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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

Co-sponsors:

Kenya Agricultural Research Institute
Australian Centre for International Agricultural Research (ACIAR)
Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

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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).

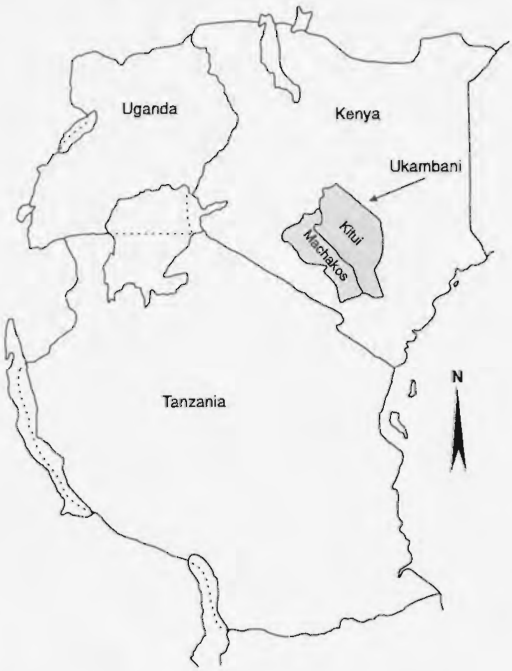

Fig. 1. Map of Kenya and some of its immediate neighbours, showing the location of Machakos and Kitui districts.

* QDPI/CSIRO Agricultural Production Systems Research Unit, PO Box 102, Toowoomba, Queensland 4350, Australia.

† CSIRO Division of Tropical Crops and Pastures, 306 Carmody Road, St Lucia, Queensland 4067, Australia.

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

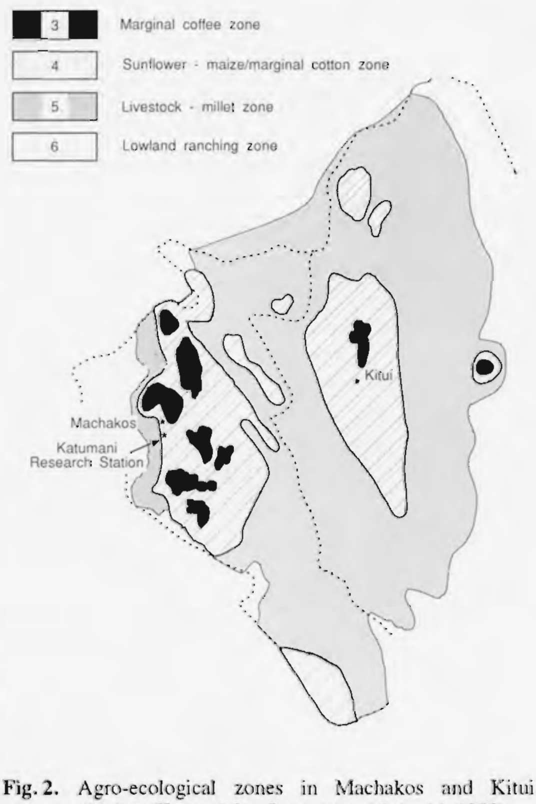

Fig. 2. Agro-ecological zones in Machakos and Kitui districts, Kenya (after Jaetzold and Schmidt 1983).

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.

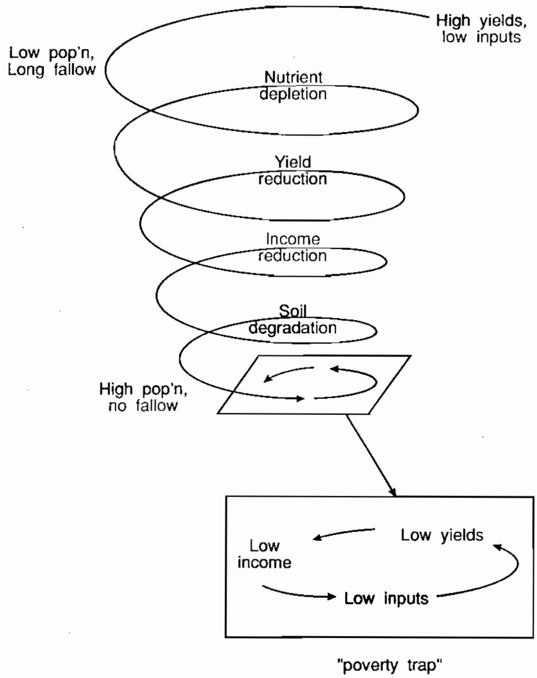

Fig. 3. Diagram showing how increasing populations and continuous cropping without inputs degrade farming systems in the semi-arid tropics to low levels of productivity (the 'poverty trap').

