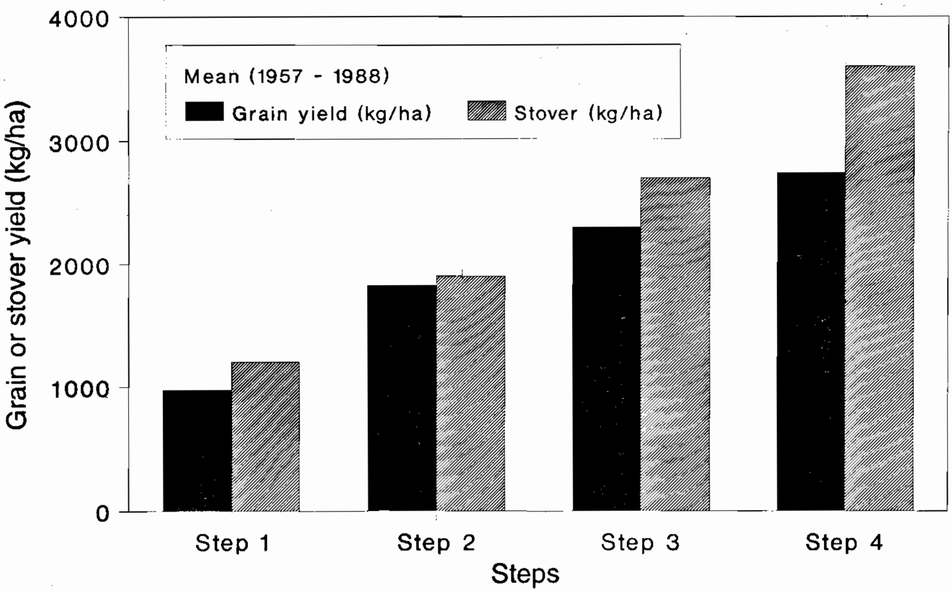

Fig. 5. Mean maize yields simulated for Katumani weather over the 1957 to 1988 period with increasing levels of inputs (details given in Table 1).

Even if it is evident that FASE is the optimal strategy for some farmers, we recognise that it will not be so for all. Farmers within this farming system differ enormously in the climate, soil and financial resources available to them and in their knowledge and abilities. Statistics from other tropical cropping regions show that fertiliser use is highest where incomes are highest and risks are lowest, such as in fertile irrigated regions (Anon. 1989). It is significant, however, that fertiliser use is increasing in dryland areas (Anon. 1989), and favourable economics are increasingly being demonstrated (McIntire 1986). A policy to encourage fertiliser use in the Machakos-Kitui Districts might bring criticisms from those especially concerned with social equity in development. However, there is a growing case that adoption of FASE by farmers with sufficient means is preferable to a continued shared slide into deeper regional poverty and food insecurity. Due largely to present or past off-farm earnings, a sizeable proportion of farmers in the Machakos–Kitui area would often enough have the means to buy a bag of fertiliser if they believe the returns to be great enough (Lutta Muhammad, pers. comm.). If the economics of FASE prove to be favourable, this initial injection of capital is the key to escape from the trap in Figure 3 of McCown and Jones (these proceedings) by initiating a gradual recovery of system productivity and income.

Although fertiliser supply is a major problem in much of the African SAT, in Machakos–Kitui, supply infrastructure is in place to serve the coffee-growers in agroecological zone III. However, little service in supplying information and advice is provided from retailers, because fixed prices limit their profits and hence their incentive to market aggressively (Abbott 1983). A further problem is that all fertiliser in Kenya is imported, and except for that which arrives as international aid, its acquisition requires foreign currency expenditure. Even if it is demonstrated that fertiliser is important in the economically optimum production strategy in the medium-potential area of Machakos–Kitui, it is possible that this would be a suboptimal policy from a national perspective. Returns may be greater in higher potential zones, especially under conditions of limited supplies and problems of negative balance of payments. However, such a comparison should not be prejudged; it should be made in the light of the best estimate of the payoffs from a FASE strategy, including effects on reduction of costly food relief for the region.

The implementation of a FASE strategy requires research on integrating a new input with the existing system. Because the marginal income benefits will be less than in wetter climates, it is important that recommendations be efficiently tailored for local circumstances. The knowledge base for this would need to be acquired from research on a considerable number of interactions with other practices, soil type, and plot history. This can be justified only if the outcome of the ex ante study indicates that the expected benefits warrant it. The primary investment of this project is in ascertaining if a FASE strategy is economically feasible. If it proves to be so, a major new research initiative will be required to develop, in conjunction with farmers, the specific recommendations for a wide range of circumstances, including farmers' attitudes and beliefs concerning risk, that occur within this region.

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