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

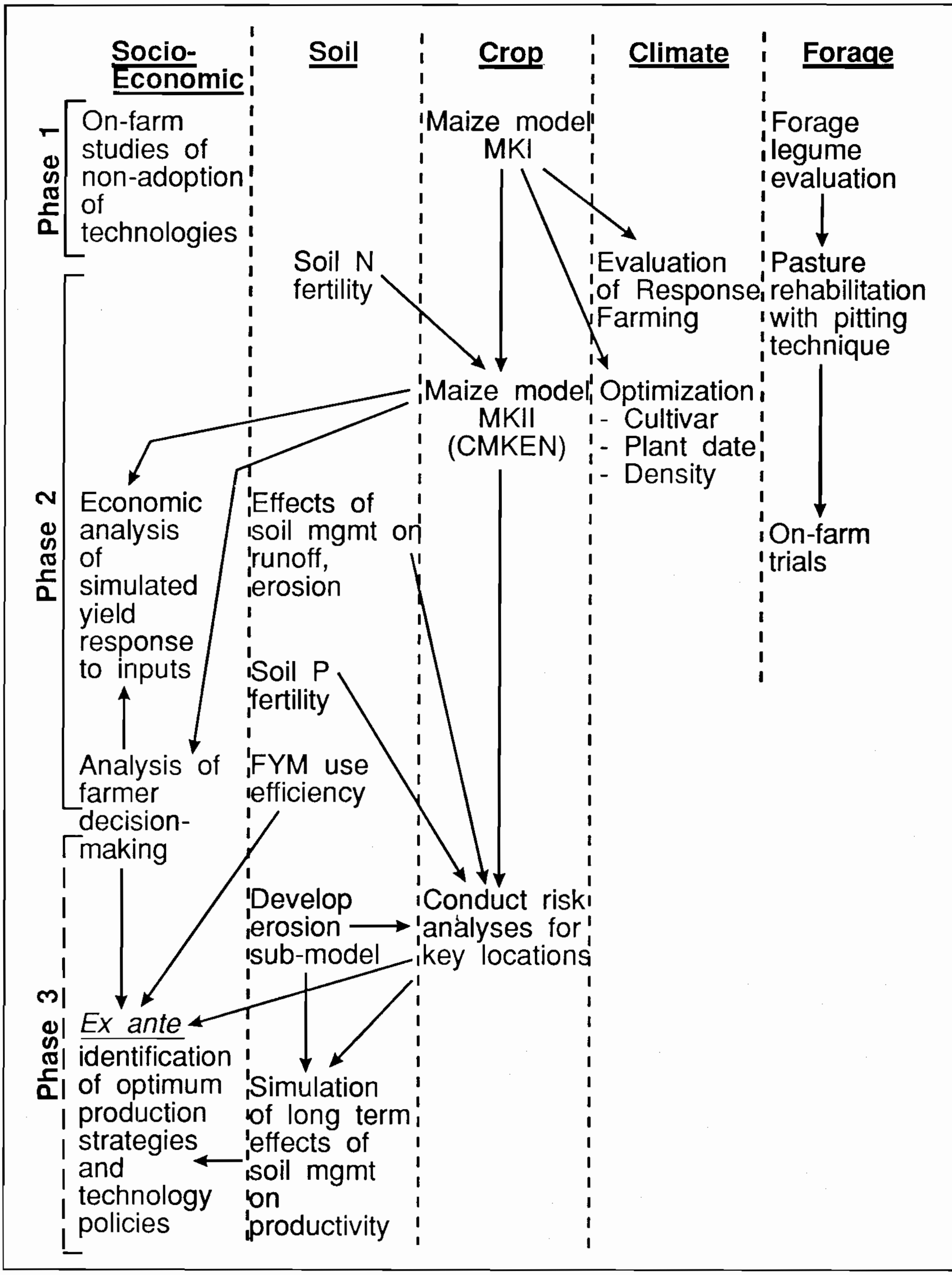

Fig. 4. Schema of research activities, disciplines and phases in the KARI/ACIAR collaborative research project on farming systems in the Machakos and Kitui districts of eastern Kenya.

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

B.A. Keating,* M.N. Siambi† and B.M. Wafula†

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.

* CSIRO Division of Tropical Crops and Pastures, 306 Carmody Road, St Lucia, Queensland 4067, Australia.

† Kenya Agricultural Research Institute, Katumani National Dryland Farming Research Centre, PO Box 340, Machakos, Kenya

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

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

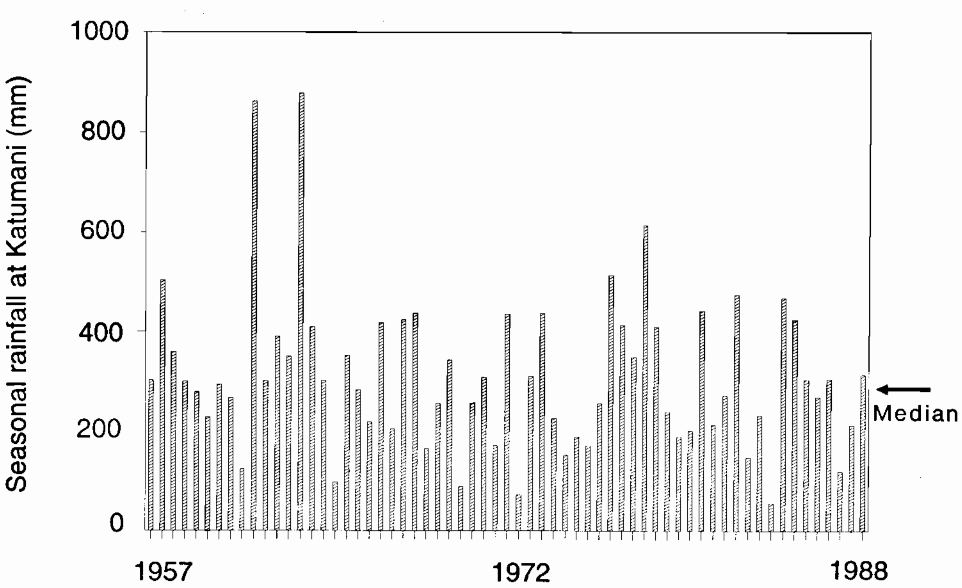


Fig. 1. The variation in seasonal rainfall at Katumani Research Station over the 1957 to 1988 period. Seasonal rainfall is defined as the period from onset to physiological maturity of KCB maize: approximately 110–130 days.

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.

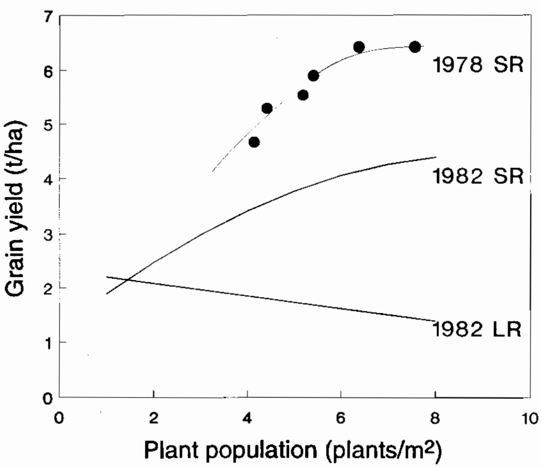


Fig. 2. Responses to plant population in maize for two wetter-than-average seasons (1978SR — 550 mm and 1982SR — 460 mm) and a drier-than-average season (1982LR — 245 mm) at Katumani (after Nadar 1984a).

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

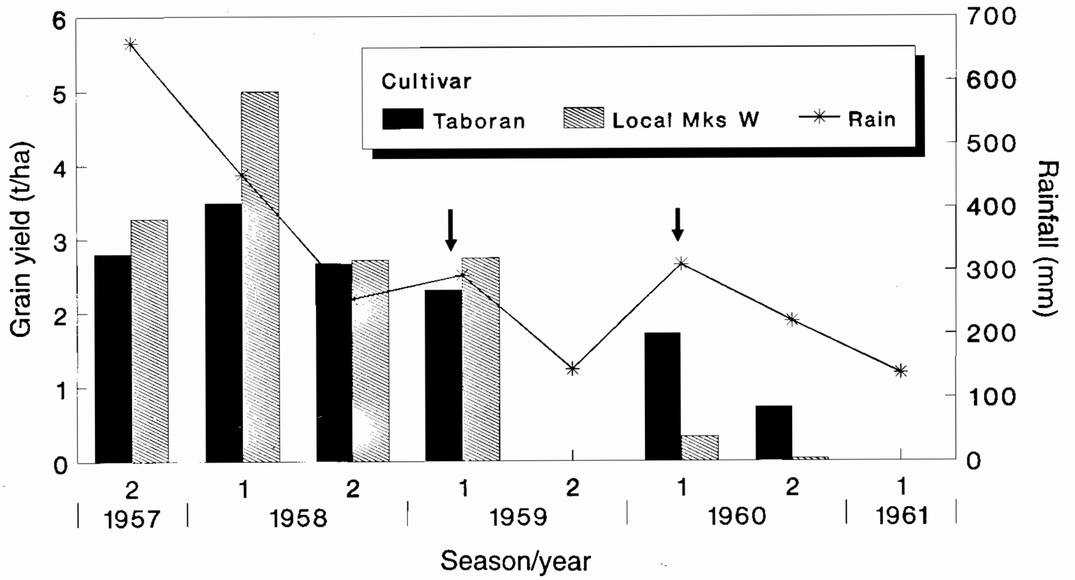


Fig. 3. Grain yield of Taboran (early flowering) and Local Machakos White (late flowering) maize over the 1957 to 1961 period at Katumani. Seasonal rainfall is also shown (after Dowker 1971). See text for explanation of arrows.

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

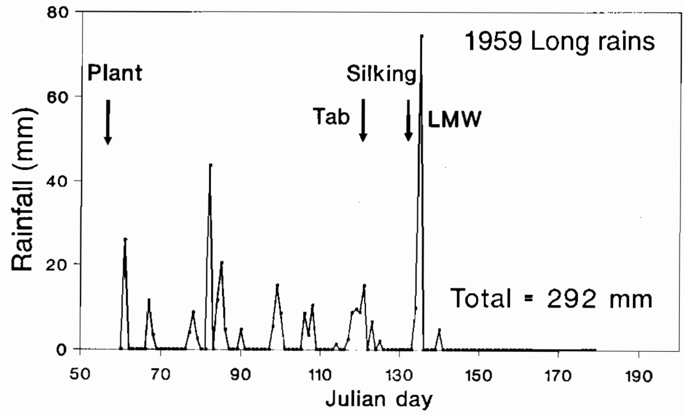
Strategies Used to Deal with Complexity and Variability

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



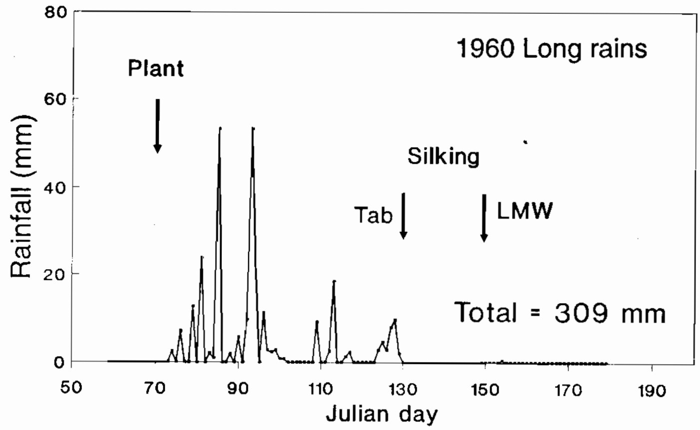


Fig. 4. Daily rainfall distribution at Katumani over the 1959 and 1960 long rains seasons in relation to estimates of planting, silking and harvest dates for Taboran (TAB) and Local Machakos White (LMW) (adapted from Dowker 1971).

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)

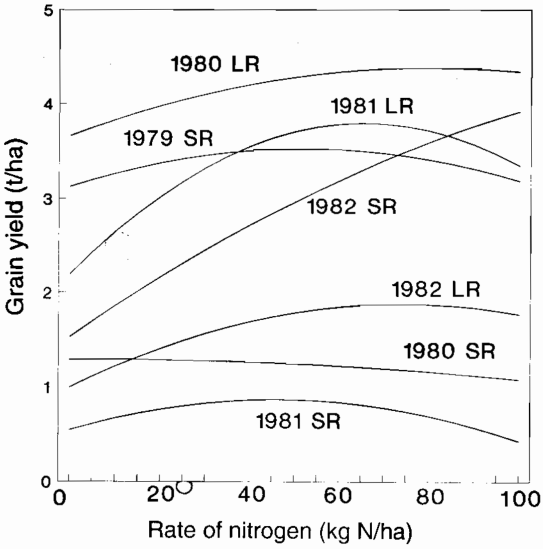


Fig. 5. Response of maize grain yield to nitrogen fertiliser at Katumani over the 1979 to 1982 period (after Nadar 1984).

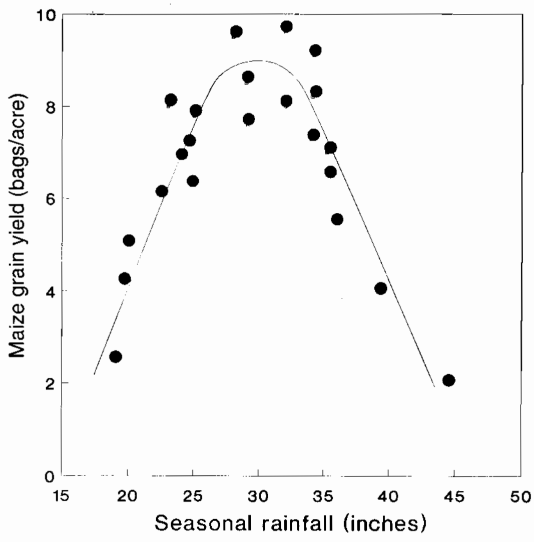


Fig. 7. The relationship between maize yield in Western Kenya and rainfall over the 1943 to 1953 period (after Glover 1957).

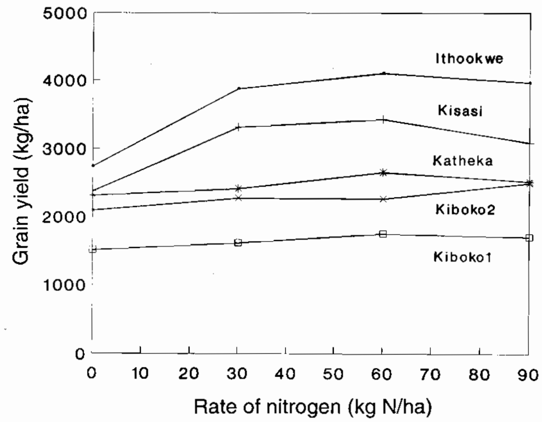


Fig. 6. Response of maize grain yield to nitrogen fertiliser at a range of sites in the short rains of 1981 (after Okalebo 1987).

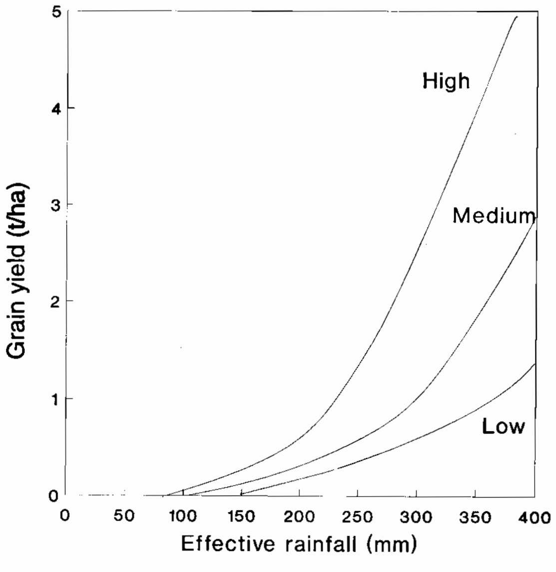


Fig. 8. The relationships between the yield of maize grain (KCB) and estimates of effective rainfall (mm) for different levels of fertility and management (after Stewart and Faught 1984).

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 — 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

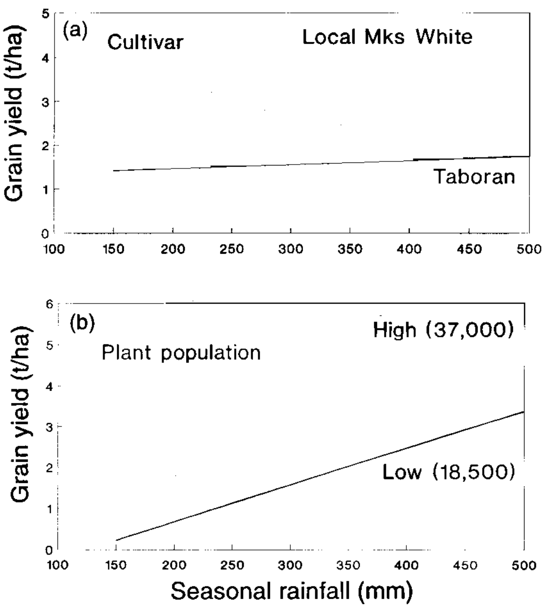


Fig. 9. Regression models of maize grain yield on seasonal rainfall for (a) two cultivars and (b) two plant populations developed by Dowker (1971).

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

B.A. Keating,* B.M. Wafula† and J.M. Watiki†

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.

* CSIRO Division of Tropical Crops and Pastures, 306 Carmody Road, St Lucia, Queensland 4067, Australia.

† Kenya Agricultural Research Institute, Katumani National Dryland Farming Research Centre, PO Box 340, Machakos, Kenya.

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

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	27-11-87	KCB	–	1.1– 6.3	12	0
	(both Field E)						
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.

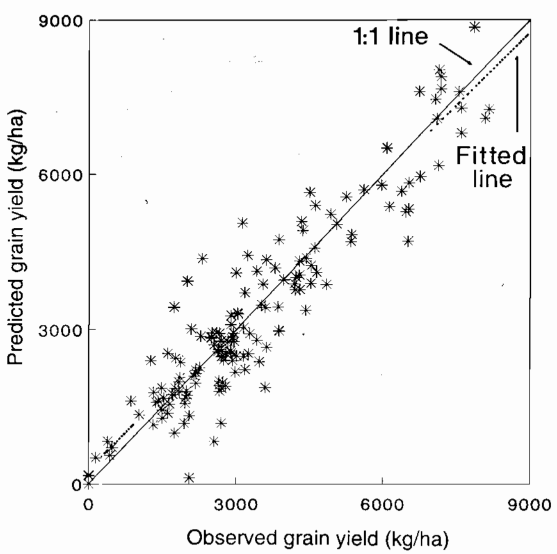

Fig. 1. Comparison of observed maize grain yield with that predicted by CM–KEN. Solid line is 1:1; the fitted (broken) line has slope (s.e.) = 0.94 (0.03); intercept (s.e.) = 249 (103), r^2 = 0.88, n = 159.

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

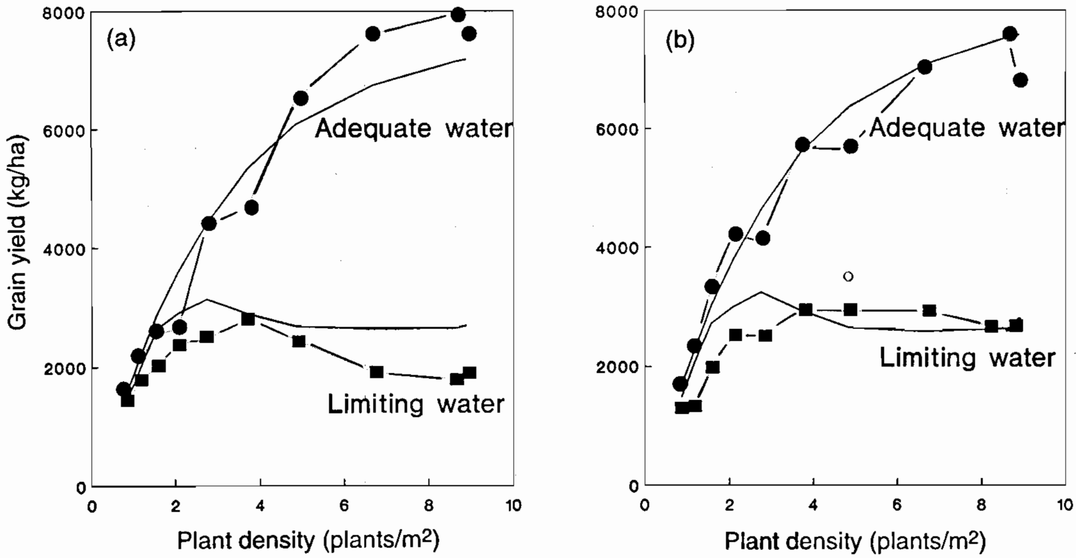

Fig. 2. Observed (symbols, broken lines) yields for maize under two water regimes (wet = circles, dry = squares) at a range of plant populations (Experiment 4). Yield predicted by CM–KEN is also shown (solid lines). Details of water regimes are given in Table 2.

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

(b) The cultivar Dryland Composite (DLC).

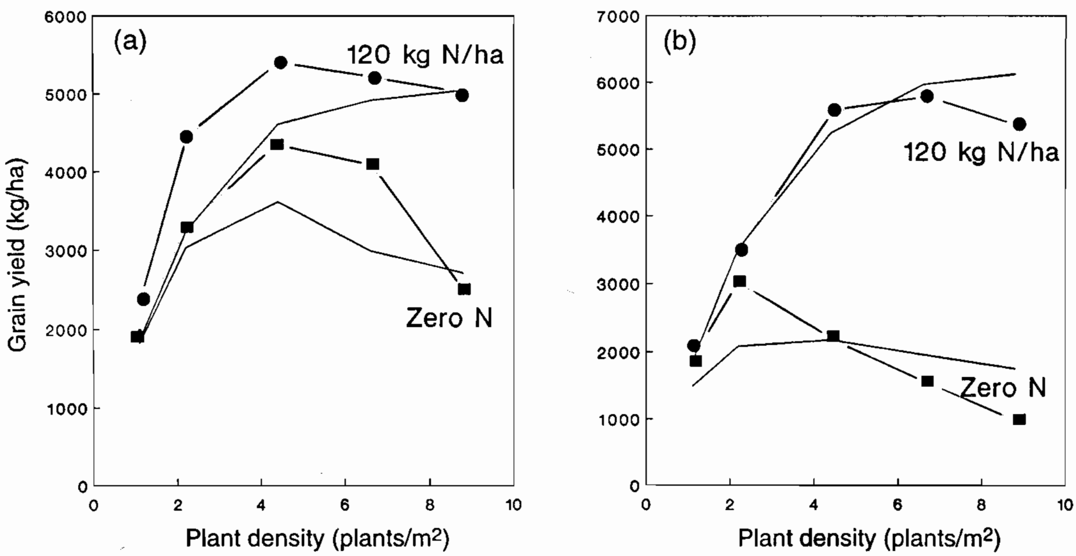

Fig. 3. Observed (symbols, broken lines) yields for maize under two nitrogen regimes (high N = circles, low N = squares) at a range of plant populations (Experiment 6). Yield predicted by CM–KEN is also shown (solid lines). Other details are given in Table 2.

(a) At Katumani – rainfed.

(b) At Kiboko under irrigation.

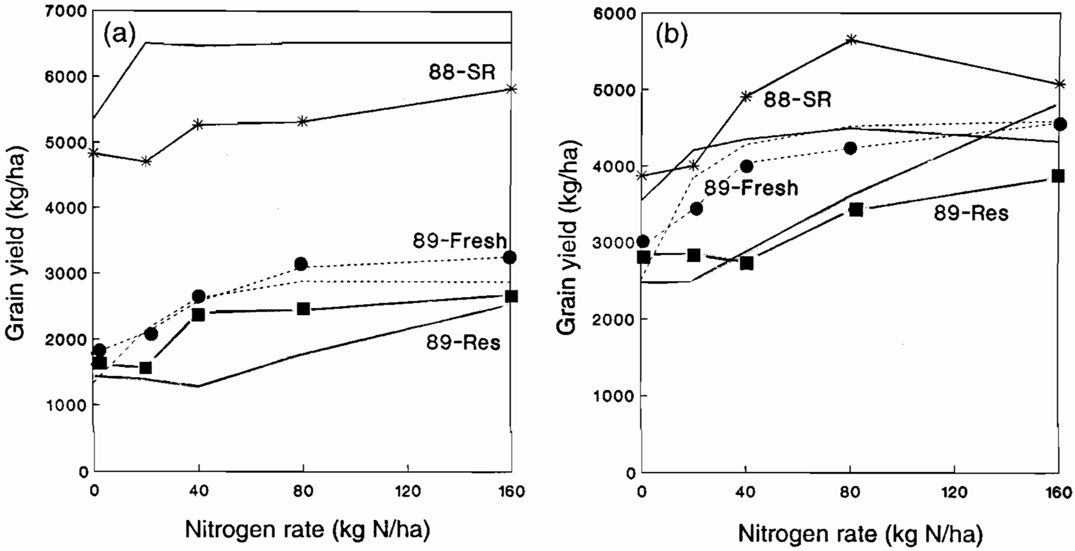

Fig. 4. Observed (symbols) yields for maize in relation to rate of nitrogen fertiliser (Experiment 7). Upper heavy solid line and * (fresh application in 1988-SR – expt 7a). Middle dashed line and round symbols (fresh application in 1989-LR). Lower solid line and square symbols (residual value of fertiliser 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.

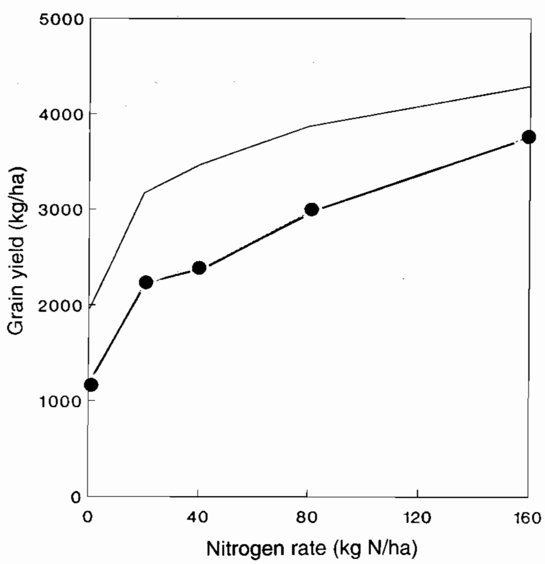

Fig. 5. Observed yields (symbols, lower line) for maize in response to nitrogen fertilisation on Kyengo's farm under farmer management (Experiment 8). Yield predicted by CM–KEN is also shown (upper line).

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.

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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

P.S. Carberry,* R.L. McCown,* J.P. Dimes,† B.H. Wall,† D.G. Abrecht,† 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.

* QDPI–CSIRO Agricultural Production Systems Research Unit, PO Box 102, Toowoomba, Queensland 4350, Australia.

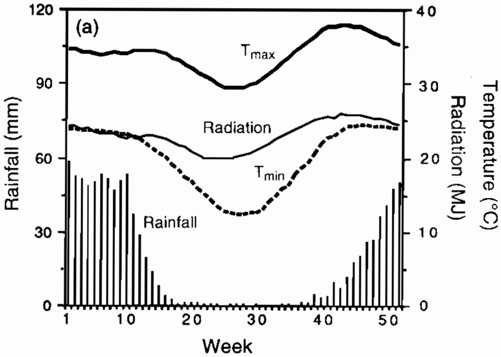
† CSIRO Division of Tropical Crops and Pastures, Davies Laboratory, PMB Aitkenvale, Queensland 4814, Australia.

§ Kenya Agricultural Research Institute, Katumani National Dryland Farming Research Centre, PO Box 340, Machakos, Kenya.

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



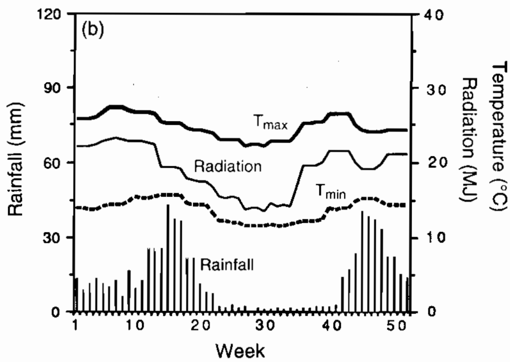


Fig. 1. Mean weekly rainfall, solar radiation, and maximum and minimum temperatures at (a) Katherine, Northern Territory, Australia (lat. 14°S; elev. 120 m; annual rainfall 871 mm); and (b) Machakos, Kenya (lat. 1°N; elev. 1600 m; annual rainfall 890 mm).

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.

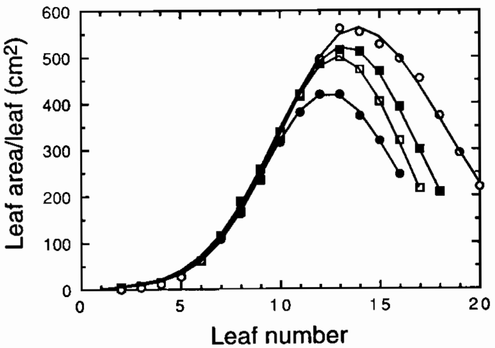


Fig. 2. Fully expanded area of individual leaves for sorghum plants with final leaf numbers of 16, 17, 18 and 20 leaves. The fitted relationship is of the form

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

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.

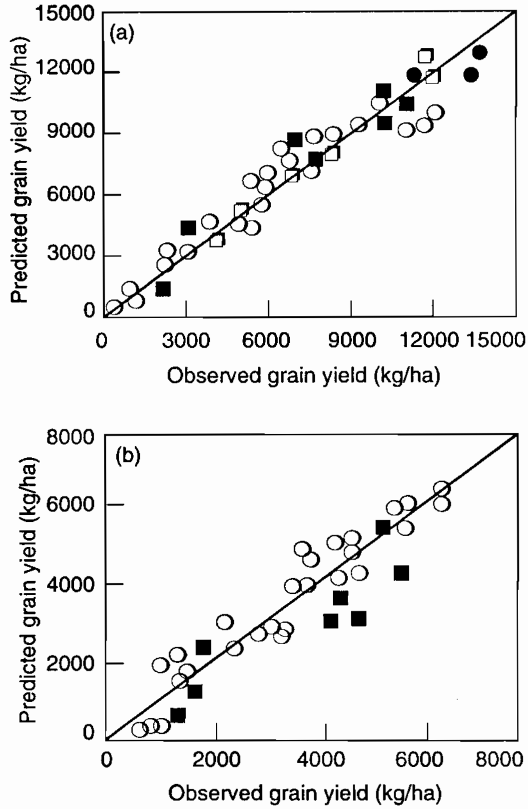


Fig. 3. Grain yields predicted by maize and sorghum simulation models versus observed oven-dry grain yields for a number of experiments: (a) maize; (b) sorghum. Key: ○ = Katherine; ▲ = N.T.; □ = W.A.; ● = S.E. Qld; ■ = N. Qld; —— = 1:1 line.

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	Sowing date	Daylength	Leaf number		Silking	
	(°S)		(h)	KCB	XL82	KCB	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

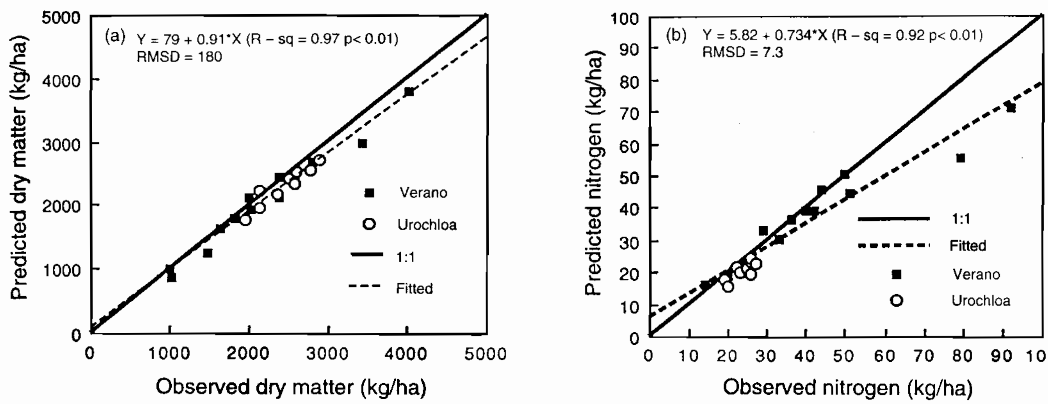


Fig. 4. Predicted versus observed recovery (kg/ha) of (a) dry matter, and (b) nitrogen from residues applied to the soil surface.

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

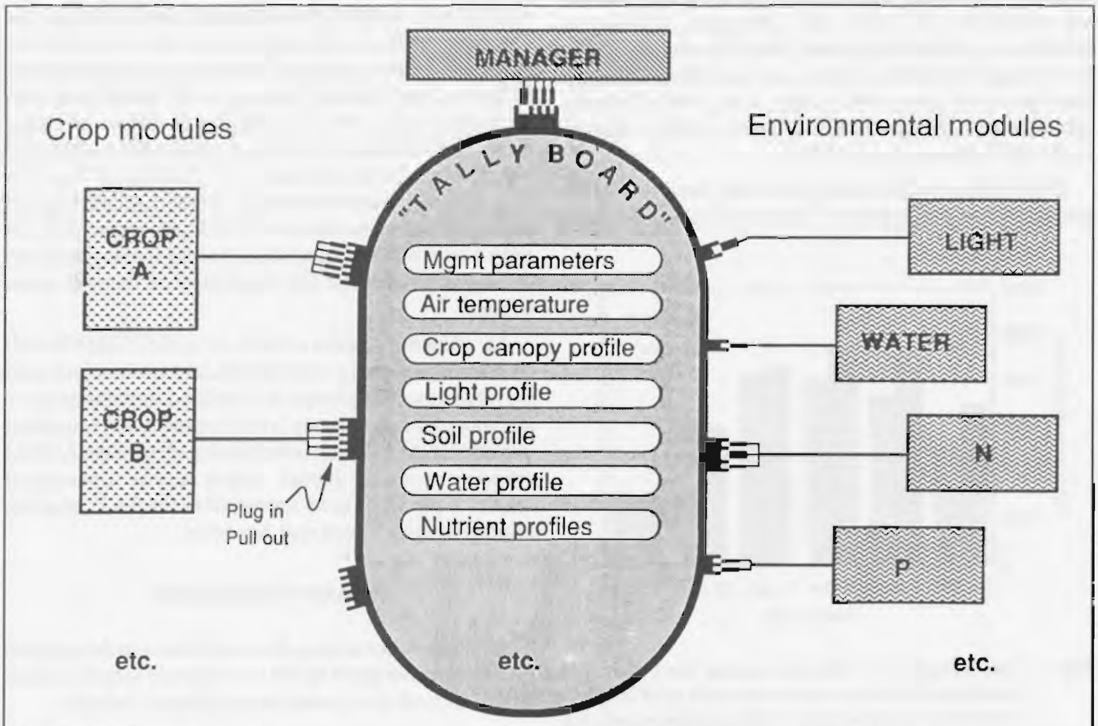


Fig. 5. Program structure of the AUSIM cropping systems model.

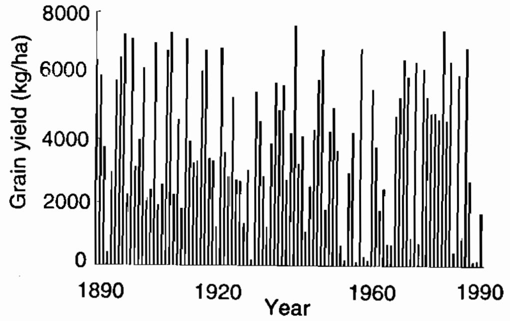


Fig. 6. Simulated maize grain yields from 1889 to 1988 at Katherine (Carberry and Muchow 1991).

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

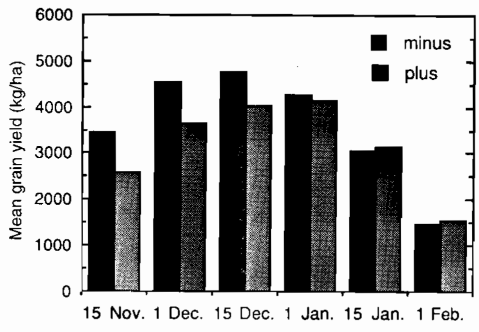


Fig. 7. The influence of different sowing dates over 100 seasons at Katherine on the mean grain yield of maize simulated with either plus or minus enhancements for simulating problems during crop establishment (Carberry and Abrecht 1991).

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.

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.

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